NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 363

Role of Highway Maintenance in Integrated Management Systems

Transportation Research Board
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M.J. MARKOW, F.D. HARRISON, P.D. THOMPSON, and E.A. HARPER
Cambridge Systematics, Inc.
Cambridge, MA

W.A. HYMAN and R.M. ALFELOR
The Urban Institute
Washington, DC

W.G. MORTENSON
Bergstralh-Shaw-Newman, Inc.
Frederick, MD

T.M. ALEXANDER
Space Development Services, Inc.
Chevy Chase, MD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report outlines a framework for integrating maintenance management with other highway and administrative management functions. This framework considers the next generation of maintenance management systems, and how they must respond to the organizational, political, and technological trends that have emerged in recent years. Maintenance engineers and managers who are responsible for performing maintenance functions, integrating maintenance decisions with other agency decision making, and obtaining budget levels necessary to maintain infrastructure in a safe and efficient operable condition will find the report useful. Also, the report will be of interest to chief administrative officers having responsibility for major management information system development decisions and to strategic planners and agency executive staff having overall responsibility for funding, budgeting, capital programming, and adapting an agency to today's changing conditions.

With the increasing demand for maintenance work and the limitation on the availability of increasingly sophisticated services, managers will have to consider maintenance with other options in a more flexible, integrated decision-making framework. Also, with the increasing use of computerized management information systems at the state level and the recently mandated federal requirements for implementation of management systems, the concept of a coordinated and integrated approach to system development promises to avoid duplication of effort through effective information sharing. Therefore, the next generation of maintenance management information systems must consider the evolving role of highway maintenance and respond to the different organizational and administrative needs of departments of transportation across the country.

Under NCHRP Project 14-9(4), "Role of Highway Maintenance in Integrated Management Systems," Cambridge Systematics, Inc. was assigned the task of designing an idealized maintenance management information system (MMIS) based on data available from all transportation information systems and developing a guide to assist state transportation agencies with its implementation. This work has shown that the shape of the next generation of MMIS is heavily influenced by concerns of implementation feasibility, cost, value to top management, and autonomy of local office management. However, a balance among these concerns can be achieved through careful selection of processes and technologies. As a result of this project, a framework for integrating maintenance management with other highway and administrative management functions has been developed. This framework, referred to as the "hub-and-spoke" approach, consists of centralized pools of shared data and common procedures (the hub) serving a number of stations (the spokes), each with the capability to access a local subset of data and to perform specialized analyses. While the hub-and-spoke concept simultaneously serves the needs for centralized and decentralized shared decision making, it is independent of computer platform and technology, and thus can be adapted to any of the variations of computer systems and architecture in use by departments of transportation today.

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Michael J. Markow, a Principal of Cambridge Systematics, was the principal investigator. William A. Hyman, Director of the Transportation Studies Program at The Urban Institute, was the co-principal investigator. The other authors of this report are as follows: Frances D. Harrison, Paul D. Thompson, and Elizabeth A. Harper of Cambridge Systematics; Roemer Alfelor of the Urban Institute; William G. Mortenson of Bergstralh-Shaw-Newman; and Timothy M. Alexander of Space Development Services. The authors wish to acknowledge technical contributions by Mr. John Marcotte of The Urban Institute to this report.

Executive Summary

■ 1. Introduction

Maintenance management systems were among the first applications of rational management principles and the (then) new technology of computers to highway operations. The development of these systems for maintenance 25 years ago was followed by systems for pavements, bridges, equipment, materials, capital programming, contract administration, and other applications to help highway agencies do their job better. Each new system took advantage of new ideas and the ever-improving technology in computer hardware and software. Because of this evolutionary process, however, today's collection of management systems in highway agencies is based upon a range of hardware systems extending from large mainframe computers to personal computers, organized in various ways from centralized to decentralized management structures. As a result, the systems are often incompatible with one another, impeding the efficient and timely flow of information among them.

Recent changes in the composition and funding of highway programs, the organizational structures and missions of highway agencies, and federal legislation governing the development and use of management systems have focused increased attention on the design and use of such systems, as well as how to make them work better together. At the same time, highway departments are revisiting their maintenance management systems to see how these systems can be updated to meet new demands on how the maintenance program must be managed, and to take advantage of new concepts, analytic procedures, and technologies that have benefited management systems in the past two decades.

The objectives of this research were to establish a new conceptual design of a maintenance management system (MMIS), to consider the integration of this system with other management systems, and to explore potential applications of new technology. The model MMIS was viewed as typifying the next-generation maintenance management approach, rather than simply an incremental adjustment to existing systems. Nevertheless, the design would permit agencies to select those components or phases of the system approach that best met their particular needs and objectives. Thus, the overall design of the model MMIS – while comprehensive – could be tailored to the requirements of agencies representing a mix of organizational structures and cultures, transportation system characteristics and requirements, and management demands.

2. Maintenance Management Today

This report looks to the next generation of maintenance management systems and how they must respond to the organizational, political, and technological trends that have emerged in recent years:

- The role of highway maintenance is evolving. There is increasing demand for maintenance work and a limited supply of increasingly sophisticated maintenance services.
- The growing use of computerized management systems seen in the past two decades will continue as the result of recent federal legislation. The concept of a coordinated and integrated approach to system development and use promises not only to avoid duplication of effort, but also to make better use of shared information and to coordinate decisions.
- Emerging technologies will enable improved data acquisition and locational-based processing, retrieval, and display of information in support of maintenance and other management information systems.
- A model maintenance management information system must respond to the different organizational and administrative needs that exist among DOTs across the country.

When current maintenance management systems are considered in light of these trends, the following assessments emerge:

- The current maintenance management systems were right for their time, helping in the planning, budgeting, monitoring, and evaluation of maintenance work, and fostering standard methods and productivity guidelines. Many changes have occurred since these systems were first developed, however; in this light, several improvements are needed in current systems, as described below.

- At both the strategic planning and the operational levels, MMSs need to be integrated more with other types of decisions governing capital improvements and operations. More recent systems developed for pavements and bridges, for example, are based upon life-cycle cost approaches and a longer analysis horizon than the 1- to 2-year outlook of most MMSs, and they include methods to identify the recommended levels of service to be provided by different activities.

- Traditional MMSs adopted a highly centralized approach to maintenance planning, scheduling, and control, which is beneficial in some ways but has limited system effectiveness in many respects. For example, centralized, outmoded data processing and reporting methods are burdensome and time consuming for field personnel and are unable to produce reports timely enough for effective management use.

- Current MMSs are not flexible enough to adjust work plans and schedules to reflect changing conditions, nor does their design approach accommodate easily to variations in workload rates (or quantity standards) and performance standards to reflect variations across a state due to geography or the availability of labor, equipment, materials, or dollar resources.

- Current systems "force fit" all activities into the same planning and analysis framework, ignoring the considerable variation in the types of activities encompassed by maintenance. Current systems also do not adequately consider the interaction among activities (precluding the analysis of tradeoffs).

■ 3. Recommended Advances in Maintenance Management

Three broad classes of improvements are recommended toward a model MMIS:

1. System components and features should be reformulated to overcome the problems identified above in current systems.

2. New types of analyses should be incorporated within maintenance management planning and budgeting, following the leads established by pavement management and bridge management systems.

3. Maintenance management should be integrated within the larger framework of management systems and functions within an agency.

Each of these recommendations is described in the sections below.

Updates of System Features and Components

Many of the system components and features that have formed the building blocks of maintenance management systems in the past will continue to be key elements in the next-generation MMIS, but the ways in which these features are defined and used should change: for example,

- **Maintenance activities:** The list of maintenance activities should be reformulated to accommodate the needs of both high- and low-level maintenance management.

- **Feature inventory:** Inventories of physical assets to be maintained should be accompanied by data on their condition and functional obsolescence. Inventories of nonphysical assets (e.g., grass to be mowed) should be accompanied by data on the level of service actually being achieved (e.g., current actual frequency of mowing).

- **Performance standards:** Resource requirements and estimated production rates should be defined more flexibly to reflect local conditions, actual availability of resources, and level of service standards.

- **Levels of service:** Distinct measures of levels of service, or quality standards, should be defined and incorporated within the MMIS's planning and budgeting routines. (Refer also to the next item and the following section on maintenance analyses.)

- **Work programs and performance budgets:** Traditional MMSs produce work programs based on needs, regardless of budget availability. An important capability of an idealized MMIS is to allow quick, realistic adjustments in work programs to meet budget constraints and shifts in priorities.

- **Work calendars:** Calendars showing the crew days needed each month to have a leveled workload should be extended to cover not only scheduled activities, but also work responding to emergencies, service requests, and other demand-driven requirements.

- **Resource requirements:** An improved MMIS needs the capability to adjust resource requirements based upon the degree of contracting expected to occur.

- **Scheduling:** Improved scheduling methods are needed to account for all of the factors affecting the assignment of resources to activities, including the work calendar, service requests, emergency and urgent work, leftovers from the previous scheduling period, and condition and distress surveys from the pavement and bridge management systems.

- **Work reporting:** Work reporting should involve a single source and instance of data entry to avoid duplication, wasted effort, and possible sources of inconsistency or error.

- **Management reports:** Reports to various management levels should be more timely, present only the information needed, and allow reporting by sections of road in addition to current reporting by organizational unit or area.

New Analyses

The next-generation MMIS should build upon the experience gained through pavement management and bridge management systems over the past 15 years, in order to base planning and budgeting upon a combination of engineering, economic, and management principles. The MMIS should be capable of performing the following types of analyses:

- Tradeoffs between routine maintenance and capital activities (e.g., resurfacing, rehabilitation).

- Tradeoffs in the levels of service to be provided in one or more activities, including the impacts of deferred maintenance.

- Consideration of both agency and user costs within a life-cycle cost framework.

- Needs analyses, assuming both unconstrained and constrained budgets.

- Optimal resource allocation.

- Reduction of data and summarization for management purposes.

These types of analyses can be performed within a framework referred to as a "demand-responsive" approach to maintenance management. This approach, similar to that employed in pavement and bridge management systems, views maintenance activities as a response to the "demand" for maintenance work – i.e., the deterioration of the highway system, or changes in its condition. Furthermore, this approach builds upon an economic framework rooted in life-cycle cost estimation, and a prediction of both the impacts (or consequences) of maintenance as well as its costs. Also, variations in the levels of service (or quality standards) by maintenance activity serve as expressions of maintenance policy, with the goal of identifying the particular levels of service among all activities that provide the optimal balance between the costs and the consequences of the maintenance program.

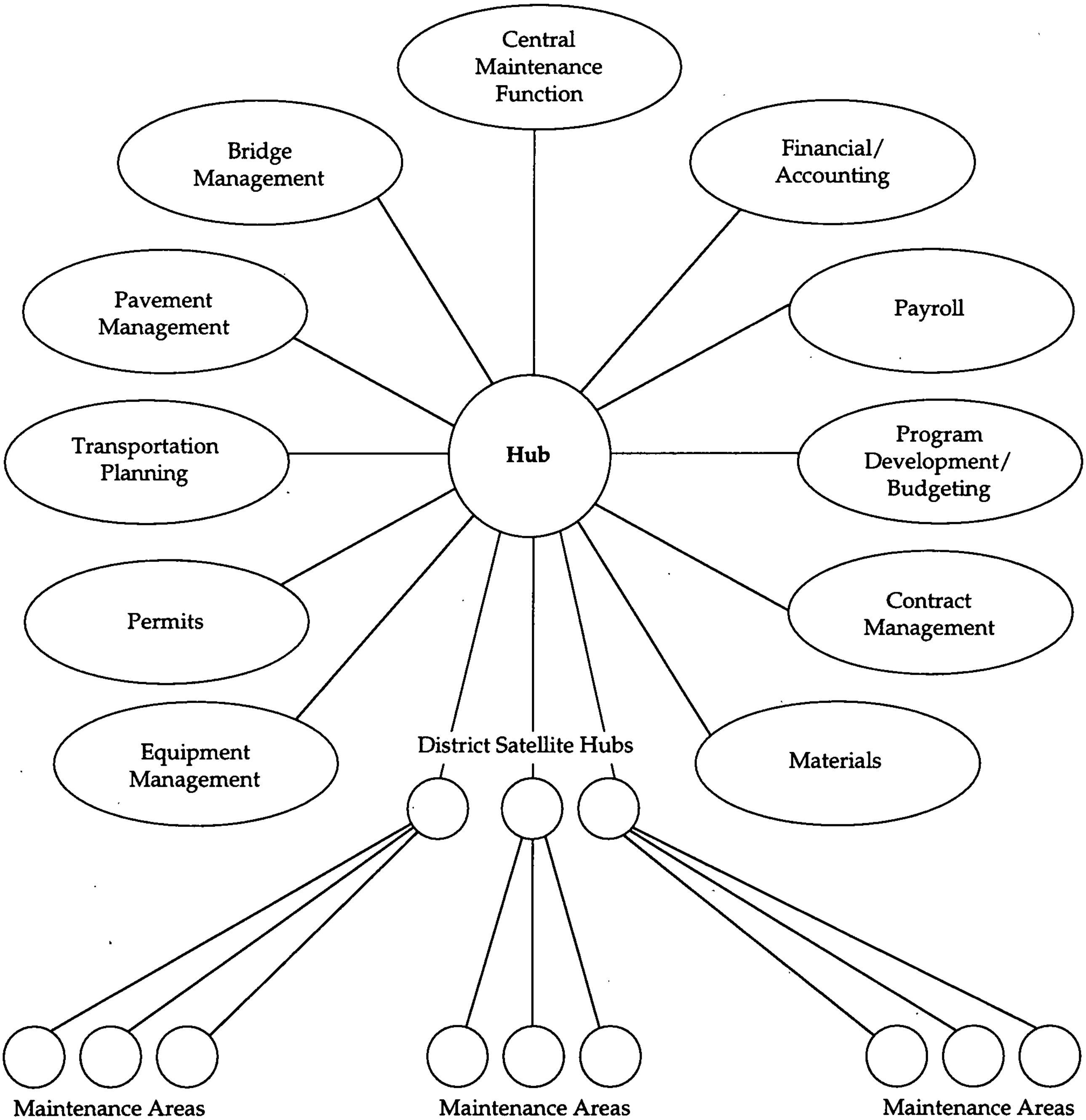
Integrated Systems Concepts

For most agencies, the next generation of maintenance management systems will feature a higher level of integration among maintenance functions, and between maintenance systems and other systems, than what exists now. Indeed, several of the analytic advances proposed in the preceding section entail information from other sources besides maintenance. Almost certainly, the next generation of systems will feature better, more appropriate integration than is typical today, taking advantage of newer technology in information processing, communication, and display, as well as a clearer understanding of the role that maintenance and integration play in the overall management of a transportation agency.

The particular approach recommended to achieve integration among maintenance and other systems is illustrated in Figure ES.1, showing the integrated system concept applied to different levels of the maintenance organization. The approach used is referred to as a "hub-and-spoke" concept, in which all data and analytic capabilities needed on a shared basis by a particular organizational unit (or level of management) are located in the hub for that respective unit or level. Information needed from other hubs is communicated when it is needed. Application packages or data needed by specific units are located either at the satellite hubs for that unit (if they are to be shared by several users), or at the terminals along the spokes of the particular users responsible for those analyses and data. Thus, the hub handles only the minimum amount of data necessary to serve its satellite hubs and terminals. Most importantly, the hub software does not have human "users" per se; rather, its "users" are the analytic programs, data reporting tools, and data entry routines that exist at the terminals or the satellite hubs at the ends of the spokes.

The hub itself is not just a computer, however. Rather, it is an organizational unit with a complete set of duties related to its prime objective of facilitating data sharing. These duties include, for example, the following:

Figure ES.1 MMIS System Concept



- Building, maintaining, and updating the corporate database.
- Establishing and maintaining the necessary telecommunications linkages among hubs and spokes.
- Exercising quality control, monitoring consistency, and enforcing needed precision on all data submitted to the corporate database.
- Providing and maintaining common-use software and utilities.
- Working with various groups within the agency to build consensus and set standards for data coding, timeliness of data submission, handling of missing values, required data precision and accuracy, locational and temporal reference systems, etc.
- Ensuring compatibility among future enhancements to hardware, software, and the central, satellite, and terminal databases.
- Providing needed support services.

A key advantage of the hub-and-spoke concept is its flexibility and adaptability: It is not based upon any assumptions of current system configuration or future plans. The hub-and-spoke approach may be implemented within a mainframe, minicomputer, or microcomputer environment, including situations that have different mixes of these types of hardware. Hub-and-spoke architecture may be installed in stages to conform to the available budget. The hub support group alluded to above should not be confused with a centralized MIS or ADP group such as those that exist in state agencies today. The support group for maintenance management must not only understand the technical issues of system hardware, software, and communications, but it must also reflect the needs and interests of the maintenance or operations side of a transportation agency. The hub support group is a provider of services, not a centralized computer agency; in fact, its staff may not even come from the MIS or ADP organization. A hub support group that provides quick, effective, forward-looking responses to systems users is critical to the success of the integrated system concept.

New Technology

Several types of new technology have reached the point of commercial availability where they could assist in the gathering, processing, and display of information for an integrated MMIS. In addition to advances in computer hardware and software, examples of this technology include the following:

- Geographic information systems.
- Global positioning systems.
- Technology for highway inventory and inspection (e.g., video and photo logs, nondestructive testing or monitoring of pavements, bridges, etc.).
- Technology for work scheduling, reporting, and inventory management (e.g., palm-size and notebook computers, hand-held portable data entry terminals, barcode scanners, electronic clipboards, voice recognition systems).

Technology enables an agency to perform tasks better, more productively and economically, or more effectively and at higher quality. Where new technology can play a role in the idealized MMIS, the recommendations of this study have indicated how an agency may best take advantage of these advances. However, the choice of new technologies, and how they are to be employed, is left to the discretion of individual agencies. The recommendations for an integrated system do not depend upon any specific technology.

1.0 Overview

■ 1.1 Introduction

This manual looks to the next generation of maintenance management systems and how they must respond to the organizational, political, and technological trends that have emerged in recent years:

- The role of highway maintenance is evolving. There is increasing demand for maintenance work and a limited supply of increasingly sophisticated maintenance services. In allocating highway resources in the future, managers will need to consider maintenance with other options in a more flexible, integrated decision-making framework.

- With the increasing use of computerized management information systems at the state level, and the new federal requirements for implementation of management systems, the concept of a coordinated and integrated approach to system development promises to avoid duplication of effort and allow for information sharing to the maximum extent possible.

- Emerging technologies will enable improved data acquisition and locational-based processing, retrieval, and display of information in support of maintenance and other management information systems.

- The next generation of maintenance management information systems must respond to the different organizational and administrative needs that exist among DOTs across the country. At the same time, the management structures, responsibilities, and procedures of DOTs may need to be revised to adapt better to the political, financial, and technological changes that are occurring.

The following sections elaborate upon these themes in laying the foundation for the findings and recommendations discussed in later chapters.

The Evolving Role of Maintenance

Recent trends in highway programs suggest that maintenance will occupy an increasingly important role, entailing a more sophisticated treatment in future road management, operations, data collection, and research. The Interstate System and other major road building efforts of the past several decades are nearly concluded, resulting not only in more mileage to be maintained, but also in an inventory of higher-standard, more intensively used roads. Funding responsibility is continuing to shift from the federal to the state and local levels of government (historically the providers of road maintenance) and to the private sector (which stands to become more involved in the maintenance and rehabilitation of the maturing road system). Emerging technologies hold several potential applications to both preventive and responsive maintenance and related tasks of highway inspection, ranging from new methods of nondestructive testing and field data collection and analysis to exciting developments in computer hardware and software technology. These and other trends are reflected in federal policy directives that promise to change the ways in which maintenance and other highway activities are viewed, managed, and evaluated.

At the same time, the highway profession today recognizes that maintenance management could benefit from gains in the research, technology, and knowledge needed to characterize maintenance operations, evaluate competing requirements and treatments, and defend maintenance expenditures in competition with other programs. For example, the long-term performance of different maintenance treatments and the quantification of the benefits of maintenance have never been satisfactorily established based upon field investigations and experience in the United States.[1]

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1 The Strategic Highway Research Program (SHRP) established a long-term pavement performance program (LTPP), which includes collection of performance data on a number of sample sections throughout the United States. Over time, the LTPP database will provide information of the effects of maintenance, construction quality, loading, and environment on pavement distress and performance.

Much of the information now available on the benefits of maintenance comes from either the subjective judgment of professionals, rendered formally through procedures such as those proposed in *NCHRP Reports 223* and *273 (1,2)*, or (for pavements) indirectly through the results of simulation models *(3)*. Although nondestructive testing devices are being introduced for road and bridge evaluation, comparatively little attention has been devoted up to now to the application of such equipment for routine maintenance, particularly preventive maintenance.

Even is such data were available for maintenance today, however, existing maintenance management systems are not well suited to incorporate this information within their decision support capabilities. This report identifies how maintenance management information systems need to change to accommodate these additional categories of information and to build management capabilities not now available.

The Need for Integration

Management systems have been developed and modified by units within highway departments since the introduction of the mainframe computer. Most were developed as independent systems within individual units and were not integrated with other transportation databases. Moreover, these management systems were developed over many years, and because of the ever-changing characteristics of computer hardware and software, are incompatible in terms of the efficient and timely flow of information among them. They are also based on various hardware systems from mainframes to PCs, in various configurations from centralized to decentralized management structures. The data structures vary from flat files through hierarchical and relational methods. Improvements in Geographic Information Systems (GIS) for transportation in recent years show promise of integrating many of these incompatible database systems.

Transfer of information among the various transportation databases would allow a better coordination of maintenance programs with short- and long-term highway improvement programs and, thus, better resource utilization. The databases include but are not limited to those developed for management systems governing pavements, bridges, equipment, materials and supplies, roadway inventory and condition, design, construction, human resources, finance, accidents, traffic, and safety, in addition to the maintenance management information system (MMIS).

New Technology

New technologies applied to maintenance management hold the promise of enabling or promoting the integrated system envisioned in this project. Some of the promising technologies that can contribute to the next generation of MMIS include new computer hardware and software platforms, networking and telecommunications, GIS, global positioning systems, new methods for data acquisition and transfer (e.g., video imagery), and new equipment for detecting road conditions important for maintenance (e.g., lasers, sensors, ground-penetrating radar).

Advances in computerized techniques involving GIS offer the potential to promote data integration across departments. Furthermore, GIS presents advantages and capabilities that go far beyond maintenance, and have very strong management implications for a DOT. Thus, it is important to conceive an integrated system design that anticipates and is compatible with GIS and similar advances.

However, state DOTs differ significantly in their approaches to new technology: in the kinds of technological innovations that are felt to be helpful to a department's operations, in the perceived benefits and uses of a given technology, and in the pace with which the department adopts and disseminates these changes. While our recommendations will therefore acknowledge technological advances and indicate where they could be used to best advantage, the recommendations will be general enough to encompass different technological assumptions.

Influence of Federal Policies

Federal highway policy has witnessed major shifts recently, through enactment of the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) and the earlier preparation of a National Transport Policy by the U.S. DOT. Since routine maintenance has historically not been eligible for federal aid, these documents do not emphasize routine maintenance directly. Nevertheless, the maintenance of the Nation's road system is clearly of interest at the federal as well as state and local levels, and this interest is inferred in several locations in these policies.

The National Transport Policy is a broad, comprehensive statement of federal objectives, priorities, and strategies in highways and other modes of transportation *(4)*. This report establishes the context for new federal directions in transportation into the next century. Among its many findings and recommendations, several have very important implications for highway maintenance:

- Maintaining existing transportation assets is identified as "the most immediate task for the transportation sector." The national policy envisions this task as a shared responsibility, with the federal government emphasizing capital repairs in its aid programs, and state and local governments taking the lead in managing facilities and maintaining them.

- The plan adopts a more flexible perspective on aid programs, seeking to encourage a broader range of options and to eliminate "unnecessary or unwise investment."

- The national policy recognizes the potential role of the private sector to join with the public sector in providing needed transportation infrastructure, and encourages the elimination or the mitigation of barriers to private sector participation in planning, owning, financing, building, maintaining, and managing transport facilities and services. Federal policies should also provide better incentives for increased participation by other levels of government and the private sector.

- The importance of early maintenance is emphasized, both to preserve existing assets and to reduce the long-term costs of facility repair. In some cases, "Federal-aid programs have detracted from effective maintenance by tending to encourage new construction at the expense of maintenance."

The 1991 ISTEA changes several aspects of federal funding, highway system management, and intergovernmental relationships regarding road programs. The implications of these measures are continuing to be assessed as the ISTEA provisions are implemented by affected agencies. While the long-term effects of these changes on maintenance programs are not yet clear, at least two areas will affect maintenance management:

- Interstate preventive maintenance of pavements will be allowable activities in federal programs if a DOT can demonstrate through its pavement management system that these activities are a cost-effective means of extending pavement life.

- DOTs are required to establish management systems for highway pavements, bridges, highway safety, traffic congestion, public transportation facilities and equipment, and intermodal transportation facilities and equipment.

The first provision illustrates the importance of an integrated approach to road management, relating pavement management and maintenance management. The second provision will likely reinforce this concept, pending rulemaking by the Federal Highway Administration (FHWA). For example, earlier rules issued by the FHWA for pavement management systems suggest the following inferences regarding maintenance *(5)*:

- The requirement for a life-cycle analysis implicitly includes maintenance as one set of actions to be evaluated, complementing pavement design, construction, rehabilitation, and reconstruction.

- Maintenance history is one of the variables that influences pavement performance (together with traffic, pavement structural and materials properties, environment, construction quality, subgrade and drainage, and variability in these parameters).

- Maintenance of the pavement surface (through activities like joint and crack sealing) is critical to retarding water from entering the pavement foundation, forestalling a primary cause of premature failure.

- Because maintenance is funded differently from capital projects, it is one of the decision variables managers have at their disposal to allocate resources throughout a road network and over time, meet critical road priorities and remain within budget constraints.

■ 1.2 Current MMS Approaches

In the early 1960s, maintenance expenditures were growing rapidly and seemed to defy control. One of the first comprehensive studies of maintenance operations (in Iowa) concluded that piecemeal efforts to improve maintenance performance would be equivalent to attempting to reshape an inflated balloon by applying pressure against one single point: "Only a grasp which encompasses all aspects of maintenance operations simultaneously can effectively control the whole and hence the cost and quality" *(6)*.

By the late 1960s, it became apparent that the problems faced by different departments were really the same problems with minor disguises. This led to the development of what became a computer-oriented, *de facto* standard for MMSs.

A number of important new features became a part of the standard system:

- **Introduction of maintenance feature inventories:** Counts of inventory items allowed workload measures to be tied to specific maintenance activities (e.g., feet of guardrail for guardrail maintenance), which provided greater equity in fund allocations and contributed to the development of more realistic work programs.

- **Computerized planning tools:** Work programs and budgets were machine-prepared, and as the computerized system took shape, estimates of resource requirements were added as well. Later versions of this system also used a computer-assisted workload-leveling process that anticipated the monthly distribution of the work in the work program.

- **Use of Crew-Day Cards:** The need to directly relate scheduling to work program quantities, and the need to provide a more immediate control mechanism (given turnaround delays from central data processing), gave rise to the use of Crew-Day Cards. These are preprinted work authorizations with one card for each crew day of work listed in the work program. By strictly limiting the amount of some kinds of work to the number of cards available – while allowing an unlimited number of cards for emergencies – quantities were generally brought under control. Since reporting was done directly on the same card, the cards also allowed for immediate review of progress (productivity).

- **Control of crew sizes:** Major efforts to control crew sizes were also built into this generation of MMS. Crew sizes and equipment needed were preprinted on the card and, in some cases, the work-reporting tabulation document provided for summarizing "standard" days separate from nonstandard. Also, by separating maintenance work reporting from the accounting process, turnaround times were improved. It also helped change the emphasis for field-level control from managing money to managing resources.

- **Changes from road section to road class-based reporting:** Road section reporting for maintenance management gave way completely to road class and activity, and class was often jurisdictional class.

NCHRP Report 131 proposed a generalized MMS derived, in part, from these efforts *(7)*. The MMS model was designed to be either a computerized or a manual system. It included the following features and functions.

- **Activity Definition:** work activities defined to facilitate planning, scheduling and control requirements, including the definition of appropriate accomplishment units and [feature] inventory units.

- **Feature Inventory:** a file of maintenance-related road features and their respective quantities, providing the physical basis for estimating annual maintenance work requirements by activity.

- **Performance Standards:** definition of the resources and work methods planned for each work activity, including expected hourly or daily production and quantities of work required per inventory unit.

- **Work Programs:** computations using feature inventories and performance standards to define annual quantities of work for each work activity and [usually] the manpower needed.

- **Performance Budget:** a budget relating dollars required to the work program activities and quantities, computed by assigning costs to individual resource requirements by activity.

- **Work Calendar:** an annual plan showing seasonal or monthly amounts of work to level the maintenance workload.

- **Resource Requirements:** a month-by-month listing of resources needed – labor and equipment by classes and materials by types.

- **Scheduling:** procedures for assigning and performing work in accordance with the work program and calendar with crew-day cards generally recommended.

- **Work Reporting:** the process of reporting efforts and accomplishments as the basis for management reports.

- **Management Reports:** reports summarizing work reporting data and comparing actual results with plans for both quantities of work and productivity.

Many states based their MMS on this standard system in *NCHRP Report 131* or some variant thereof. Descriptions of the components included in this system configuration follow.

Activity List

In designing their maintenance management systems, states differed in their approaches to activity definition: i.e., the number of activities and the level of detail at which maintenance operations were described. Nevertheless, the grouping of activities is fairly consistent from state to state. Activities which are typically included in maintenance programs are the following:

1. Maintenance of Roadway and Shoulder Surfaces: joint and crack sealing, premix leveling, milling, seal coats, fog and slurry seals, short bituminous resurfacing, patching of spalls, partial slab replacement, slabjacking, blading, and repairing and reconditioning unpaved shoulders.

2. Maintenance of Drainage Facilities: periodic structural inspection, manual cleaning, and removal of debris from culverts, catch basins and inlets. Also, replacement of culvert pipes, installing underdrains, and cleaning, reshaping and restoring ditches.

3. Roadside Maintenance: both hand and machine mowing, brush cutting, herbicide treatment, fence maintenance, and litter pickup.

4. Bridge Maintenance: painting of steel components; cleaning and flushing bridge deck surfaces, bridge seats, drain holes and sidewalks; and repairing and replacing handrails, curbs, sidewalks, joints and supports.

5. Winter Maintenance: stockpiling deicers and sand, plowing snow and ice, applying abrasives and chemicals, removing ice on structures, and post-storm cleanup such as opening waterways and washing down equipment.

6. Maintenance of Traffic Control Devices: repair and replacement of signs, directional markers, delineators, guardrails, crash attenuators, traffic signals, controllers, flashing signals; initial painting and re-painting of pavement stripes and messages; and installation and re-placement of raised pavement markers.

7. Emergency Maintenance: temporary repairs, traffic control and cleanup in response to emergency conditions that storms, floods, traffic accidents or other disasters cause.

8. Public Services: care and cleaning of roadside parks, rest areas, and weigh stations.

9. Other Maintenance: equipment repair and maintenance, building and grounds maintenance, materials handling and storage, and supervision and training.

Activity definitions are the building blocks of the MMS, dictating the measures used for accomplishments and for feature inventories. Important activities are defined primarily by technical purpose and then by any added factors affecting the conditions under which the activity is planned or scheduled. For less significant activities, broader measures are often used. Overhead activities are also included in the list so that work programs and budgets will be inclusive.

Feature Inventory

A roadway feature inventory allows the maintenance program to be based upon field quantities of items requiring maintenance work. A typical MMS roadway inventory accomplishes the following:

- It organizes data on roadway features in a way that is consistent with the definition of maintenance activities described earlier.

- It maintains a count or quantity of items requiring maintenance by location (e.g., by route, milepost, etc.) and management unit (district, maintenance area, etc.).

- It provides a basis for estimating annual or biennial maintenance work requirements. (Refer to the discussion below of performance standards for elaboration of this point.)

Inventory data in typical maintenance management systems are collected and stored in "roadway inventory units" that provide the basis for work program estimation. They not only provide a physical measure of the road features important to maintenance, but also relate to the work units defined for each activity. For example:

- Pavements, shoulders, ditches, and other items running along the length of the road are measured by an appropriate lineal unit: e.g., lane miles of pavement, ditch miles of drainage ditches, fence miles of fences, right-of-way miles of right-of-way, etc.

- "Point" structures and features are represented by a count: e.g., numbers of bridges, culverts, catch basins, manholes, signs, signals, luminaries, etc.

- Areal features are quantified by corresponding measures: e.g., acres of mowable grass, trees, brush, vegetation to be sprayed, etc.

Existing maintenance management systems were generally designed with feature inventories that captured the quantities of items as noted above, but not their respective conditions.[2] This approach is different from that now taken, for example, in pavement and bridge management systems, in which component condition is not only an explicit part of the respective pavement or bridge inventory, but it is also used as a key input to the optimization or other analytic procedures that are part of the management package. This difference in concept of a feature inventory should be considered in MMIS updates, particularly if they are to be integrated with other management systems.

Performance Standards

A performance standard is developed for each work activity. The standard includes (1) the measures for work accomplishment and for feature inventories; (2) quantity standards – accomplishment quantities per

[2] An exception to this statement is illustrated by the system of "recordable conditions" developed as part of Ohio's approach to maintenance management *(8)*.

inventory unit for each road class; (3) productivity values – either average daily production or accomplishment quantity per labor-hour; (4) the resources required for an efficient operation; and (5) a standard crew size and (optionally) standard costs for the activity. In addition, the purpose of each activity and the quality standards associated with the activity are generally included in an operations manual.

The performance standards tie together the work accomplishment units for an activity, and the inventory units of the specific road feature corresponding to that activity, in the number referred to as the quantity standard (sometimes also referred to as the workload rate). The workload rate assumes a constant rate of work generation annually or biennially, and is the number used to generate maintenance work program requirements from the inventory features. It also assumes a steady state: i.e., that the work done each year is sufficient to keep up with the rate of deterioration of similar features throughout the network, so that the work required next year will be at the same rate (assuming no major changes in the size or composition of the road network). For example: if the work accomplishment unit for a pavement-patching activity is "tons of premix," and the inventory unit for that activity is "lane mile of pavement," then the quantity standard for that activity would be in units of "tons of premix per lane mile of pavement."

Work Programs

Work programs list projected work by activity, giving the following information:

- Estimated work quantities, stratified by management unit, road classification, or other appropriate division.
- Projected daily production of each activity, in work accomplishment units.
- Resulting program requirements in terms of crew days and labor hours by activity.

A program estimate is developed for each applicable work activity. The work quantity for the activity is computed for each road class using the feature inventory for the activity along with the quantity standards from the performance standard.

The number of crew days of work needed for the year is computed using the annual work quantity and the average daily production from the standard. Labor hours are computed using the standard crew size and the working hours per day.

The work program provides physical targets (objectives) as well as target resource allocations and limitations.

Performance Budgets

Performance budgets are work programs with cost estimates tied to individual activities and to work quantities. As such, the performance budget represents a performance objective as well as the basis for allocating funds.

Work Calendars

A work calendar shows the number of crew days needed in each month of the year to have a leveled workload. This tool serves as a guide to the development of schedules plus it provides the basis for evaluating progress throughout the year.

Resource Requirements

A resource requirements report shows the amounts needed of each resource type to perform the work program. This report is also by month showing needs related to the calendar. It is a guide to the allocation of specific labor, equipment, and materials.

Scheduling

There are a wide variety of scheduling procedures in use among the current MMSs. All of the systems generally provide ways for supervisors to make field notes of work that needs to be done and to match these needs with the work program and calendar. The systems also provide for the supervisors to decide specifically when and where each activity is to be performed and in combination with what other activities on a given day to make effective use of personnel and equipment.

Many of the systems use crew-day cards as an aid to scheduling. In some cases they are preprinted; in other cases the supervisor or lead operator fills them out daily. This card has key information from the performance standard preprinted on it as well as the date and instructions from the schedule. It makes provision for individual names and equipment unit numbers to be entered as a part of scheduling.

Work Reporting

The essential information to be entered into the MMS are the actual resources used and the accomplishments for each item of work. The crew-day card is often used for this purpose with the added advantage of allowing for an easy and immediate review of progress.

Management Reports

The current MMSs all provide a variety of management reports designed so that managers at all levels can identify problems and take corrective actions. While the details of reports may differ among systems, most MMSs typically include the following types of outputs for the various levels of management:

- Performance budgets tabulating, for each activity, projected labor hours, workloads, and costs; equipment, rental, and material costs; contract workload and costs; and total costs.
- Reports of force account (i.e., state forces) labor: workload, hours, and costs by activity. (These data may also be summarized by district.)
- Monthly labor requirements by activity.
- Equipment and materials analyses, showing the projected usage and associated costs of each class of equipment and material, and distinguishing between state-owned equipment versus rented units. (These data may be stratified by activity, or summed within the management unit for all activities.)
- Work accomplishment reports, detailing actual accomplishments versus planned.
- Resource usage reports, comparing planned labor, equipment, and materials requirements versus actual usages to date.
- Work production analyses, comparing actual production versus the standard or average production rate.

1.3 Critique of Current Systems

The maintenance management systems developed in the 1960s and 1970s were among the earliest attempts to apply the (then) new technology of computers and new concepts of performance budgeting to managing road networks and facilities. In its planning, monitoring, and control functions, the process of maintenance management was transformed from a highly subjective activity relying strongly on the judgments of foremen and local managers to a more structured activity based upon objective, quantitative information on (1) the quantity of road inventory to be maintained, (2) the resources and time required to maintain that inventory according to some standard, and (3) the costs of performing the required maintenance. As the result of maintenance management, work quantities were stabilized, balance was achieved among work activities, and improved work methods were introduced. Perhaps most important, for the first time maintenance managers had quantitative data on which to base decisions.

Maintenance management systems were right for their time. They have been an important and effective mechanism over the past 20 years in helping to plan, budget, monitor, and control maintenance work, and in establishing standard methods and productivity guidelines. Many changes have occurred since then, however, in the highway programs themselves; in the expectations of road managers on the part of administrators and political leaders; and in the state of the art of managing transportation networks in terms of techniques, tools, and technology now available. In this light, several areas in need of improvement in current maintenance management systems are described below.

Integration

At both the strategic planning and operational levels, MMSs need to be more integrated with other types of planning and decision making regarding capital improvements and operations.

At a basic level, the approach taken in existing maintenance management systems predates that applied in subsequent pavement, bridge, traffic, safety, capital programming, and other management systems. For example, the latter systems typically are based upon life-cycle cost approaches, thereby adopting a much longer analysis horizon than the typically 2-year outlook of most MMS. These life-cycle analyses are based upon predictions of facility condition and performance over time, derived from a knowledge of current facility condition. Maintenance management systems, on the other hand, rely upon the assumption of steady-state work requirements from one year to the next, as embodied in the quantity standards (or workload rates). Whereas pavement, bridge, and capital programming systems may employ a decision-making procedure (e.g., optimization, cost-effectiveness, project ranking, or other algorithms) that balances the costs of a project against its benefits or consequences, maintenance management systems make no attempt to quantify the benefits of the work performed.

These inherent differences in system database, design and operation are reflected in the lack of an integrated approach to decision making as DOTs apply these systems. For example, one could conceive of an iterative loop between, say, a maintenance management system and a pavement management system in addressing the best, most cost-effective strategy for maintaining pavements. The PMS could analyze long-term alternatives in pavement actions, and recommend not only the appropriate capital repairs, rehabilitation, and reconstruction projects and their timing and location, but also the appropriate level of periodic and routine maintenance. These recommendations could be incorporated within the maintenance management system as planning and budgeting guidelines, in lieu of the quantity standards or workload rates now applied. The maintenance management system could then track work accomplishment against these guidelines, and provide information to the pavement system on work accomplished and updated productivity standards and unit maintenance costs. In fact, this interaction rarely takes place, for pavements or other highway features.

At a more detailed level, planning for periodic maintenance projects such as culvert replacement or pavement base repairs needs to be distinguished from routine maintenance planning and treated in a more integrated manner with other activities. One key change to MMSs that will allow for better integration is incorporating the ability to consider specific road sections (rather than classes of sections within particular maintenance areas) in planning and scheduling. Another is to base maintenance work planning on an expanded set of information including condition ratings, traffic and accident levels, treatment histories, and planned construction project status.

Decentralization

Traditional MMSs have featured a centralized approach to maintenance planning, scheduling, and control, which has been beneficial in some ways but has limited system effectiveness in many respects. Centralized (and outmoded) data processing and reporting methods have been burdensome and time consuming for field personnel, and have been unable to produce sufficient timely reporting of results for effective management use. Emphasis on adherence to centrally prepared plans and statewide standards has strained relationships between field personnel and central staff without resulting in improved productivity or effectiveness of work.

The focus on using MMS for centralized budgeting and work planning as opposed to field-level planning has meant that work plans are frequently out of sync with actual conditions. Lack of credibility of planning values (e.g., statewide performance standards, which do not recognize adequately the differences in work requirements that arise on roads of different functional classes, in different geographic regions, and those served by work crews of different compositions and with access to different equipment and materials) has been a significant problem. There is a need to shift planning and management responsibility to levels that are closer to where the actual work is accomplished, and to provide interactive computerized tools, which are geared toward helping maintenance personnel to do their jobs more effectively.

Data centers are no longer geared to receiving data sheets from the field to be key-punched onto cards for later processing. Data entry should be done closer to the work location, where errors can be detected more easily and corrected. The data center would then receive these field inputs electronically for routine processing and sharing as required.

Flexibility

Current MMSs are geared toward maintaining a strong linkage among budgets, work plans, and work accomplishment. Unfortunately, this linkage has not left enough room for the flexibility to adjust work plans and schedules to reflect changing conditions. There is a need to allow for re-planning of work as time goes on, and greater degrees of freedom for managers to reschedule activities or shift resources across categories of activities. Increased flexibility would also allow for easier coordination with nonmaintenance activities. The reporting capabilities of MMSs also need to be more flexible to meet the diverse needs of different users.

Both field and central office maintenance managers want more direct involvement in the maintenance management process. They are no longer content to work everything out by hand and then meticulously code the changes to "feed" the computer. They would like the maintenance management system to support directly their planning efforts, and would like to know where they stand without the dependence upon a centralized data center and the long turn-around times involved in the old procedures. They would also like to see information selectively, rather than being deluged with large, periodic outputs.

Sophistication

Current MMSs tend to "force fit" all activities into the same planning framework. While there are benefits to this simple and straightforward approach, there is a need to make more use of tailored approaches, which can produce more realistic and useful results. There is also a need to incorporate improved operational planning and scheduling methods into MMSs, which take into account the location and availability of resources, and allow for evaluation and use of contracting options.

Current systems do not adequately consider the interaction among activities. Activities should be redefined within activity groups so that each activity's technical contribution to the functional group is made clear and so that the tradeoffs among the activities may be evaluated and improved.

Feature inventories should be expanded to include additional information affecting maintenance decision making. For example, condition ratings, types of damages, traffic conditions, congestion levels, accident histories, past treatments, and planned or programmed work would all provide useful information for maintenance planning. This information should be available in a form designed to provide timely assistance as the maintenance decisions are being made.

Performance standards currently represent "average conditions", and need to be refined to take into account different work circumstances as reflected in an expanded feature inventory. For example, different quantity standards might be defined for different condition levels (such as light, moderate, and extensive cracking, etc.) Standards should also include information related to situations where changes are needed in crew sizes, equipment complements, materials needs, and so on.

■ 1.4 Overview of Recommendations

The shape of the next generation of Maintenance Management Information systems is heavily influenced by concerns of implementation feasibility, cost, value to top management, and autonomy of local office management. Careful selection of processes and technologies can achieve a balance among these concerns.

The recommendations presented in subsequent chapters of this manual are in two broad areas:

1. Enhancements to current capabilities to manage highway maintenance; and

2. Integration of maintenance management with other highway and administrative management functions, involving a new system configuration referred to as "hub and spoke."

Enhanced Maintenance Management

In the 25 years that maintenance management systems have been in existence, many accomplishments have occurred in the science and practice of highway management systems:

- Management decisions have been placed in an economic as well as a technical context. Furthermore, there is a growing recognition and acceptance of the fact that actions taken on a highway system often have consequences that extend into the future, leading to the application of life-cycle cost techniques.

- New mathematical techniques are available to assist in management decisions, including optimization methods to identify the best course of action among several alternatives over time.

- New computer hardware and software, coupled with new technology for data collection and processing, have enabled more timely, more reliable, and more effective analysis, display, and communication of information to the appropriate people.

These advances have benefited to a large degree pavement management and bridge management systems, particularly those systems that have been developed in the past 5 to 10 years. To date, maintenance management systems have not taken much advantage of these developments. One set of recommendations in this manual, therefore, is the updating of the analytic basis for maintenance management to incorporate concepts of life-cycle cost estimation and, when appropriate, new mathematical techniques. This approach entails considering the demand for maintenance – i.e., the factors that affect the need for maintenance work – as well as the resources (including costs) required to provide maintenance services. This new approach to managing maintenance presents the following opportunities to maintenance managers not generally available in current systems:

- It provides a basis for analyzing different scenarios for maintenance activities (i.e., which activities to perform, when, where, and to what level): for example, to justify budget requests in terms of the benefits or impacts of maintenance as well as costs, or to assess the consequences of deferred maintenance.

- It provides a basis for linking predictions of maintenance management systems with those of pavement management and bridge management systems, and for coordinating efforts among these functions.

Hub-and-Spoke Architecture

To simultaneously serve needs for centralized and decentralized shared decision making, the next-generation MMIS calls for the hub-and-spoke framework shown in Figure 1. This is a fundamental change from the way current maintenance management systems are organized. Its central component – the hub – includes shared data, telecommunications, generic analytical tools, and technical services having value to the user community. An organizational unit, having a manager and staff (not necessarily a part of the current automated data processing center) is created for the hub, but the scope of the hub is deliberately limited. The hub-and-spoke architecture can be implemented in many different ways depending upon the organizational structure to be served and other factors:

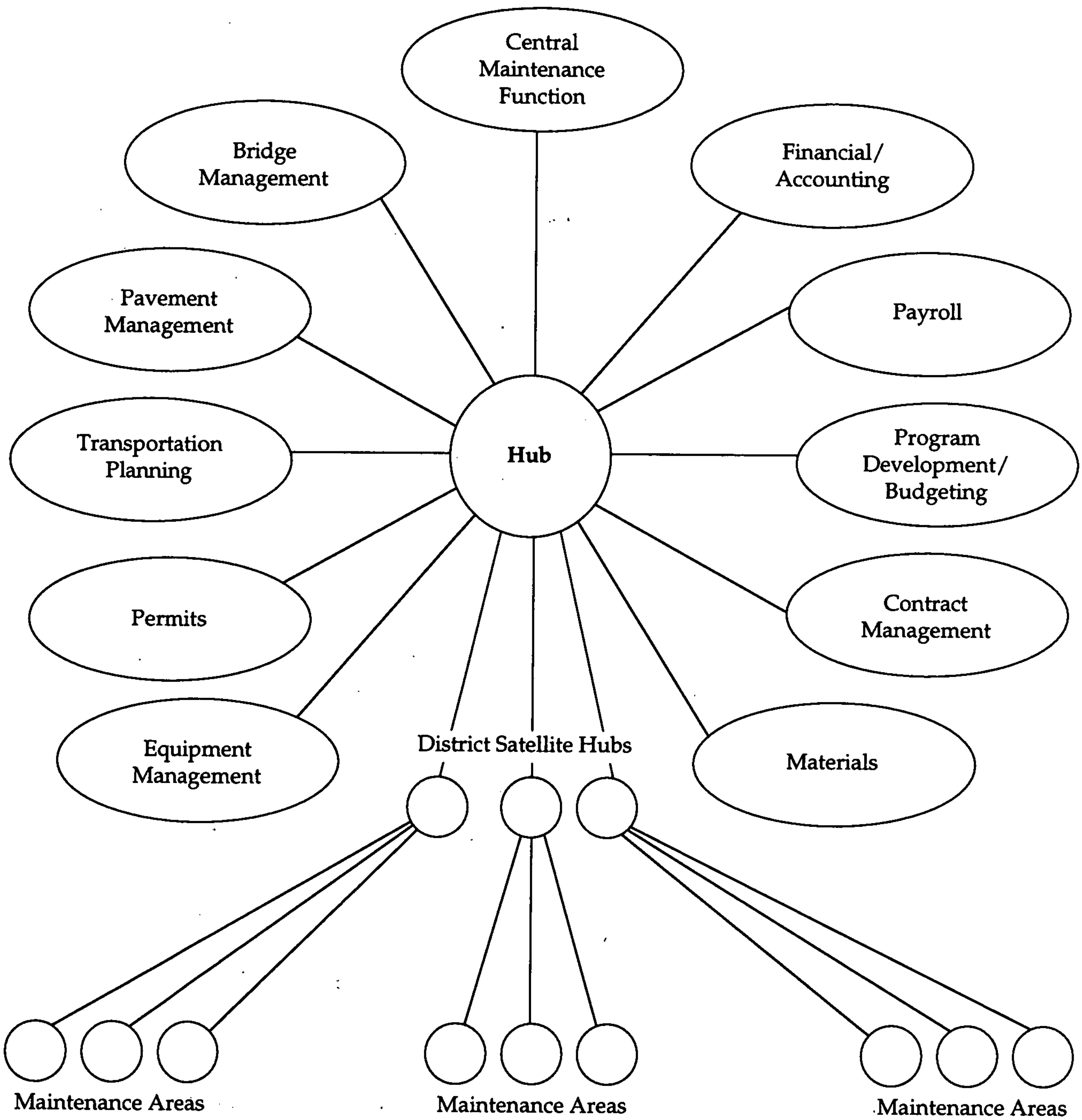
- A mainframe or minicomputer with a front-end processor and direct telephone linkages to terminals;
- A client-server environment on a headquarters Local Area Network (LAN) with linkages to LANs at the local ends;
- A client-server environment on a Wide Area Network (WAN);
- Part of an Integrated Services Digital Network (ISDN) expressly designed for high-speed data transfer of traditional data, text, images and voice.

With a hub-and-spoke system, each terminal needs only one data connection through which it receives all the outside data it needs. The presence of support staff in the hub unit makes it relatively easy to set up and maintain this connection.

Organizational Commitments and Procedural Support

The organizational hurdles to MMIS implementation are in many ways more difficult than the technical hurdles. A well-planned implementation strategy is needed, focusing on the following elements.

Figure 1. MMIS System Concept



1. **Develop a maintenance strategic planning capability that is an integral part of the department's overall strategic planning process.** For maintenance management to be proactive and not merely reactive, it is essential that there be effective strategic planning for maintenance. Strategic planning must concern not only maintenance but also must be an integral part of department-wide strategic planning. Sound strategic planning provides for the following:

   - **Environmental scanning** to evaluate possible internal and external changes and an examination of all key issues that may impinge on maintenance and the full set of important issues maintenance may impact. Among the key issues are

     - Role of bridge and pavement management vis-a-vis maintenance management;
     - Changes in federal, state or local administrations;
     - Expected budget levels;
     - Organizational change;
     - Technological advances;
     - Environmental concerns;
     - New laws and regulations;
     - Privatization and contracting;
     - Quality management;
     - Union work rules; and
     - Internal and external demands for performance monitoring.

   - **Assessment of threats and opportunities**, which may significantly diminish or enhance the effectiveness or efficiency of maintenance questions.

   - **Exploration of alternative scenarios** to perform "what-if" analysis concerning issues of critical importance to maintenance managers.

   - **Identification of the risks, rewards, and costs of options** to assess the net benefits of various alternatives.

   - **Development of an action plan** to identify key strategies, tactics, and policies that become part of a business plan, programs and budgets.

2. **Gain the full support of top management.** Undertaking the development, implementation, and continued support for the MMIS requires the full backing of the Chief Administrative Officer (CAO). The CAO should have an appreciation of the breadth and depth of the undertaking and be prepared to marshall the resources necessary to make the implementation of the MMIS succeed and to ensure its continued viability.

3. **Enlist a champion.** The likelihood of success will be greatly increased if there is a champion to spearhead the effort. Many difficulties will be encountered and a person with a vision, energy, tenacity and, above all, the ability to work and communicate effectively with a wide variety of people will be critically important.

4. **Establish MMIS organizational unit(s) and provide dedicated staff and funding.** The MMIS has different organizational requirements depending upon its phase of evolution. Along with an organizational structure there needs to be appropriate staff and funding for each evolutionary phase.

   - **Requirements and planning phase.** The head of the agency should appoint a task force with representatives from all key areas of interest (e.g., maintenance, BMS, PMS, safety, planning, traffic, finance, accounting, materials, research). The task force will carry out the important roles of coordination and building a consensus regarding the features of the MMIS.

   - **Implementation.** Organizational units need to be formed and provided sufficient staff and budget to carry out the functions of the hub and the satellite hubs, to establish communication linkages, to purchase hardware and software, and to compile or, as necessary, collect the following types of data:

     - Inventory data,
     - Condition and level-of-service data,
     - Agency and user cost data, and
     - Historical data.

   - **Continuing evolutionary phases.** At the outset of implementation, resources should be provided for the continued support for the MMIS as well as for its periodic evaluation, updating, and improvement. Failing to do so will result in its eventual obsolescence.

5. **Provide for a customer orientation.** Successful organizations have a clear understanding of their customers and are highly responsive to them. An MMIS customer orientation will be manifest in two ways.

   - **External customers.** These include other public agencies (such as that responsible for a statewide GIS), public utilities, elected officials, media, public interest groups, and taxpayers.

   - **Internal customers.** Each in-house unit that either impacts or is impacted by maintenance management decisions is a customer. A great deal of attention needs to be paid to the information needs, level of detail, accuracy, and access requirements of each one.

An important task during implementation is to identify who will have a terminal linked to the hub (or satellite hub), and who will receive tailored products. Product specifications should be defined in the requirements and planning phase.

6. **Emphasize results, performance, and quality.** The MMIS needs to produce credible, realistic work programs and schedules; accurately report and track accomplishments, and ensure that high productivity is matched with high quality. Agencies with a results and performance orientation are likely to have the following:

   - A system for periodically assessing the condition of physical assets and the level of service for each activity achieved as a result of the annual work program. Level-of-service goals should reflect demands of commerce and the motoring public.

   - Periodic reporting of performance measures useful to different levels of management.

   - An effective quality assurance/quality control program.

   - An ability to analyze the effect of maintenance policy in economic terms, such as the congestion delay costs associated with maintenance work zones and the user cost (e.g., accident, travel time and accident cost) of a deteriorated infrastructure.

   - Performance or end-result specifications for pavement restoration, rehabilitation, and reconstruction projects.

7. **Provide for top-down and bottom-up inputs.** Neither highly directive management from the top of the organization nor completely decentralized decision making is sufficient for effective maintenance management. Procedures should be put in place to ensure important decisions benefit from both top-down and bottom-up perspectives.

8. **Decentralize decisions to proper level.** Decisions should be made by the manager closest to the original source of information needed to make the decision, while providing for appropriate management review and oversight. Field decisions should be made by crew leaders and their supervisors who are most knowledgeable about local conditions and the concerns of constituents living and working in their area. Top management should not be involved in routine day-to-day management decisions requiring detailed and localized knowledge except to provide policy and program guidance, set budget levels, and address irregularities and exceptions.

9. **Establish organizational procedures to support shared decision making.** Simply setting up new organizational units for the MMIS without procedures to ensure ongoing coordination and shared decision making invites turf problems and organizational fragmentation. The agency should put in place procedures using teams, task forces, and Total Quality Management concepts to ensure:

   - **Vertical coordination** up and down the chain of command (e.g., Crew Leader, General Supervisor, Maintenance Superintendent, District Maintenance Engineer, District Engineer, State Maintenance Engineer, Chief of Operations, State Engineer, Deputy Secretary, Secretary)

   - **Horizontal coordination** among different organizational units that interact at roughly the same level of the vertical hierarchy, for example, among managers in headquarters responsible for maintenance, bridge, pavement, safety, congestion, materials, equipment, financial, and accounting systems as well as the automated data processing unit.

   - **Network/program-level versus project/operational-level:** There is a dynamic tension between the kinds of decisions made through network and program-level decision making versus project and operational-level decision making. It is critically important to install formal procedures that tie these two levels together, bring tradeoffs into the open, and provide for resolution of conflicts. Otherwise program/network level decisions become completely disengaged from project/operational decisions and vice versa, creating serious problems.

   - **Internal-external coordination:** There is also a dynamic tension between internal and external demands placed on the agency, especially through the budgeting process that involves internal staff on the one hand and elected officials on the other. The portion of the MMIS that concerns programming and budgeting can most effectively mediate between the great many internal and external parties that exert pressure and influence.

10. **Develop an effective maintenance budgeting process.** Developing and communicating budgetary needs to the head of the agency and to elected officials in order to successfully secure the funding required is a challenging process. The MMIS should have well-established procedures for carrying out the budget process. Guidelines for such a process can be found in a pending NCHRP report on effective state maintenance budgeting practices (Project 14-9(1)).

11. **Establish procedures for evaluating contracting out and other privatization issues.** Effective cost-containment requires periodic

assessment of the cost savings and other pros and cons of performing work with in-house staff or contracting out. This issue does not only pertain to road and bridge work but also to design, implementation, maintenance, and upgrading of various elements of the MMIS. Guidance for establishing procedures for contracting can be found in *NCHRP Report 344 (9)*.

12. **Provide for modularity, platform independence and open architecture.** Policies should be established that ensure the design of the MMIS does not foreclose paths of evolution, whether these paths are analytical, organizational, or technological.

    - **Modularity.** A modular design that accommodates "plug compatible" hardware, software, and telecommunications technology is conducive to evolutionary change. Modular and open architecture (of which the hub-and spoke system is a specific example) facilitates making significant upgrades and the migration to the next-generation system.

    - **Open architecture.** The accompanying telecommunications architecture should also be open, perhaps consistent with the Open System Interconnect Reference Model of the International Standards Organization or a similar open system reference model likely to be developed for Intelligent Vehicle Highway Systems.

    - **Platform independence.** This means that the hub (and satellite hub) database can operate on the hardware and software of any vendor that can satisfy the requirements and specifications. Hardware and software specifications should permit the greatest flexibility possible in the choice of specific hardware and software products and ensure that technological advances can be easily accommodated (including central processing units, operating systems, database manager, peripherals, and applications software).

13. **Identify the critical path, including pilot studies for the requirements, implementation, and continuing phases.** The design and implementation of an MMIS are highly complex because of the large amount of coordination required throughout the agency in order to develop the necessary database and the decision support tools. An agency should develop a critical path schedule for the requirements, design, implementation, and ongoing phases of the MMIS. Pilot studies play an important role in MMIS implementation. As many key features of the MMIS as possible should be implemented on a pilot or test basis before full scale implementation. The schedule should explicitly identify these pilot studies.

14. **Establish continuing procedures for assessing the benefits and costs of MMIS features.** Careful attention needs to be given to the costs and

the value added of each feature the MMIS will have. A rule of thumb, sometimes applied to geographic information systems, is that the costs of hardware, software, and continuing data collection will be in the ratios of 1:10:100, respectively. In addition, overall cost will be affected by desired data transfer rates, organizational structure, and staffing. There should be explicit procedures for initial and continuing assessment of the costs and value added associated with the following features of the MMIS:

- Network topology and required data transfer rates between links and nodes;
- Type and distribution of hardware (e.g., location of central and satellite hubs and connecting terminals);
- Storage requirements and location of databases;
- Software (database management, data interchange, communications, summarization, and analytical models for decision support);
- Data collection;
- Organizational structure and staffing (including training).

15. **Establish a procurement process for hardware, software, and professional services.** Agencies will need to work through their procurement office to obtain the necessary hardware, software, and professional services (if not a wholly in-house effort) to implement the MMIS. However, the unique requirements of the MMIS suggest the need for additional procurement procedures that include:

    - Benchmarking of selected hardware, software, and telecommunications technology;
    - Identifying price-performance tradeoffs;
    - Developing specifications and RFP's appropriate for the MMIS.

16. **Provide for recruitment, education, and training.** To obtain staffing for the MMIS, some will be reassigned from existing duties within the agency and others will be recruited from outside the agency. Once the core staffing is in place and the hub established, managers in the satellite hubs and users of the MMIS both in and outside the agency will require education and training. There will need to be adequate resources and procedures, including training manuals and materials.

17. **Provide for effective reporting, presentation, and communication of information and analysis.** Considerable attention should be devoted

to providing users with output from the MMIS presented in useful form, both to aid their own decisions and to assist and provide input into the decision of others. The MMIS should support:

- Computer graphics;
- Map production (desirably through GIS);
- Multimedia presentations;
- An executive information system.

18. **Build in MMIS performance evaluation and feedback.** Implementation and continued operation of the MMIS can easily stray off course without periodic overall evaluation and feedback from users. During the requirements, design, and early implementation phases, evaluation of principal features should occur before they are cast in stone and fully implemented. Waypoints that provide opportunities for evaluation include:

    - Preliminary design of network topology,
    - Preliminary specification of dictionaries,
    - Prototypes of computer software for key decision support tools.

Periodic evaluation should continue once the MMIS has been implemented to identify areas needing improvement and make progress toward the model system.

1.5 Organization of Manual

This manual is organized as follows:

- Chapter 2.0 describes recommended enhancements to maintenance management systems to manage maintenance better. These recommendations include both updated concepts to guide the development of management system components (e.g., activity lists, performance standards), as well as a more fundamental approach to maintenance management to apply life-cycle cost techniques. These recommendations may be applied individually or as part of a comprehensive update of MMS. They do not require an integrated system configuration as described in subsequent chapters, although they would derive added value from being included as part of integrated system development.

- Chapter 3.0 presents the concepts of integrated systems in a general way, discussing the pros and cons of integration, benefits and costs, and general considerations. This chapter provides an introduction to material presented in Chapters 4.0 through 6.0.

- Chapter 4.0 goes into greater depth on the operation of integrated systems and their implications for maintenance management, including more detailed explanations of the hub-and-spoke concept and how it operates, locational reference systems, and data communication.

- Chapter 5.0 discusses new technologies available to enable more efficient, effective, and reliable system operation and data collection and processing – including geographic information systems, global positioning systems, new inspection technology, and technology to assist work scheduling, reporting, and inventory management.

- Chapter 6.0 considers system implementation in terms of different system architectures that are possible; hardware, software, and communications requirements; and implementation strategies (or "migration paths").

2.0 Recommended Enhancements

2.1 Introduction

Chapter 1.0 presented a history of maintenance management system development, and identified system components that are found in most MMSs still in use today. A more detailed review of how system elements relate to maintenance management decisions, and the organizational levels at which these decisions are taken, is given in Appendix A:

- Appendix A categorizes and structures the types of management decisions that are made with respect to highway system maintenance in state DOTs.
- It describes the types of information (both inputs and outputs) associated with each of these decisions.
- With this framework established, it identifies the opportunities to apply this information within an integrated approach to management.

Based on this analysis, several types of recommendations have been developed to improve the way that maintenance management can be accomplished. These recommendations relate to both the individual components of an MMIS, and to the types of analyses it is designed to perform. Furthermore, these recommendations are independent of the integrated system concept proposed in later chapters of this manual.

Although an integrated system approach would strengthen several aspects of maintenance management itself and contribute to a more efficient use of resources department-wide, the recommendations below stand on their merits and could be implemented within current systems, without resorting to an integrated system strategy.

Each agency should be encouraged to have a manager (preferably the state maintenance engineer), knowledgeable in the depth and breadth of the maintenance function, to analyze the agency with respect to the information requirements, decisions, and organizational levels cited in Tables A.1 and A.2 of Appendix A. This review will be very useful to assess how a new MMIS (particularly one that is integrated with other systems) can best be implemented within the agency.

2.2 System Components and Features

Many of the system components and features that have formed the building blocks of maintenance management systems over the past 25 years will continue to be key elements in the next-generation MMIS. However, the way in which these features are defined and used may need to change. Following are recommendations for change based upon discussions with state DOTs and analyses of future maintenance management requirements:

- **Activity List.** The list of activities addressed by a traditional maintenance management system should accommodate the needs of both high- and low-level maintenance management. High-level management is concerned with policy, planning, programming and budgeting and does not need any more activities than are necessary to define the basic building blocks of the traditional maintenance management system, including feature inventories. Broad categories of maintenance activities facilitate the programming and budgeting process, especially when it is necessary to communicate with elected officials and other external audiences such as the press and public. At the lower level of the maintenance organization, managers involved in day-to-day field operations need more detail. They should be permitted to define activities and associated localized performance standards to facilitate decentralized decision making and foster innovation that results from new approaches to maintenance. A related requirement is to be able to determine which of the detailed categories used at the lower levels of the organization compose the classification of maintenance activities used at the higher levels.

- **Feature Inventories.** Existing maintenance management systems were generally designed with feature inventories that capture linear (pavements, shoulders, ditches), point (bridges, culverts, signs, signals), and areal (mowable grass, rest areas) features. This approach is different from that now taken. In pavement and bridge management systems, component condition is not only an explicit part of the respective inventory but also is a key input to the optimization or other analytic procedures that are part of the management packages. Inventories of physical assets to be maintained should be accompanied by data on their condition (e.g., reflectivity and damage of signs) and functional obsolescence (e.g., guardrail that no longer meet safety standards). Inventories of maintenance features that are nonphysical assets should be accompanied by data on the level of service being achieved (e.g., mow grass three times per season so grass does not exceed 8 in.).

- **Performance Standards.** These need to be applied in a less rigorous way than they have in traditional maintenance management systems so they can be used in conjunction with condition and level-of-service data and reflect local conditions. Traditionally, performance standards tie together the work accomplishment units for an activity and the inventory units of the specific road feature corresponding to that activity, the number referred to as the quantity standard (sometimes also referred to as the workload rate). The workload rate reflects norms of productivity and accomplishment based upon a standard work method and complement of labor, equipment and materials. The workload rate assumes a constant rate of work generation annually or biennially and is the number used to generate maintenance work program requirements from the inventory features. It also assumes a steady-state (i.e., that the work done each year is sufficient to keep up with the rate of deterioration of similar features throughout the network), so that the work required next year will be at the same rate (assuming no major changes in the size or composition of the road network). These assumptions are frequently unwarranted. A requirement of an improved traditional maintenance management system is to base budgets, programs, and fund allocation formulas not only these norms or averages, which reflect productivity expectations, but also on the condition and the difference between actual and desired level of service of maintainable elements. There should be two sets of performance standards:

  1. A set suitable for planning, programming, budgeting, and allocating resources to districts or local areas;

  2. A set, prepared by each district, local area, or perhaps even crew leader, that reflects local conditions and the most efficient work methods. In addition, local managers should be able to define, with approval of management, alternative localized performance standards, in order to have a basis for testing the comparative efficiency

and cost-effectiveness of various work methods, types of equipment, types of materials, and size of crew.

- **Work Programs and Performance Budgets.** Traditional maintenance management systems produce work programs that are based on needs, regardless of budget availability. The lack of realism with respect to available funding and the inability to quickly scale programs to reflect alternative budget levels under consideration undermines the credibility of many maintenance management systems. In traditional maintenance management systems, adjustments to level of service are the principal means for accommodating reduced or increased funding. But most maintenance organizations find it impractical to change performance standards and other parts of the maintenance planning and programming process quickly enough to respond to rapid changes in budget levels. An important capability of an improved traditional maintenance management system would be to be able to quickly and realistically adjust work programs to reflect likely budget limitations, and not base work programs solely on unconstrained needs estimates or estimates that reflect rigid level-of-service standards embedded in quantity standards.

- **Work Calendars.** A work calendar shows the number of crew days needed in each month of the year to have a leveled workload. This tool provides a guide to the development of schedules and provides the basis for evaluating progress throughout the year. An important shortcoming of the work calendar is that it pertains only to work activities that are scheduled throughout the year. It does not pertain to demand-responsive maintenance, which includes emergencies, service requests, problems identified in daily patrols, and many kinds of pavement and bridge distress evident in pavement and bridge condition surveys. Procedures need to be developed to enlarge the work calendar to address demand-responsive needs, particularly those which are seasonal in nature and can contribute to an imbalance in workload over the year.

- **Resource Requirements.** In the traditional maintenance management system, a resource requirement report shows the amounts of each resource type needed to perform the work program. This report is produced also by month showing needs related to the calendar. It is a guide to the allocation of specific labor, equipment and material. However, under relentless staffing and budget constraints, as well as political pressures, many agencies are increasingly turning to contracting, which can affect estimates of resource requirements. An improved maintenance management system needs the capability to adjust resource requirements based on the degree of contracting expected to occur.

- **Scheduling.** Scheduling involves planning maintenance activities weekly or biweekly and assigning labor, equipment and crews to the planned activities daily. Scheduling enables maintenance supervisors to simultaneously make progress on achieving the program set out in the work calendar (based on the annual work program) and in addressing more immediate needs. Traditional scheduling systems do not account for all the important inputs that ought to enter scheduling decisions. Improved scheduling methods are needed to allow maintenance supervisors to select activities from the work calendar, service requests, emergency and urgent work, leftovers from the previous schedule period, and condition and distress surveys from the bridge and pavement management systems.

- **Work Reporting.** The essential information entered into the MMS are the actual resources used and the accomplishments for each item of work. A daily work report or crew-day card is often used for this purpose. However, instead of being the single source of information for data entry, crew leaders frequently must fill out many other reports with duplicative information. In addition to a daily work report, crew leaders may have to fill out an equipment and materials usage report and furnish labor hours to a time keeper who fills out a time sheet. Work reporting should involve a single source of data entry for all reports to avoid duplicative and wasteful effort. Better yet if the information is entered once into a computer, which avoids transcription and keying in the data. All necessary reports – accomplishments, resource usage, time sheets, roadway feature inventory updates – should be generated from this single source of data entry. This information should be entered locally, so it is available for immediate local use.

- **Management Reports.** The traditional maintenance management systems provide a variety of reports designed for managers at all levels. These reports include performance budgets, reports of force account labor, monthly labor requirements by activity, equipment and materials analysis, planned versus actual work, planned versus actual resource usage, and actual production versus the standard or average production rate. Management reports have limited utility in most traditional maintenance management systems because reporting is geared to areas or organizational units and not to sections of road. This hinders many types of management analysis, particularly comparing maintenance versus capital improvements for a section of road. Existing systems, which permit summary reports only by area or organizational unit, should be modified to permit reporting by road section, such as between mileposts.

2.3 New Analyses

Effective maintenance decision making in complex organizations depends upon the ability to combine engineering, economic, management, and other important inputs and perspectives, including environmental and safety. Besides the traditional maintenance management system capabilities (see Section 1.2), the next generation MMIS should be able to perform the following, nearly all of which have an economic analysis component in addition to engineering and managerial inputs:

- **Maintenance/Capital Tradeoffs.** The pros and cons of spending more money on maintaining versus improving a physical asset, such as a bridge, pavement, or interstate sign structure, should be analyzed by life-cycle cost analysis or an equivalent method of economic analysis. Figure 2 presents a one-page primer on life-cycle cost calculations.

- **Level-of-Service Tradeoffs.** The pros and cons of spending more money on maintenance activities involving nonphysical assets (e.g., mowing, ditch cleaning, snow and ice control, rest area maintenance) should be addressed by formal analytical procedures for assessing level-of-service tradeoffs, such as direct utility analysis and conjoint analysis. These procedures can also extend to evaluating the advantages and disadvantages of shifting funds among maintenance of physical assets versus such maintenance operations as mowing, litter pick-up, and snow and ice control.

  The North Carolina Department of Transportation has applied an optimization procedure called "Algorithm for Selecting Optimal Policy" (ASOP) for selecting the best level of service for different types of bridge maintenance subject to budget constraints *(10)*. The procedure was developed under two NCHRP projects and applies to all types of maintenance *(1,2)*.

- **Agency and User Cost Analysis.** The economic analysis of maintenance requires models for estimating current and future agency costs. Agency cost models may be based upon historical data or expert elicitation. User costs are important for assessing congestion delay associated with maintenance work zones and for calculating the benefits of road and bridge improvements. User costs are most commonly defined as the sum of accident, vehicle operating, and travel time costs.

- **Needs Analysis.** Two types of needs analysis are required: unconstrained and constrained. Maintenance managers need to be able to identify proposed maintenance expenditures whose benefits exceed costs, regardless of funding availability. Benefit-cost analysis can be used to justify increased expenditures on maintenance. Analytical

Figure 2. Primer on Life-Cycle Cost Analysis

Life-cycle cost analysis is a method for identifying an action with the lowest present value of costs over its lifetime. It is particularly useful in assessing agency costs and illuminating the tradeoffs in expending extra dollars on maintenance versus capital improvements. Life-cycle cost calculations take into account the "time value of money," the rate which equates the satisfaction a person gets from receiving a dollar tomorrow (say 1 year from now) and receiving a dollar today. This time value of money also reflects the "opportunity cost," defined as the rate of return one might earn in the next best use of funds.

The main steps in life-cycle cost are as follows:

1. Identify the analysis period, say 20 years or long enough to represent the longest-lasting option under consideration.
2. Identify each option and establish an initial cost.
3. Construct life-cycle cost profiles, which describes the type of actions, timing, and costs associated with each option over its life.
4. For each cost that occurs in year n, multiply by $1/(1+r)^n$, the discount factor, where r is the discount rate or "time value" of money, to obtain the time stream of discounted costs.
5. For each option, sum the discounted costs to obtain the "present value" of costs.
6. Select the option with the lowest present value of costs to identify the least-cost option.

Example

Three pavement treatments are under consideration: The first is slurry seal every 7 years at $25,000 per slurry seal. The second is resurface with 1 and 1/2 inch asphalt concrete every 10 years for $50,000 per resurfacing. The third is do nothing for 15 years and reconstruct for $140,000 followed by a slurry seal every 7 years. Assume a 25-year analysis period and a discount rate of r=.06. The discounted present value of Option 1 is lowest, so slurry sealing every 7 years is the best choice.

	Year 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25					Sum
Option 1	Slurry 25,000 (1+.06)	Slurry 25,000 $(1+.06)^7$		Slurry 25,000 $(1+.06)^{14}$	Slurry 25,000 $(1+.06)^{21}$	$58,622
Option 2	Resurface 50,000 (1+.06)		Resurface 50,000 $(1+.06)^{10}$		Resurface 50,000 $(1+.06)^{20}$	$90,660
Option 3				Reconstruct 140,000 $(1+.06)^{15}$	Slurry 25,000 $(1+.06)^{22}$	$65,355

LEAST-COST OPTION IS SLURRY SEAL EVERY 7 YEARS procedures for determining needs consistent with a realistic financial plan or imposed budget limitations are also required. Analytical tools capable of this include incremental benefit-cost analysis, marginal analysis, integer programming, and dynamic programming. Figure 3 is a one-page primer on incremental benefit-cost analysis. The next-generation MMIS should have the capability to perform needs analysis with and without budget limitations for the next budget cycle and for the longer term. Figure 4 shows a bridge management system with this capability.

- **Optimal Resource Allocation.** Highly related to procedures for making constrained-needs estimates are procedures for optimal resource allocation. Methods for determining the best set of maintenance and improvement actions over time given a budget constraint can provide estimates of optimal future spending. However, there are many additional resource allocation problems which economic analysis and operations research tools can help solve. These include optimal short-run scheduling of labor and equipment for daily maintenance operations and determining the optimal level of service for various maintenance activities given a budget constraint.

- **Optimal Routing.** Under some circumstances – such as emergencies, incident management under congested conditions, and sharing of maintenance personnel among areas or districts – deployment and routing of maintenance personnel can be complex. There are many readily available analytical procedures for determining the shortest or quickest path over a network of roads. These types of analytical procedures offer opportunities for cost savings and productivity enhancement. There are also algorithms for selecting the best route subject to constraints such as overweight and oversized loads.

- **Data Reduction and Summarization.** Calculations and special analytical methods for processing raw data are an important part of an MMIS. These include

    - Spreadsheet column and row totals;
    - Statistical measures such as mean, mode and variance, and type of frequency distribution function; and
    - Sophisticated procedures from signal processing, statistics, and econometrics for filtering out noise and outliers and adjusting data for autocorrelation (data with patterns of correlated errors).

Figure 5 shows a functional diagram of one example of an integrated management system approach, viewed from the standpoint of maintenance management, which highlights key management systems, analytical components, and operational elements:

Figure 3. Primer on Incremental Benefit/Cost Analysis

Benefit/cost analysis is frequently used in transportation analysis to compare the benefits and costs resulting from various project alternatives. The benefits are frequently expressed in terms of savings in user costs – accidents, travel time, and motor vehicle operating costs. The costs are often life-cycle costs, where the time streams of benefits and costs are converted to discounted present values in a manner similar to that shown in Figure 2. In a dynamic decision process model, however, the costs may be expressed as long-term average costs of consistently following a given policy.

When facilities have multiple project alternatives, incremental benefit-cost analysis can efficiently find a near-optimal set of alternatives that maximize the total benefit achieved from a given budget.

Example

Suppose improvement options for two facilities, A and B, are being considered. For A, options are to do nothing, rehabilitate, or replace. For B, options are to do nothing or to rehabilitate. In order to assess which of these options should be selected, a table is prepared listing project alternatives. This table (see below) shows that each alternative has benefits which exceed its costs. However, selecting an alternative based on the simple benefit-cost ratio will not necessarily maximize net benefits. Looking at this problem from an incremental benefit-cost perspective, one starts from the alternative giving the highest benefit relative to cost, and adds or substitutes other alternatives having successively lower incremental benefit-cost (IBC) ratios until the ratio goes below 1.0 or until the budget is exhausted. The least expensive alternative is to do nothing. However, if there is a budget of at least $250,000, the best increase in benefits relative to costs is gained by choosing Rehab A. Then next-biggest IBC is gained by adding Rehab B, if the budget is at least $550,000. Finally, if the budget is at least $850,000, a positive IBC indicates that replacing A, rather than rehabilitating yields the highest benefit. Therefore, it is apparent that the optimal action for A depends on both the overall budget constraint and the costs and benefits of competing projects. This explains why network-level and project-level analyses can yield different results.

Analysis of Alternatives (Thousands of Dollars)

	Benefit ($)	Cost ($)	Δ Benefits ($)	Δ Costs ($)	IBC (Δ B/Δ C)	B/C
Project A						
Do Nothing	0	0	–	–	–	–
Rehabilitate	1,500	250	1,500	250	6.00	6.00
Replace	2,000	550	500	300	1.67	3.64
Project B						
Do Nothing	0	0	–	–	–	–
Rehabilitate	700	300	700	300	2.33	2.33

Figure 4. Major System Components of a Bridge Management System – Pontis

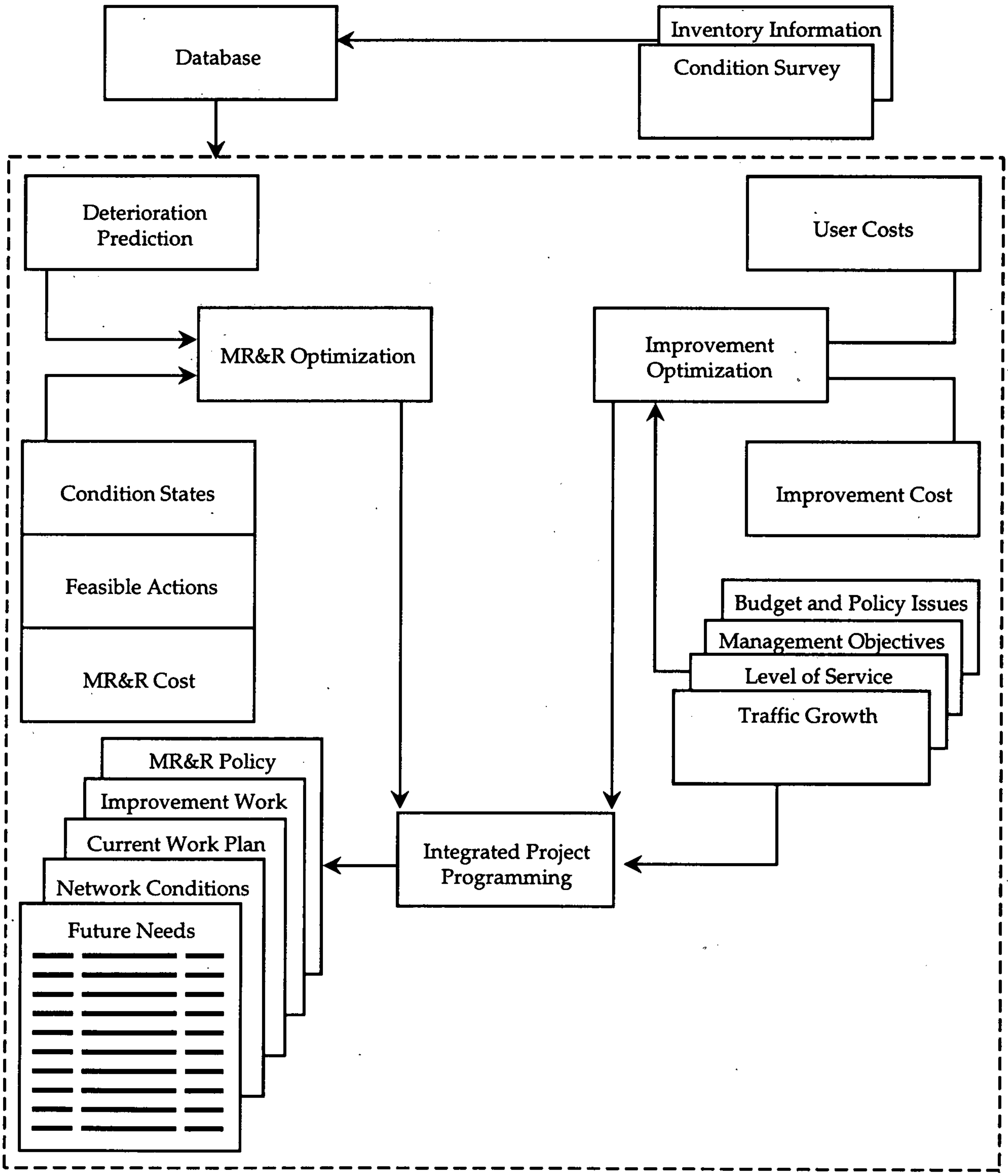
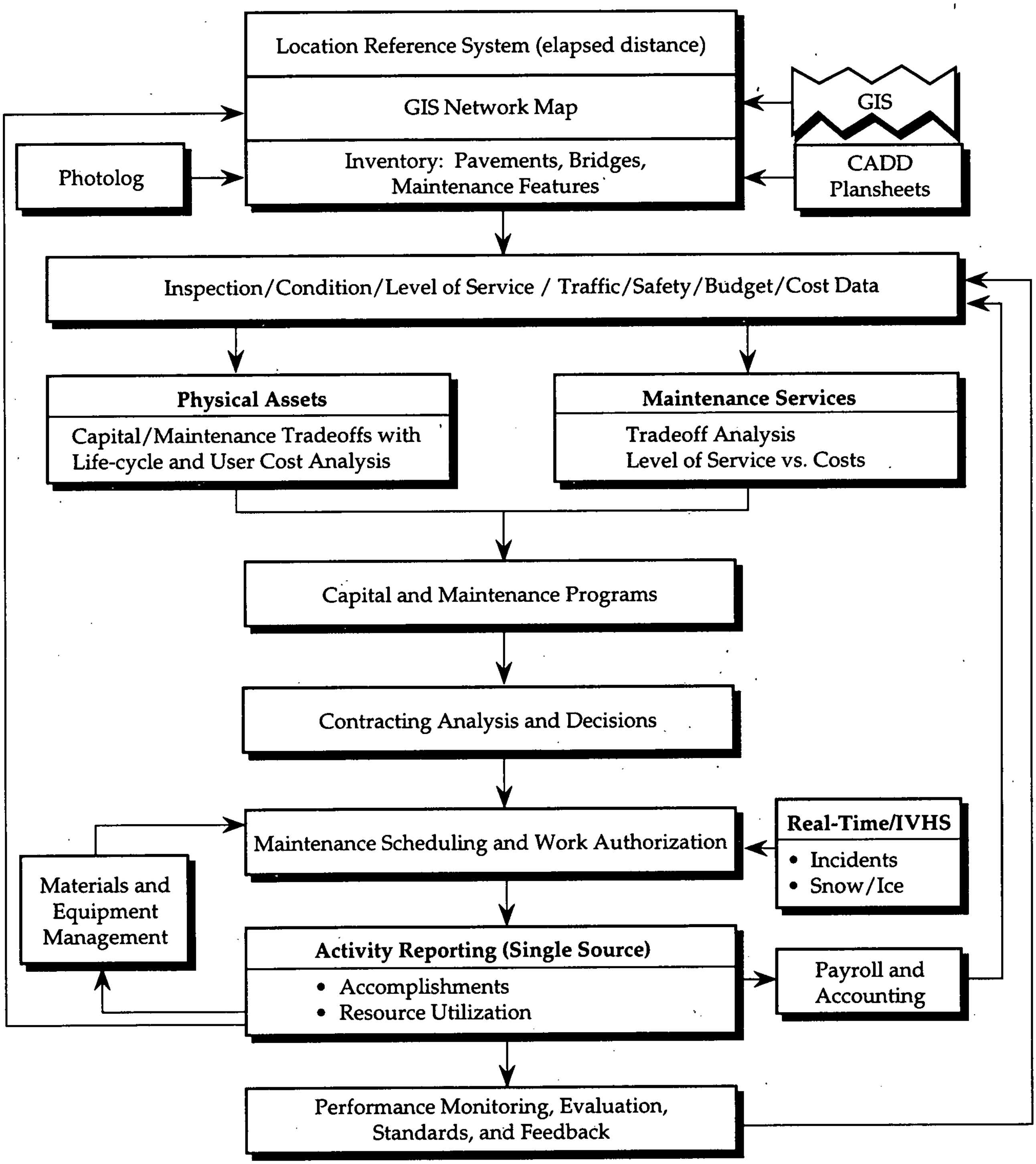


Figure 5. Example of an Integrated Management System Approach



- The central database contains inventory data on pavements, bridges, and other maintainable features as well as data that come from other management systems and databases (traffic, congestion, safety, equipment, materials accounting, etc).

- The inventory is tied to a locational reference system based on elapsed distance from reference markers and with a further tie (highly desirable but not necessary) to a GIS/network map.

- Life-cycle and user cost analysis are used to make capital and maintenance tradeoffs.

- Other analytical procedures assess tradeoffs between level of service and costs for other maintenance activities.

- Capital budget development is coordinated with the maintenance plan and program. The maintenance plan is based partly on maintenance methods and standards (crew sizes, equipment types, materials needed, quantity standards, quality standards), but also includes

  - Activity levels;
  - Level of service to users (benefits);
  - Resources and budgets; and
  - Costs.

- Short-run schedules are derived from the maintenance plan with response-based inputs including real-time data on traffic incidents and snow and ice conditions. Ingredients include

  - Annual work program;
  - Daily patrols;
  - Service requests;
  - Urgent and emergency needs.;
  - Leftover work from previous schedule period; and
  - Condition survey data from BMS, PMS, etc.

- Resource utilization is reported to appropriate management systems, such as

  - Materials Inventory;
  - Equipment; and
  - Finance/Accounting/Payroll.

- There is performance evaluation and feedback.

Figure 5 is an important example (but not the only example) of an integrated system approach. A more detailed explanation of its components follows.

Location Reference System, GIS Network Map, and Inventory Database

Transportation agencies use various data types and structures to support maintenance management and other applications including pavement management, bridge management, and budgeting. Location should serve as basic parameter for referencing inventory data elements. Highway inventory databases in an integrated maintenance management system may consist of records pertaining to pavement, bridges, and maintainable roadway features. Inventory information may reside in databases, on photologs, or plan sheets stored in a Computer-Aided Design and Drafting (CADD) System. Geographic information systems and other reference systems used in MMIS should provide consistent and accurate representation of maintenance on the road network, including those pertaining to its location, coverage, and the element involved. A GIS-based road network map can provide a unified platform for structuring inventory and inspection information on pavements, bridges and maintenance features.

The creation of highly accurate cartographic base maps for GIS generally depends on the improved mapping technology, especially those based on the satellite Global Positioning System (GPS). Geographic coordinates like latitude and longitude can be obtained using GPS to provide exact locations. However, these coordinates have to be tied in to a unique road link or intersection to be meaningful in MMIS.

Other Types and Sources of Data

Other types of data needed for maintenance management include conditions and level-of-service characteristics of maintainable elements, traffic volumes, safety or accident statistics, and budget and cost parameters. Sources of this information are as follows:

- Condition inspection surveys;
- Pavement management systems for pavement condition input to MMIS;
- Bridge management systems or structures data files of the highway agency, which store inspection information related to the condition of the principal components and elements of bridges or structures;
- Transportation planning unit or traffic unit for traffic volume, composition, and level-of-service measures including accident rate and congestion; and

- Labor, material, and equipment accounting systems that keep track of employee wages, equipment rental costs, material unit prices, and other cost information.

These data are used in conjunction with inventory information to develop, analyze, and evaluate work plans to be carried out by the maintenance staff.

Maintenance Planning – Physical Assets and Maintenance Services

A model maintenance management system needs a number of analytical capabilities. Among the most important are

- Level-of-service tradeoffs;

- Capital/maintenance tradeoffs; and

- Agency and user cost analysis.

A level-of-service system for maintenance relates to the condition of the maintainable elements (physical and nonphysical assets) and specifies the condition levels to be maintained for each element. When the condition of a specific element falls below the level specified, the appropriate maintenance response is triggered. A maintenance level-of-service system helps an agency in developing maintenance programs that address both agency and user needs. Level-of-service tradeoffs analysis should include evaluating the advantages and disadvantages of shifting funds between maintenance of physical assets and maintenance operations designed to achieve desired level-of-service goals (such as mowing for aesthetic considerations, snow and ice control for safety).

Analysis of capital/maintenance tradeoffs involve determination of the relative attractiveness of maintaining versus improving physical assets such as bridge decks, roadway shoulders, or overhead signs. Both maintenance and capital improvement options usually increase the level of service of the physical assets. However, improvement projects require more capital resources and often result in better performance of the physical assets in terms of capacity, deterioration, maintainability, and other long-term characteristics.

The maintenance management system also requires models for estimating both current and future agency costs and user benefits (savings in cost) associated with capital improvement projects, maintenance of physical assets and maintenance services to improve level-of-service goals. Agency costs consist of capital and labor resources, interests on borrowed funds, overhead costs, and other expenditures incurred initially and in the future to carry out the maintenance/improvement options. User benefits may include reduced travel time, lower vehicle operating costs, greater convenience or ease of use, and lower risk of accident.

Finally, a cost-benefit analysis that seeks to determine the potential outcomes of maintenance and improvement actions over a reasonable time period, with or without budget constraints, will assist in determining the economic feasibility of alternative projects and programs. This analysis should incorporate optimization procedures that can identify not only the best options or set of options but also the most effective way of doing them.

Capital and Maintenance Programs

Capital and maintenance programs are the products of the analysis of capital/maintenance and level-of-service/cost tradeoffs. Most states have short-run (1 year), mid-run (5 to 6 years), and sometimes long-term capital programs (6 to 20 years). The agency must determine the portion of "capital" improvements that will be accomplished within the maintenance program. This portion often consists of "small-scale" or low-cost improvement projects, which are frequently addressed in the "betterment" category of a state's maintenance program. Federal funding eligibility and local funding contributions often dictate the precise allocation of work between the capital and maintenance "betterment" programs. Both these programs typically consist of a listing of schedules of projects and their associated costs.

The full maintenance program is a description of all the maintenance activities in addition to maintenance betterment that will be carried out over the program period. Program descriptions for maintenance other than betterment will consist of project listings for activities such as deep patching and resurfacing to improve surface friction. For other activities, the program description will consist of allocations of funds for the program period among different maintenance activities, identifying the funds needed for different objects of expenditure (i.e., labor, equipment and material) for the period, and a schedule for accomplishing the activities, often expressed as crew-days per month per activity.

Contract Analysis and Decisions

Contracting maintenance work has been very effective in reducing highway agency costs especially by taking care of seasonal work loads and eliminating the peaks and valleys of equipment and labor resource requirements. According to an NCHRP study on maintenance contracting *(9)*, the major reasons for contracting maintenance services are to

- Supplement in-house staffing, especially for peak work loads;
- Obtain the use of specialized equipment;
- Obtain the services of specialized personnel;
- Obtain services at lower cost;
- Meet executive policies;
- Perform emergency work; and
- Improve responsiveness.

Agencies with maintenance management systems capable of determining productivity and cost-effectiveness of various work procedures find it easier to evaluate the relative attractiveness of contracting to doing the work in-house. A model maintenance management system should have a component that assists in defining and evaluating contracting options as well as helping the agency manage its contracted maintenance activities.

Characteristics of maintenance management systems that support contract analysis and management include the following:

- Identifies peak periods of maintenance needs when the available resources (personnel, equipment, etc.) are not adequate to perform required activities simultaneously.
- Has the complete database of potential contractors and all the related information (e.g., types of services, unit costs of work).
- Performs cost-benefit analysis of in-house versus contracted activities.
- Determines the exact location and quantity of work to be performed.
- Provides performance standards and specifications for contracted activities.
- Generates drawings and maps of maintenance elements to help the contractor better understand the nature and scope of the problems.
- Provides a complete documentation of requirements for contract administration and implementation.
- Allocates staff and resources to inspect and evaluate the quality of contract work.

Maintenance Scheduling and Work Authorization

Maintenance agencies seek to ensure that short-run schedules conform with the statewide annual work programs and at the same time meet local needs. Headquarters is also concerned that scheduling takes place so as to enhance the programming and budgeting process including determination of adequate staffing and equipment availability year round. These goals should carry over to district and lower-level management units whose aims are to ensure that maintenance is consistent with overall district needs and works toward accomplishment of the annual maintenance program.

Short-run (weekly or bi-weekly) scheduling procedures help field managers effectively manage labor, materials, and equipment for various maintenance operations. Scheduling usually occurs at the third or second levels of management, e.g., superintendent or field supervisor, respectively. The goal is not to overburden lower-level field supervisors with laborious paperwork, procedures, and computations. Short-run scheduling considers various inputs, which vary from state to state and may include the following:

- Priority listings based on pavement and maintenance needs surveys;
- Programmed low-end betterment work not contracted out and which is fundamentally maintenance;
- Monthly schedule based on the annual work program;
- Residual work from previous daily work assignments;
- Completed supervisor patrol forms;
- Service requests; and
- Emergency and other urgent needs (congestion and incidents that may come from real-time monitoring systems/IVHS technologies, snow and ice control).

Planned maintenance activities recorded on the schedule should be automatically listed among the activities appearing on a daily cost report data entry screen or printed form.

Pennsylvania DOT incorporates scheduling with cost reporting by preparing bi-weekly schedules in advance on a computer, and printing out planned work on a partially completed daily cost report *(11)*. Upon completion of a planned activity, the crew leader furnishes the information on resource usage and accomplishments. If the planned work was not undertaken, spaces on work reports for resource usage and accomplishments are left blank.

For very short-run scheduling – either same day or next – a means to enable second-level field supervisors to assign crews and equipment to activities and crew leaders should also be provided. Data collection technologies such as a PC, laptop, or electronic clipboard, are capable of combining these inputs for scheduling. In many respects the most logical place to combine these inputs is on a desktop PC installed at the staging area where crews are deployed to the field, although a portable computer, which the field supervisor may take home, might also prove to be convenient. Computer-aided weekly and bi-weekly scheduling have been demonstrated in the NCHRP Project 14-10 on Advanced Data Acquisition Technology for Maintenance Management Systems *(12)*.

The following are short-run scheduling requirements taken from the above NCHRP study that would meet the needs of supervisors and field managers applying a next-generation maintenance management information system:

- Displays candidates for scheduling from various input sources.
- Helps combine candidate activities into a weekly or bi-weekly schedule using simple heuristics or an expert system.
- Includes back-up maintenance activities.
- Identifies sections scheduled for imminent 4R work, which therefore do not warrant maintenance.
- Assigns federal-aid project number for specially funded projects due to floods, storms, tornadoes, etc.
- Describes location of work both in terms of verbal (English) description and either elapsed distance from a known reference point or a geographic coordinate system.
- Records signature approval necessary for scheduling – approval should be legally admissible in tort liability cases.
- Issues daily work orders based on bi-weekly/weekly schedules.
- Is at least as easy as current paper methods.
- Provides information on budget balances for activity, labor, equipment, materials.
- Provides information on equipment/material availability.

- Provides information on cost-effectiveness of methods.

- Provides information on consistency of bi-weekly schedule with annual work program for routine maintenance.

- Provides feedback on accomplishment of the following nonroutine maintenance activities, such as (1) urgent and emergency repair needs, (2) priorities based on maintenance needs surveys, (3) programmed betterment work (from multiyear programs), (4) residual work from previous daily work assignments, (5) completed supervisor patrol forms, and (6) service requests.

Activity Reporting

Maintenance accomplishments and resource usage are usually reported on daily work report forms, which sometimes take the form of crew cards. Crew-card data provide maintenance headquarters and units

- A basis for evaluating planned versus actual work and the adequacy of the maintenance budget;

- A foundation for evaluating productivity of maintenance units in districts as well as a basis for determining whether adjustments to quantity and performance standards may be required;

- The required information for accounting and fiscal functions by keeping track of labor, equipment, and materials used;

- Inputs for preparation of timesheets and payroll documentation and accounting; and

- Documentation that can help reduce tort liability costs.

Crew-card data help the superintendent (third-level maintenance supervisor) determine whether his/her crews are accomplishing this portion of the annual work program. The superintendent uses crew-card data to evaluate variances from performance standards. These data can also contribute to identifying more cost-effective methods of working and periodic revisions to performance standards. Budget ledgers and balances are derived from crew-card data. Previous accomplishments are an input into bi-weekly work schedules. To the extent that equipment status is recorded along with usage, crew-card data help in assigning equipment to crews.

The purpose of crew-card data collection at the level of the crew leader (first-level field supervisor) is to obtain the most accurate description of the accomplishments and resource usage as possible. The information recorded on crew cards consists of the activity description; location; accomplishment; and labor, equipment, and material usage, plus supplementary information unique to each highway agency. As part of daily cost reporting, the data should be assembled in such a way that it can be stored and printed on a bi-weekly timesheet in conjunction with other information that must be filled out on timesheets.

Reporting of data should conform to policies and procedures of headquarters and other levels of the organization. In addition, reporting within an integrated system should also pertain to a materials inventory system, an equipment management system, the financial and accounting standards, and the preparation of timesheets and payroll. Requirements typically pertain to the exact type of information that must be furnished and the frequency of information reporting.

For most crew leaders, daily work reporting on paper is convenient and easy. However, the information on crew-day cards is often transferred to a computer or to other forms. Field offices could eliminate the laborious paperwork and reduce data entry time for processing crew work information using electronic devices, which automatically upload the information to the host computer and/or prepare the needed reports. The turnaround time for most of the maintenance management reports and other related posting requirements can be significantly reduced when the information from the field operations are transferred automatically from the field devices. Telecommunications using regular and cellular phone, or other remote data communication, can make two-way data transfer possible without directly interfacing the equipment with the host computer, thus making communications to or from remote locations fast and easy *(12)*.

Crew-card data collection at the field level should also permit summarization of data in such a way that it can help headquarters efficiently manage the maintenance program and determine the adequacy of the budget. Statewide summaries of planned and actual accomplishments and resource usage broken down by district and sub-district levels are essential derivatives of field data.

More specific requirements pertaining to maintenance activity reporting and the technologies that would aid in the process include the following:

- Ordinary maintenance should be reported to headquarters within 24 hours;

- Accomplishments of urgent maintenance should be reported by the end of the work day;

- Emergency maintenance of statewide concern should be reported immediately;

- Crew accomplishments and resource usage must be reported to the general supervisor by the end of the day so that information can be used to plan the following day's work;

- Locational accuracy requirements should be within 50 ft, except for urbanized sections of road or for integration of data between systems, where 3 ft is more appropriate;

- Required accuracies of 50 ft in nonurban areas and 3 to 15 ft in urban areas or for system integration may be achieved using a GPS receiver, a base station, and differential processing;

- Accuracy of material and equipment usage should depend upon the maintenance activity and item;

- Data reporting from the districts has only to be so reliable as to meet the requirements for timeliness;

- Increased reliability is needed to furnish information on accomplishment reporting for emergency repairs;

- Field data collection devices adopted for work reporting should meet requirements for field devices set out in *NCHRP Report 361* on advanced data acquisition technology (e.g., remote data transfer, error checking, and data verification) *(12)*.

Equipment Management

Effective inventory, control, and management of equipment commonly used for maintenance help agencies use their resources in the most economic way. Some agencies have developed or are using equipment management systems to deal exclusively with tracking the cost, performance, and use of equipment for various operations including construction, maintenance, and emergency activities. A maintenance management system should be linked to a state's equipment management system if one exists. Otherwise, selected functions of such a system should be built into the maintenance management process.

Equipment management systems in highway agencies should have the following features in order to fit within the framework of a next-generation maintenance management information system:

- A menu-driven system that is user-friendly.
- A database query procedure that permits easy sorting and analysis of data to examine equipment rental rates to determine if they are cost-effective.
- A reporting capability (e.g., list of equipment models and makes in fleet).
- Ability to charge a variable rental rate based on unit costs that may vary from one district or geographic area to another.
- Means for exception reporting (e.g., classes of equipment underutilized, units with brake problems).
- A proactive scheduling system for equipment maintenance and repair shops.
- Procedures for analyzing equipment replacement needs that include the true cost of ownership (associates the probability of failure with degrees of utilization and provides the economic reason for early retirement If there is a high probability of breakdown).
- Ability to choose between equipment with high and low reliabilities.
- Means to examine which equipment/labor/material combinations are most cost-effective.
- An effective means of integrating equipment maintenance scheduling and work scheduling.
- Provides shop statistics, i.e., location of management problems and needs for training.
- Utilization of a barcode system in the shops to capture labor activity, equipment, parts numbers and other materials usage.
- Reports information in real-time, especially when there is urgent or emergency field work that depends on intensive equipment deployment.
- Assists in daily control of cash flow.
- Means to forecast equipment needs based on the projected maintenance work program and other factors.
- Ability to associate vendor quality feedback with the equipment and parts inventory.

Materials Inventory and Management

In addition to equipment, highway agencies maintain large inventories of materials and stocks in their warehouses, shops, garages, and yards. Some of these materials are used to make other materials or structures that are placed in the field (e.g., signs, guardrail, culverts), which then become part of roadway inventory. Warehouse and roadway feature inventory and management are essential elements of maintenance management systems. The costs associated with keeping these inventories in adequate supply and in good condition can be minimized if they are properly handled by the maintenance management system.

Existing procedures for managing and maintaining materials inventory in the warehouses and stock yards should be responsive to the various aspects of maintenance management. The following are minimum requirements for maintenance management systems that satisfy the above condition:

- Has an up-to-date database inventory of materials in stock at different levels of the agency (i.e., in central warehouses, district yards).
- Employs means to quickly and accurately record or report all the transactions affecting the inventory including receipt, storage, distribution, and disposal.
- Provides a list of sources or vendors of various materials and the costs associated with their procurement.
- Assists in identifying how much, how many, and when specific materials should be ordered to ensure their availability for maintenance.
- Generates statistics and summary reports pertaining to material usage, costs, and other information needed for accounting and budgeting.

Some of these requirements can be met by automating many of the manual or paper-based recording and data updating tasks. In the *NCHRP Report 361*, data collection equipment including hand-held data terminals, barcode scanners, electronic clipboards, voice recognition terminals, cellular phones, and GPS receivers have been shown to offer better and improved ways of managing inventory operations in shops and warehouses and even tracking the use of key materials such as signs in the field. Two-way electronic transfer of information between most of these devices and a host computer that supports the maintenance management system can result in significant savings associated with the costs of keeping the inventories *(12)*.

More effective management and control of materials will result if the warehouse inventory can be tied to the roadway inventory. It is often difficult and unwieldy to maintain a comprehensive and systematic procedure for recording various transactions that affect the inventory of stocks and properties. It is even more difficult to connect warehouse inventory to field inventory, which impedes the availability to field personnel of useful information about materials that become highway assets. Many technologies, including those discussed in *NCHRP Report 361 (12)* can improve the process of recording and managing warehouse inventory, and enhance the field operations either through better information about material availability, or through tracking over their lifecycles material inventory stocks (such as signs), which become part of the roadway inventory.

The Urban Institute developed and field-tested a cradle-to-grave sign inventory and maintenance management system using a hand-held data terminal and barcode scanner as the core technology *(12)*. The objective was to track and record each action taken over the lifecycle of a sign and to record the condition of the signs in the field. Sign transactions that were programmed for data collection using the field device include fabrication, stocking, distribution, issuance to sign crews, field installation, inspection, repair or cleaning, replacement, and disposal. The process is applicable to a wide variety of stocks and materials to improve their use for maintenance management.

Performance Monitoring, Evaluation, Standards, and Feedback

Monitoring and evaluation of work accomplishments and methods help maintenance agencies control and assess their overall performance. It is extremely useful for agencies to know the productivity, efficiency, and quality of work accomplished – which are measures of the success of the maintenance programs, the crews and the overall objectives of the organization. The following MMIS capabilities will allow performance monitoring and evaluation:

- Reconciles material inventory with usage;
- Summarizes planned versus actual labor, equipment, and material usage;
- Compares planned versus actual work accomplishments;
- Tracks equipment, material, and contract quality;
- Determines productivity of inputs (resources) in terms of work accomplishments per resource unit;

- Compares productivities of different work methods; and
- Reports expenditures and costs associated with each activity.

Work monitoring and evaluation has always been a problem for highway agencies due to the time it takes to load the information into the computer, process it, and send it back out to maintenance manager. Also errors in work reporting, unintentional or otherwise, frequently go undetected, resulting in unreliable reports. In some maintenance organizations, crew leaders use the average daily production rates in reporting their accomplishments, which defeats the purpose of performance evaluation. Electronic data collection devices offer means to automate the reporting of work accomplishments and resource usage and minimize or discourage errors associated with acquiring and transmitting data from the field.

Quality of maintenance activities can and should be measured to some extent through quality control programs. Agencies should have comprehensive quality control programs and should conduct inspections of field operations, equipment, personnel, and office operations.

Virginia DOT *(13)* established a Maintenance Quality Evaluation (MQE) program in order to evaluate statewide maintenance performance. The program compares aggregate level-of-service quality measures for all maintainable elements with the desired minimum level of service for the highway system. The objectives of the MQE program are to monitor the quality of maintenance, to determine inconsistencies in highway performance, and to provide consistent levels of service.

The results of performance and maintenance quality evaluation should serve as feedback to the maintenance management system. Performance standards should be examined and modified if necessary to reflect actual conditions encountered and reported in the field. These standards need to be applied in a less rigorous way than they have in traditional maintenance management systems so they can be used in conjunction with condition and level-of-service data and reflect local conditions. As a result, district and local area supervisors should be able to define and use performance standards that are most appropriate for the locale. In short, the performance evaluation function of the MMIS should test the comparative efficiencies, productivities, and cost-effectiveness of various work procedures, equipment, material types, and crew sizes.

2.4 Benefit-Cost Framework

The analytic capabilities described in the preceding section can be structured within a benefit-cost framework. Not all maintenance activities may be amenable to this approach – it is often difficult to assign benefit values to maintenance activities, particularly if they are performed to meet aesthetic requirements or similar criteria that are difficult to quantify. Nevertheless, many activities – especially those related to pavement or bridge preservation, safety, and efficient movement of traffic – can be structured within a benefit-cost framework, in which benefits may be quantified in terms of extension of facility life, reduced costs of traffic movement or accidents, and therefore lower life-cycle costs.

Two basic approaches to representing maintenance in this way can be conceived:

1. An approach that does not entail direct optimization of the best solution, as shown in Figure 6.

2. An approach that does apply optimization techniques, as illustrated in Figure 7.

These two approaches differ only in the mathematical techniques used, not in their basic ideas or results. Both approaches rely on an economic as well as a technical basis for evaluating the need for, as well as the effects of, routine maintenance; both approaches require explicit statements of management decisions governing the level of maintenance to be accomplished for each activity; and both approaches consider the demand for maintenance, as explained below.

Annual maintenance is viewed as a demand-responsive operation; that is, a function of the damage accumulated in the highway system in a given year. This deterioration can be estimated from the initial condition of the system (i.e., its as-constructed quality), its rate of deterioration over time, and past maintenance performed. Beyond these physical conditions, however, maintenance workload requirements are also subject to policy decisions defining the type, location, and extent of work to be provided. Maintenance policies are expressed through quality standards or levels of service specified for the set of maintenance activities over all sections of the road system. Elements of this demand-responsive methodology are summarized in the top half of Figures 6 and 7.

Maintenance policy evaluation entails a comparison of both relative costs and relative impacts between the strategy under consideration and other maintenance and capital investment options available. Although the use of an optimization model suggests itself, in fact the definition of general

Figure 6. Maintenance Analysis Through an Iterative Approach

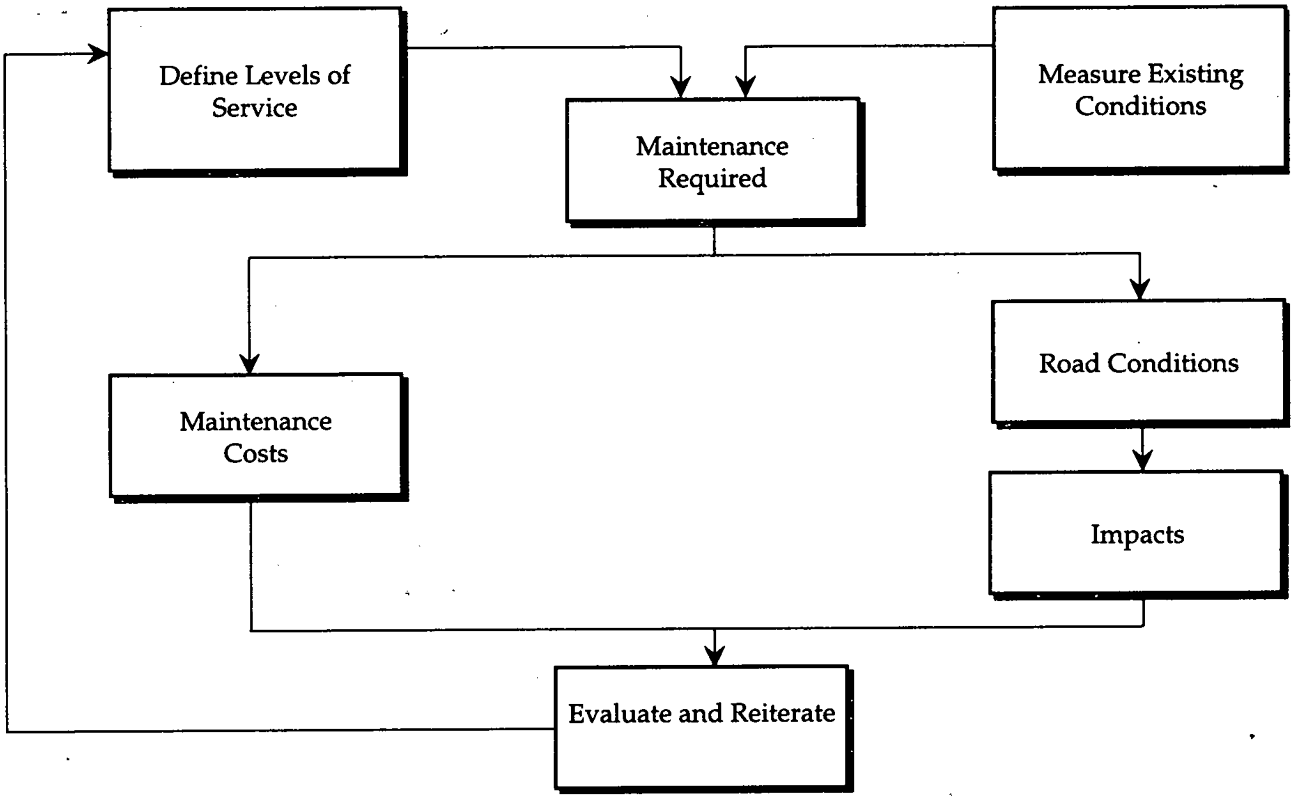
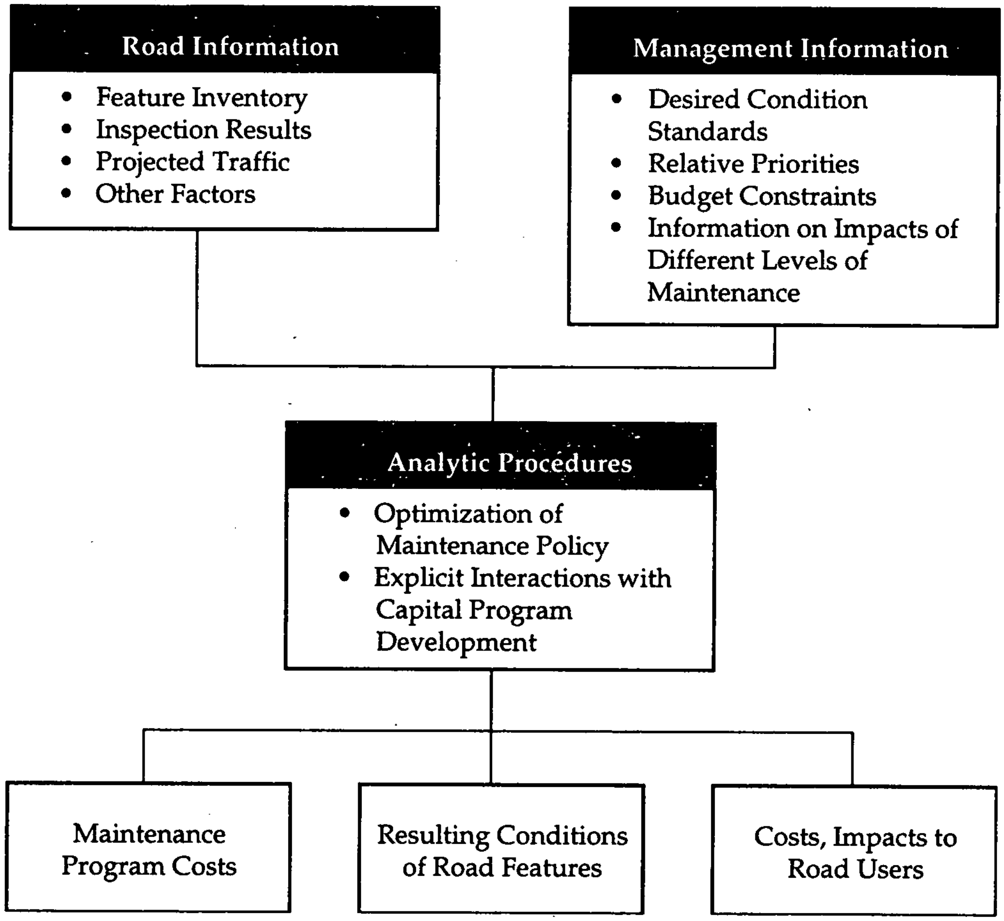


Figure 7. Maintenance Analysis Through an Optimization Approach



optimization rules for a maintenance program may be complicated in practice, because of the relatively large number of activities (with their quality standards); the degree to which one activity can substitute for another; and the options in scheduling (or deferring) maintenance. Also, in the general case where impacts are multidimensional, and evaluation cannot be reduced to simple benefit-cost terms, it becomes very difficult to state what the "best" maintenance strategy should be. On the other hand, if benefits of maintenance can be reduced to monetary terms, optimization is entirely feasible.

Broadly speaking, the approach in Figures 6 and 7 may be applied to address two types of situations. The first situation would be to constrain the values of the impacts desired – in other words, to establish some range of road system benefits that must be sustained through maintenance and rehabilitation, and not to allow the road system to degrade below the established threshold. One could infer both the maintenance policies and costs necessary to accomplish this target level of service. The second type of situation would be to constrain costs – in other words, impose a budget limitation. One could then vary maintenance policies to attempt to maximize favorable impacts while remaining within the cost ceiling.

3.0 Integrated System Concepts

3.1 What Is Integration?

Integration means different things to different people. To some, integration implies the large, centralized work order processing systems now in existence in many transportation agencies. To others, it means a merging of maintenance management systems with other related systems, such as Geographic Information Systems or Pavement Management Systems. In fact, maintenance managers have many other alternatives besides these two, and the best solution will vary in different agencies.

This chapter will explore the various ways of looking at integration, starting with a definition of the problems that integration is meant to solve. For most agencies, the next generation of maintenance management systems will feature a higher level of integration among maintenance functions, and between maintenance systems and other systems, than what exists now. Almost certainly, the next generation will feature better, more appropriate integration than is typical today, taking advantage of better information technology and a better understanding of the role that maintenance and integration play in the overall management of a transportation agency.

■ 3.2 General Concept

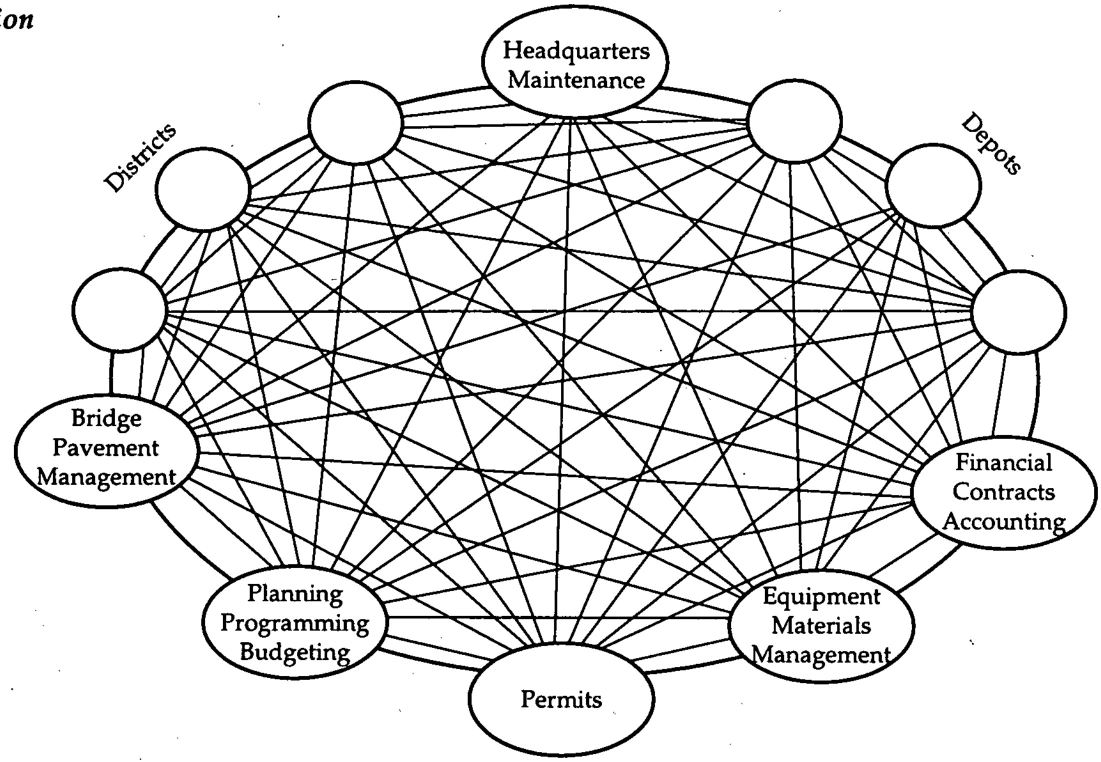
One of the chief management concerns that integration is meant to address is the problem of system complexity and manageability. Maintenance management, particularly its planning function, needs many different kinds of data from many sources. Other agency systems, especially the ISTEA-mandated management systems, also have diverse data requirements, which overlap those of each other and of the MMS. If expensive duplicative data collection and inconsistency are to be minimized, there is a strong agency-wide need for data-sharing. This is a point that needs to be emphasized: it is possible, even today, to implement far better maintenance management system capabilities, in terms of their responsiveness to management needs at every level, than what is in common use today; and it is not necessary (in many agencies) to incur large amounts of additional data collection costs and staff reporting inconvenience to achieve this. What is needed is far better handling, sharing, and usage of the data already available. These steps will, in turn, support efforts toward data timeliness, quality, and integrity.

Figure 8 illustrates the difference between the data flows of unmanaged data-sharing, which is the default solution to the problems of lack of integration, and the far more manageable situation where effective integration is accomplished. The primary difference between the two models is that the latter has an organizational and technical entity whose chief responsibility is the sharing of data. An effectively integrated system insulates each contributor and user of data from most of the problems of data interchange, and permits a concentration of technical resources – a critical mass – in a position where it can benefit the entire agency. It is clear that the integrated model is a lower-cost, higher-quality solution to the data-sharing problem.

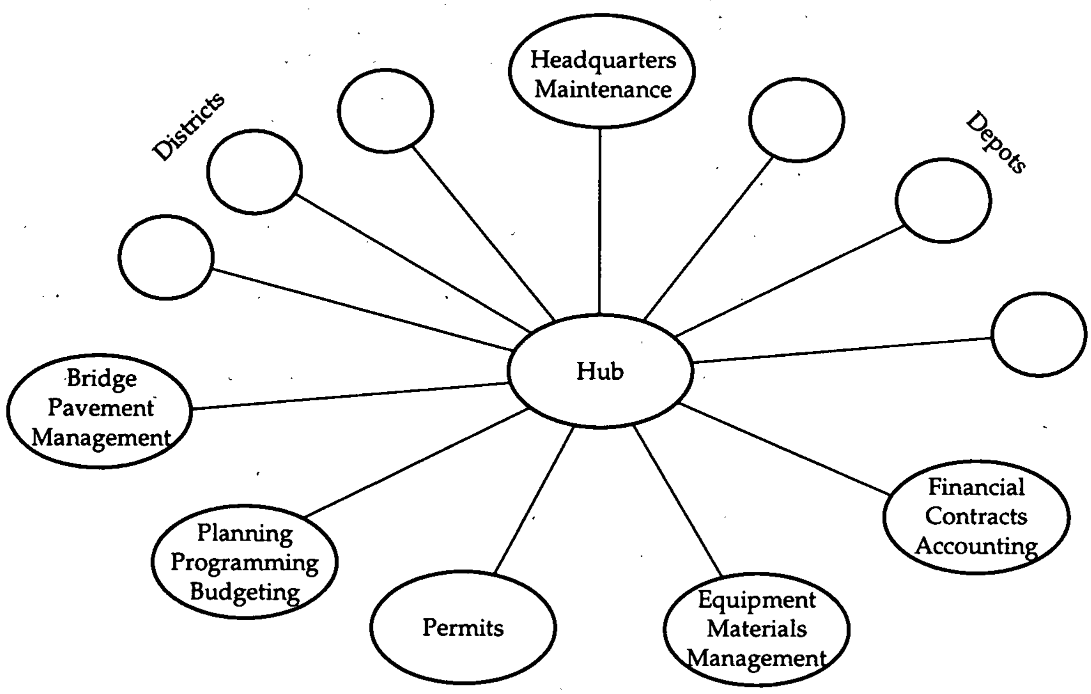
Consistency of policy is another goal of integration, and one of the biggest obstacles to policy consistency in existing transportation agencies is an inability to measure how policy in one part of the agency affects other parts of the agency. This leads, for example, to situations where pavement and bridge management policy dictate a heavy reliance on preventive maintenance and life extension, while the maintenance division finds itself underfunded or underequipped in its activities necessary to implement a preservation policy. Improving management communication is, of course, one part of the solution to this problem; but another part is eliminating the frequent inconsistency among different parts of the agency in the manner in which existing conditions are measured, future actions are planned, and past actions are recorded. Integration of the definitions of these basic elements of data is a necessary step in better policy integration, and this is a place where the next generation of maintenance management system will be very helpful.

Figure 8. Benefits of Integration

Nonintegration



Integration



3.3 Pros and Cons of Integration

Implementers of an integrated maintenance management information system have to be aware that successful implementation depends on striking a proper balance between competing forces: while integration is generally beneficial, it can be taken too far, and there are drawbacks to be avoided. The following is a discussion of the most significant pitfalls, followed by a statement of the important advantages, of system integration.

Drawbacks

The perceived disadvantages of system integration are as follows:

- **Micro-management.** Older maintenance management systems, in an attempt to keep their software simple, often stored all of their most detailed data in a single centralized database. Under this situation, there is a legitimate concern on the part of local maintenance managers that over-zealous district and headquarters managers can use the information to second-guess local tactical decision making.

- **Drowning in Data.** On the other hand, from the headquarters perspective, the use of a single centralized database provides so much detailed data that it is very difficult for management to effectively use it. Management needs to see the forest, not necessarily the trees. Massive centralized maintenance databases were a technical convenience at a time when computers lacked the power to store data in a more useful way; but this type of MMS organization has led to user inconveniences and even mutual suspicions, which are counter-productive to good maintenance.

- **Excessive Dependence on Data.** Another danger of maintenance management systems is that decision making and management performance evaluation might become too heavily dependent on data, or might become skewed by the nature of the data that happen to be available. For example, a currently developing problem with maintenance management systems is that very good life-cycle cost data are starting to become available on the impacts of maintenance policy, and yet the data concerning road user benefits of maintenance quality are still quite poor. Without data, decision making concerning the tradeoff between facility preservation and user benefits becomes an excessively political or arbitrary question, perhaps placing too little emphasis on preservation; but too much dependence on data can lead to the opposite extreme, where user benefits are ignored because they are not easily measurable. A successful MMS recognizes the limitations of data and provides a framework in which both subjective and objective policy inputs can be properly and fairly combined.

- **Too Much Expenditure on Data Quality or Timeliness.** Data collection, storage, and transfer are expensive, and the cost of improved quality or timeliness can sometimes be disproportionate to the benefit. What's more, different MMS users have different quality and timeliness requirements. For example, upper management places a far higher value on the comprehensiveness of data, the assurance that their information fairly represents the entire statewide highway network, than on the reliability or even availability of any individual time card. It is unnecessarily expensive to provide every MMS user, regardless of location or organizational level, with the same level of detail, quality, or timeliness that the individual depot manager needs for his own operation.

- **Not Enough Expenditure on Quality or Timeliness.** Here again, the MMIS implementer has to perform a balancing act, because the output of any computer system is only as good as the input. To strike the necessary balance, the system developer must stand in each user's shoes and ask what level of quality is really necessary. For upper management, for instance, a small random sample or summary of timecard data, combined with an exception list, may be nearly as valuable as a comprehensive statewide timecard database, and is preferable if it lowers the system cost or improves the timeliness of the reports which they use.

- **Making the System too Complicated.** Maintenance techniques and management issues have become increasingly sophisticated in recent years, but this does not necessarily imply that the MMIS should be more complicated from the user standpoint. Also, since the state-of-the-art in software development has improved dramatically, development costs for a system that is more user-friendly and more capable than what has been available in the past may actually be lower than before. The key considerations in controlling the complexity of any software system are modularity, incremental development (building the most fundamental modules first), strong user involvement in every phase of the design and development (even though this may appear to be initially rather expensive in management time), and appropriate use of hardware (for instance, asking the mainframe to do only what it does best, and having terminals or other machines do what the mainframe does poorly).

- **Loss of Flexibility.** No one, no matter how routine his or her job, wants to have a life regimented by a computer. There is a very fundamental difference between a MMS that makes decisions, and one that informs human decisions. The latter system, which is far superior, provides alternatives, illustrates their pros and cons, and gives users feedback on various decisions they might make. No matter how good the system is, there will always be instances where it must be bypassed. A good MMS design anticipates the places where flexibility is required, and ensures that the users' exercise of this flexibility does not unduly compromise the data quality or serviceability of the system.

- **Loss of Power.** Of course, a big concern about integration is that users lose control over what they feel is their own data, and thereby open themselves to unwanted scrutiny by supervisors or third parties. Humans are not perfect: they don't in every instance make the best possible decisions in their day-to-day activities. Yet, computers are assumed to report their mistakes perfectly. MMS design, especially the control of the level of detail available to users, can partially alleviate the potential for over-exposure of normal human fallibility; but this problem will always be present in a data-sharing environment.

All of these considerations are legitimate concerns of MMS users. The most fundamental means of overcoming them are good design, as described in the preceding paragraphs, and benefits, which make the costs worthwhile to each affected person.

Benefits

The benefits of integration, which can potentially be achieved by the next generation of maintenance management systems, are substantial. Among them are the following:

- **Flow of Information and Responsibility.** Put most succinctly, managers have a more accurate picture of what they are managing. Effective integration matches available data to each user's responsibilities.

- **More Thorough Information.** Many different factors affect maintenance decisions and scheduling. A good maintenance manager is resourceful in finding relevant information about such issues as accidents, traffic, rehabilitation plans, etc., but he or she often spends a considerable amount of time doing this, with uncertain quality of the results. A well-integrated MMS should make this task much less time-consuming and much more reliable.

- **Data Needed for MMS Come from Many Sources.** Every unit of a department of transportation produces data for its own purposes, and certain extracts or derivatives of each unit's data may be valuable for maintenance management. Integration provides a convenient means for each data-producing organizational unit to make its data available to others, including maintenance.

- **Many Other Parts of an Agency Need Maintenance Data.** The increasingly important role of maintenance means that maintenance information and concerns are increasingly important to nonmaintenance decision making. It is frustrating to management and the public alike when scheduled maintenance activity, combined with unrelated but nearby activities of another DOT unit, combine to cause unexpected traffic jams. In a more strategic sense, the people responsible for pavement and bridge management find it nearly impossible to accurately develop a multiyear schedule of rehabilitation projects when they have no data on the effectiveness of maintenance.

- **Critical Mass.** Data collection and database management have significant economies of scale. A well-integrated system makes efficient use of expensive data collection equipment and technical personnel, and avoids duplication of effort.

- **When Money Is Scarce, Good Information and Strategy Can Stretch It Further.** This is the most significant economic benefit of integration, because it reflects the central purpose of a maintenance management system, which is to improve management decision making by making it more informed. The next generation of maintenance management system will have planning capabilities that use historical data on costs, deterioration, and traffic to directly estimate the potential savings due to better strategic maintenance planning. Network-level pavement and bridge management systems already have this capability.

- **Competitive Weapon.** Information is power, especially when other state agencies are competing for scarce funds by using more and more sophisticated and quantitative justifications for their budget requests. A state DOT must become more integrated in its data management just to keep up with competing agencies.

■ 3.4 Costs of Integration

Figure 9 shows schematically the various costs of an integrated maintenance management system over time. Each arrow in the figure represents an investment. Those in the top half are for labor; those in the bottom half are for hardware and software. The relative magnitude of investments is indicated by the lengths of the arrows. The elements of this diagram are as follows:

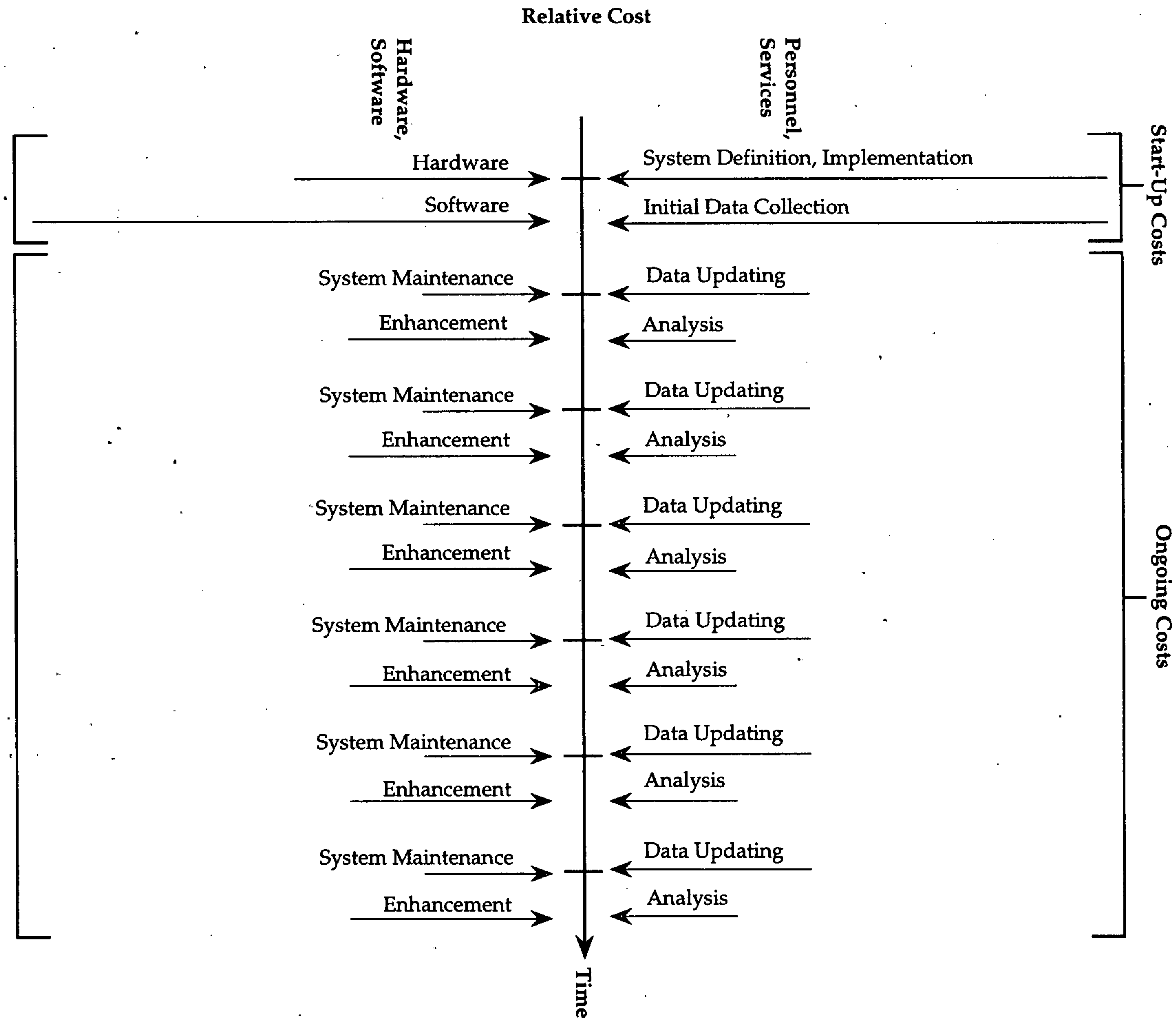


Figure 9. Costs of Integration

Start-Up Costs

- **System Definition and Implementation Effort.** Any maintenance management system development effort requires this. For a truly integrated system, this activity must be expanded to include a preliminary analysis of the data-sharing needs of the agency as a whole, so that the resulting capability will be compatible with the rest of the agency's management systems.

- **Data-Sharing Mechanisms (Hardware/Software).** An integrated database environment may actually have lower hardware and software costs than a nonintegrated environment, because, as Figure 8 shows, there is less usage of data transfer mechanisms. All provisions for data compatibility among different system users (for instance, software to convert latitude/longitude to route/milepoint, or to roll up accounting codes into broader categories or perform cost allocation) are made in just one location, instead of having to be made on every individual user's system.

- **Software Development.** In an integrated MMS, software development includes separate modular systems for each group of users (e.g., headquarters managers may use a system that is much different from the one used in the districts), plus development of a database that provides the linkage among the separate systems. If similar user capabilities are offered in an integrated and nonintegrated form, the integrated form will tend to be less expensive because of its modularity.

- **Database Establishment.** Integration requires the establishment of a "corporate database," which includes selected maintenance data (which should be only a small subset of the total volume of data produced by the overall MMS), along with data from numerous other sources. This activity is more expensive for an integrated MMS than one which is not integrated, but once accomplished, it benefits all other management systems in the agency and lowers their cost.

Ongoing Costs

- **Data Collection and Updating.** As discussed earlier in this manual, certain basic kinds of data are essential to a successful MMIS. For an agency that already collects the necessary data, integration should lower costs because of the elimination of duplicative effort, and the ability to more efficiently adopt new data collection technologies. Data quality control and standards coordination should also be less expensive because these communication-intensive activities can be concentrated in a smaller number of people.

- **Analysis.** Currently, maintenance management analysis is a time-consuming activity, usually requiring considerable time to acquire data beyond what is available in the MMS. A major goal of integration is to shift this workload to a centralized technical staff, dedicated to a data-sharing function. The cost of MMS usage should therefore decline substantially.

- **Hardware/Software Maintenance.** If implemented according to the principles described here, an effect of integration should be an overall reduction in the amount of custom-developed computer code that has to be maintained, an increase in its modularity, and a somewhat increased level of agency-wide standardization of software. These should tend to reduce software maintenance costs. The effect on hardware maintenance is uncertain, because even though machine requirements should be somewhat lower, and standardization greater, the critical mass encouraged by integration may lead to investment in more technologically advanced data collection equipment, which could have higher maintenance costs.

- **System Enhancement.** All technologically advanced equipment and software eventually become obsolete if not periodically updated and enhanced. This is true of any system regardless of its level of integration. If integration succeeds in lowering the overall amount of code to be maintained, it should also lower the cost of enhancement. However, any successful implementation effort tends to perpetuate itself through the mechanism of enthusiastic users demanding increasingly more functionality.

- **Overall, Integration in the Next Generation of MMIS Should Have the Effect of Lowering the Life-Cycle Cost of the System, Compared to the Better Systems in Operation Today.** Experience with decision support systems in the past decade, however, has indicated that system users tend to convert any cost savings into improved functionality or increased usage, so that the end result is a system cost savings that is less than expected, and an impact on management decision-making quality which is greater than expected. In attempting to estimate the cost saving benefits of integration, therefore, it is prudent to ignore the time savings of system users, and concentrate on the amount of time spent collecting and transferring data. Current costs of these activities can be measured and compared among peer agencies to determine the potential savings.

Two lessons illustrated by the diagram are as follows:

- The least significant start-up cost component is for hardware acquisition; and

- Ongoing costs of integration are significant and need to be anticipated.

3.5 Mechanism of Integration

There are many ways of accomplishing integration in a MMIS. How any individual agency chooses to do it will depend on many factors, so wide variance from one agency to another can be expected. Moreover, even within an agency a variety of mechanisms may be used, including the use of technologically primitive but flexible mechanisms used as backups for more advanced methods.

- **Manual Data Sharing.** The simplest method of data sharing is an agreement to copy data onto a disk or tape and carry or deliver it to its intended recipient. Simple and flexible, this method is in widespread use, especially for delivery of software, where the vehicles can be mass-produced, or for ad hoc exchanges among parties who do not routinely share data. This method is among the most expensive and least reliable however for periodic exchanges that are not mass-produced. Technical people often refer to this method as "sneakernet." Two modes of manual data sharing are clearinghouse, where a single person or group collects diskettes or tapes and makes copies on request for others, and point-to-point, where each producer of data sends a disk or tape to the recipient on demand, with no middleman.

- **Automatic Data Sharing.** This method is distinguished from the previous one primarily by the medium of data transfer, which is over wires or other electronic means and may involve a local-area network, a wide-area network, or a dial-in telecommunication. The method is efficient for frequent transfers of data. Alternative modes are

  - **Centralized bulletin board** – data to be shared are copied to a central storage device such as a mainframe disk, where others can access it.

  - **Centralized directory** – a centralized storage device contains information on the location of data, rather than the data itself. Data requests are fulfilled by transferring the data directly from its source to the recipient. This mode has lower storage costs but higher telecommunication costs.

  - **Point-to-point** – the recipient connects with the source of the data directly, without the involvement of any centralized facility.

- **Standardization of Data.** Further integration is achieved, with either manual or automatic methods, if the data producers and users can agree on standards for definitions of data items, quality and completeness, security, and updating schedules. When a centralized data-sharing facility is involved, the standardization permits that facility to accomplish some routine but time-consuming and indispensable tasks, such as combining data from multiple sources, extracting data subsets, summarization, allocation, converting reference systems, and scheduled transfer of data without user supervision. This level of standardization facilitates most of the operational cost savings opportunities described above, including data collection, data transfer, and user analysis time. An invaluable tool to support these capabilities is a good multiuser database manager.

- **Standardization of Analysis Techniques and Products.** This level of integration builds on the preceding level. It involves the standardization of data items that are not directly collected in raw form, but are generated from an analysis of raw data. Such items include transportation system performance (pavement and bridge condition, traffic congestion, safety in a general sense, highway user attitudes, etc.), work accomplishments, work plans, and costs. With this information, the maintenance manager can develop policies and work programs that take into account the actions of other parts of the agency. Similarly, the results of a maintenance manager's analysis of maintenance effectiveness can influence the output of pavement and bridge management systems. Within the maintenance function, this level of standardization permits headquarters, district, and local offices to agree on maintenance performance targets which are more significant and less restrictive than miles-plowed or potholes-filled: namely, the level of service experienced by highway users.

- **Policy Integration.** When the preceding levels of integration have been achieved, top management can begin to use this information for broad-based policy analysis of such critical questions as: what is the best division of resources between maintenance and construction? what is the best maintenance staffing complement? how much new equipment is needed, and how much depreciation should be expected? is the agency serving the public better than it did last year? can that be proven convincingly to the Legislature?

- **Decision-Making Integration.** In certain cases, integration of systems can lead to integration of decision making, or even an organizational trend toward centralization or reorganization. This may be a desirable result when current decision making is inconsistent or fragmented, or when the agency consistently fails to achieve policy goals. However, since reorganization is a common occurrence today in state DOTs, and since system integration can be an effective treatment for fragmented decision making, it is equally possible that system integration may be a force which forestalls reorganization.

- **Combining Systems.** As an alternative or addition to the integration of data and policy, a maintenance management system may achieve integration by combining separate systems. For instance, an agency with separate home-grown systems for work recording and cost estimation may want to combine these two computer programs into a single program that is capable of updating its own cost factors. This method is especially useful when combining two systems that have the same set of users. However, the larger combined system, if not designed to be internally modular, could prove to be less flexible and more expensive to maintain than the original separate systems. In maintenance management applications, it is usually more efficient to keep the systems separate, but modify then so that they can exchange data to support the desired enhanced features.

- **Monolithic System.** In speaking of integrated information systems, a picture that frequently comes to mind is of one grand new system that is bigger and more comprehensive than ever before. Managers with system development experience will flee when presented with this image, because they are aware of how difficult it is to keep such projects under control and satisfy a large and diverse user group as user needs change during the development process. In the days when mainframe computers were the only machines capable of handling the volume of data processed in maintenance management, the forces for organizing and building large systems were strong. Now that decentralized computer usage is the norm in most agencies, and database management tools are well developed as data-sharing mechanisms, a monolithic maintenance management system is rarely, if ever, an attractive prospect when separate, more functional, and more flexible systems can be developed at lower cost.

■ 3.6 Scope of Integration

Agencies implementing an integrated maintenance management information system have a broad array of choices about the functions and organizational levels that are to be included. A common and effective implementation strategy is to begin with a core system that can stand alone, and then expand by adding new modules that bring in new users and build bridges to new outside systems. Generally, the data-sharing hub, such as a corporate database, is the first to be implemented, and it is connected with a few existing systems, including the existing MMS, to begin operation and prove its value. A total organizational commitment is necessary to make this a success, and so top management involvement is essential. In many states, the ISTEA-mandated management systems, which also benefit greatly from data-sharing, have been a driving force in the establishment of a data-sharing unit. Similar activities are occurring extensively in the private sector, making data-sharing architectures a hot issue among data processing professionals. A sensible expansion path for a new MMIS may be as follows:

1. Concurrently with the hub, development or adaptation of maintenance-related systems that depend on the hub can begin

   - Maintenance control and reporting;
   - Work order generation and tracking;
   - Monitoring; and
   - Planning.

2. Migration of the system through organizational levels also happens simultaneously, by establishment of appropriate data transfer, summarization, and allocation procedures

   - Between crews and depots;
   - Between depots and districts;
   - Between districts and headquarters; and
   - Between headquarters maintenance management and upper management.

3. Integration can continue to closely related functions

   - Equipment management;
   - Materials management;
   - Cost tracking;
   - Payroll; and
   - Contract management.

4. Integration can continue to the ISTEA management systems

   - Pavement management systems;
   - Bridge management systems;
   - Safety management systems;
   - Intermodal facility management systems;
   - Congestion management systems; and
   - Transit facility management systems.

5. These uses also provide a natural extension to planning and development functions

   - Programming and budgeting;
   - Transportation planning; and
   - Permits.

Figure 10 illustrates the potential of a broad-based integration of systems. This overall picture is an MMIS, even though many of its elements, such as accounting, programming, and so on, are not primarily maintenance systems.

■ 3.7 Integration Considerations

Choices of depth and scope of integration, as described previously, and of technical implementation, as described in this section, yield in combination an extensive universe of different system designs that can serve the purposes of an MMIS. The following factors influence what design is right for any given agency:

- **Organizational Structure and Decision-Making Processes, Including the Amount of Decentralization.** Greater decentralization of organizational structure tends to imply greater use of small computers and a larger number of small software modules. If fragmented decision making is to be avoided, a decentralized agency may want to place emphasis on policy integration in the MMIS.

- **Agency Size and Highway System Usage.** Larger agencies will generally have more resources to apply to the MMIS and will want a more extensive system.

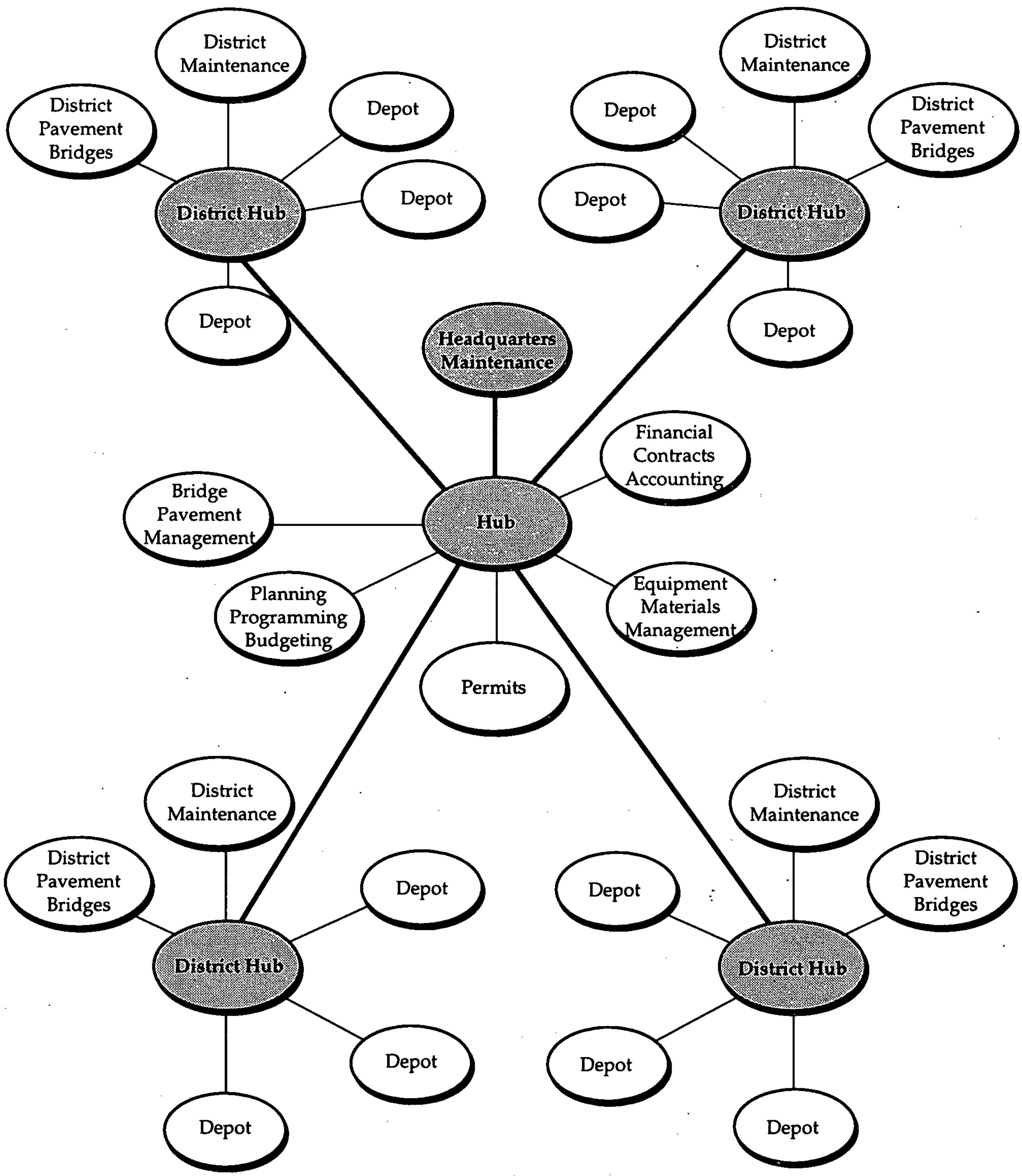
- **Scale and Urgency of Typical Maintenance Needs.** States that do not experience heavy traffic or rapid physical deterioration tend to place less emphasis on MMS development.

- **Diversity of Maintenance Skills and Equipment.** States with a high level of diversity in maintenance can benefit from an emphasis on data standardization to facilitate technology transfer among districts.

- **Policy Concerns, Historical Problems, and Stakeholders.** These have an important effect on what specific functional modules receive emphasis.

- **Existing Systems Which Do or Might Support Maintenance.** Occasionally it is possible to save existing systems and weld them together into an integrated MMIS by providing data-sharing linkages. This requires a detailed case-by-case evaluation, because the most expensive kind of software development is modifying an existing system to fit a system architecture for which it was not originally designed, especially if the original system is not well modularized.

Figure 10. An Integrated Maintenance Information System



- **Status of Other Systems with Which MMS Might Interface, and General Agency Computer Technology Trends.** Technology preferences and technical staff capabilities vary substantially from one agency to another.

- **Available Long-Term Support Mechanisms.** It is extremely important that the agency have an in-house support capability for its hub data-sharing system; this should not be contracted out, because it is too intimately tied to every aspect of agency operations. For the analytical modules and workstation packages, support by vendors or other agencies (e.g., AASHTO) can be preferable, since the agency then benefits from the pooled resources of multiple user states in the maintenance and enhancement of the software.

- **Level of Top Management Support.** Strong top management support is essential to a successful data-sharing system; lack of it will tend to make integration efforts less effective, and therefore a less attractive investment.

■ 3.8 Standardization of Data

Technical design of an integrated MMIS includes the same issues that normally arise in any significant system development effort. Design of the hub places special emphasis on certain generic issues that impact not only the MMIS, but also all other management systems. General concepts are presented below; additional details will be given in Chapter 4.0.

Many seemingly arcane data standardization issues consume enormous amounts of system developer time to resolve. Without a hub capability, the MMIS developer and each other management system's developer must re-invent the solutions to basically the same problems.

- **Reference Systems.** Reference systems are fundamental to any analytical task, and often have significant inertia due to long history of usage. What surprises many managers is the number of incompatible reference systems in use in the typical state DOT.

  1. **Geographic.** Many states have state plane coordinate systems that are used in route location and other large scale engineering tasks. However, bridges and interstate activities, such as defense, tend to rely on latitude and longitude. Global Positioning Systems also provide their locations in terms of latitude and longitude. For existing roads and facilities, a route and milepost system is common. Surprisingly, many states have multiple route/milepost systems that

may overlap and may be inconsistent with each other: a frequent situation is to have one system for the state highway network, another for local roads, and perhaps a separate one for the old Federal Aid system. Another frequent situation is to have one system for numbered routes (which is confused by the fact that a single facility may carry multiple signed routes), and a separate system for legal documents. The state police usually have their own system for recording the location of accidents. All of these systems need maintenance, because new construction, re-designation, and re-alignment all require changes. This is probably the most expensive standardization issue to undertake; states are spending up to several millions of dollars on GIS implementation, much of this money going toward cleaning up geographic references.

2. **Time.** Every state DOT has multiple ways of measuring time. Certain activities occur on a calendar year basis, but most accounting activities occur on a fiscal year basis. Activities related to federal funding often occur on the federal fiscal year cycle. Often it is useful to also recognize a legislative year cycle. Maintenance planning has to recognize that the number of days in a year is variable: snow can occur on any of the 365 or 366 days of the year, but crack sealing normally happens only on weekdays.

3. **Account and project identification conventions.** Every state DOT has a set of accounting code conventions and a project numbering system. However, any given maintenance action that a crew might take could have more than one possible identification code, depending on the use to which the data are to be be put. This historically has made it very difficult to use maintenance accomplishment data in a pavement management system, for instance.

4. **Dimensionality.** The world of transportation data is not necessarily three-dimensional: this is convenient for design work, but often it is more convenient to show road segments as one-dimensional lines, for maps, or as two-dimensional surfaces, for pavement management. Bridges are three-dimensional for design, two-dimensional for deck maintenance, and one-dimensional or point data for maps.

It is not necessary, for the purpose of an integrated MMIS, to change all reference systems so that only one or two are in use; this would be a very expensive undertaking. What is necessary is to have a centralized unit, the hub, which provides the service of converting data from one reference system to another according to a master reference database which it assiduously maintains. Users can then keep the references with which they feel most comfortable or can work most effectively, and feel confident about their accuracy.

- **Definitions.** This is another difficult standardization issue, and one of the best examples is cost. For instance, what is the cost to seal cracks on 10 miles of road? Is it just the cost of the crew and materials? Does it include some share of the equipment and tools used? Does it include a share of the maintenance of the equipment, or of office overhead? Does it include a police detail? If done by contract, does it include project supervision and the cost of contract administration and accounting? Does it include contingencies? Obviously, the definition is different for different purposes: a valuable hub service is to use cost allocation models to convert from one definition to another and to clearly inform data users of what definition is being provided.

- **Quality Level.** Quality costs money, so the agency needs quality standards to define how much quality is worth having. There are several components of data quality:

  1. **Accuracy.** A good quality-control effort costs 1 to 5 percent of the original data collection cost. This includes data consistency checks, reasonableness checks, manual reviews of field data collection forms and timecards, and spot checks in the field.

  2. **Precision.** Doubling the number of digits of precision doubles the data storage cost and at least doubles the labor and equipment cost for data collection.

  3. **Completeness.** The last 5 percent can cost as much as the first 95 percent. Missing data in any transportation database is a fact of life, so it is important for the hub to monitor the level of completeness of data it distributes and inform the users. By recognizing that a data set is always a less-than-100 percent sample, analytical programs such as for maintenance planning can avoid being stymied by missing data.

- **Updating Frequency.** A system that provides real-time access to up-to-date data can cost 10 times what a system offering weekly or monthly updates would cost. Most (but not all) MMS functions do not need real-time data access, and by recognizing this can be made much less expensive to develop.

- **Updating Reliability.** Users may not be concerned about the immediacy of data updating, but they are concerned about consistency; knowing, for instance, that a report on work accomplishments always is up-to-date as of the end of the previous month.

■ 3.9 Standardization of Analysis

Many of the data items that are widely used in an MMIS are not directly collected in the field, but are the result of analytical procedures. Pavement condition, for instance, is normally a combination of observed and measured indicators in nearly all maintenance and pavement management systems. Incompatibilities in the way these quantitative indicators are calculated can be a source of expensive and unnecessary wheel-spinning in system development. Among the analytical products that are most frequently shared within the maintenance function and with other functions are the following:

- Condition of the highway network;
- Benefits and costs;
- Policy objectives;
- Budget categories, criteria, and constraints; and
- Levels of accountability.

It is not necessary that every part of the MMS use exactly the same definitions for these quantities; it is only necessary that the definitions be compatible, so that there is a reliable and defined way to convert data from one definition to the other.

4.0 Integrating Data and Decisions

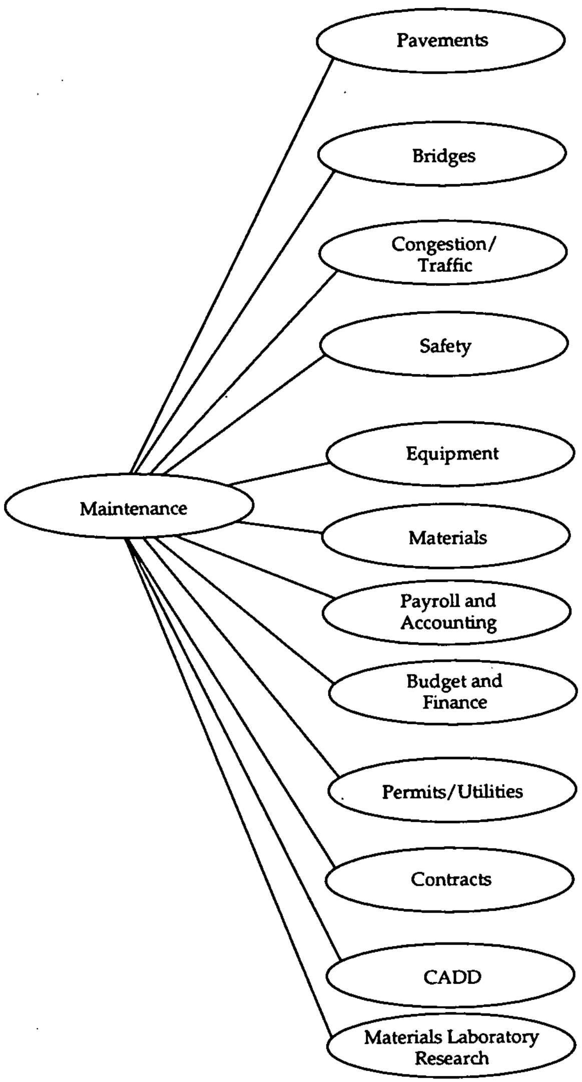
4.1 Introduction

A fundamental requirement of an integrated system environment is that the maintenance management system furnish and receive information relevant to the other management systems and decision support tools. Many organizational units are either already equipped or planning to acquire management information systems and decision support tools that have a bearing on maintenance. These include management systems for maintenance, pavements, bridges, safety, congestion, contracts, permits, accounting, equipment, materials, capital planning and programming, and weather reporting. The maintenance elements of each of these management tools need to be interrelated. Figure 11 shows the types of information that should be routinely exchanged between maintenance and other management systems throughout an agency as well users outside the agency. How this exchange is accomplished with a hub-and-spoke system concept is described in the following sections.

4.2 Data Sharing at the Hub

The hub permits the sharing of two fundamental categories of data. The first pertains to the way information has been stored in the past, typically

Figure 11. Example of Data That Need to be Exchanged Between Maintenance and Other Management Areas



Management Systems	Inputs to Maintenance Management	Outputs of Maintenance Management
Pavements	• Pavement inventory • Condition and distress data • Programmed/scheduled work • Projected deterioration • Feasible actions	• Pavement maintenance activities • Maintenance work completed • Planned maintenance • Pavement maintenance costs
Bridges	• Bridge Inventory • Element bridge conditions • Projected deterioration • Feasible actions	• Bridge maintenance activities • Bridge maintenance work completed • Planned bridge maintenance • Bridge maintenance costs
Congestion/Traffic	• Programmed/scheduled work • Current and projected traffic • User delay • Costs of maintenance work zones	• Planned lane closures • Added inventory due to capacity expansion
Safety	• Past and projected accidents • Analysis of safety benefit of maintenance actions	• Elimination or reduction of safety hazards due to maintenance actions • Hazardous conditions not yet addressed
Equipment	• Equipment availability • Rental rates	• Equipment usage • Equipment needs
Materials	• Material availability	• Material usage • Material needs
Payroll and Accounting	• Labor, equipment and material costs • Historical maintenance cost data	• Labor, equipment and material usage
Budget and Finance	• Approved maintenance budget and program level	• Constrained and unconstrained maintenance programs needs • Recommended maintenance budget level
Permits/Utilities	• Scheduled utility work • Location of utilities • Environmental permits	• Scheduled maintenance
Contracts	• Job status • Contract specifications • Workzone management plans • New maintainable features	• Planned contract maintenance • Completed contract maintenance • Contract work inspection/quality assurance
CADD	• Plan sheets • Engineering drawings	• Revisions to plan sheet based on maintenance work
Materials Laboratory Research	• Revised pavement and bridge deterioration rates • New maintenance treatments	• Pavement and bridge maintenance research issues

in mainframe-based systems developed between 1965 and 1990. A second concerns the way much information will be stored in the future, and how it will permit data storage and transfer of multimedia (text, imagery, voice/sound and active data). The two categories of data are as follows:

1. Various forms of alphanumeric and similar data found in flat, hierarchical and relational databases (numbers, character strings, ASCII files, etc.).

2. Objects including text (case law, regulations, bibliographies, files from computer bulletin boards); images (maps, documents, plan sheets, graphs, charts, photographs, video); voice (speech recognition for field data collection); and data objects that are specific to, or contain, executable programs, such as CADD drawings, spreadsheets, and hypertext.

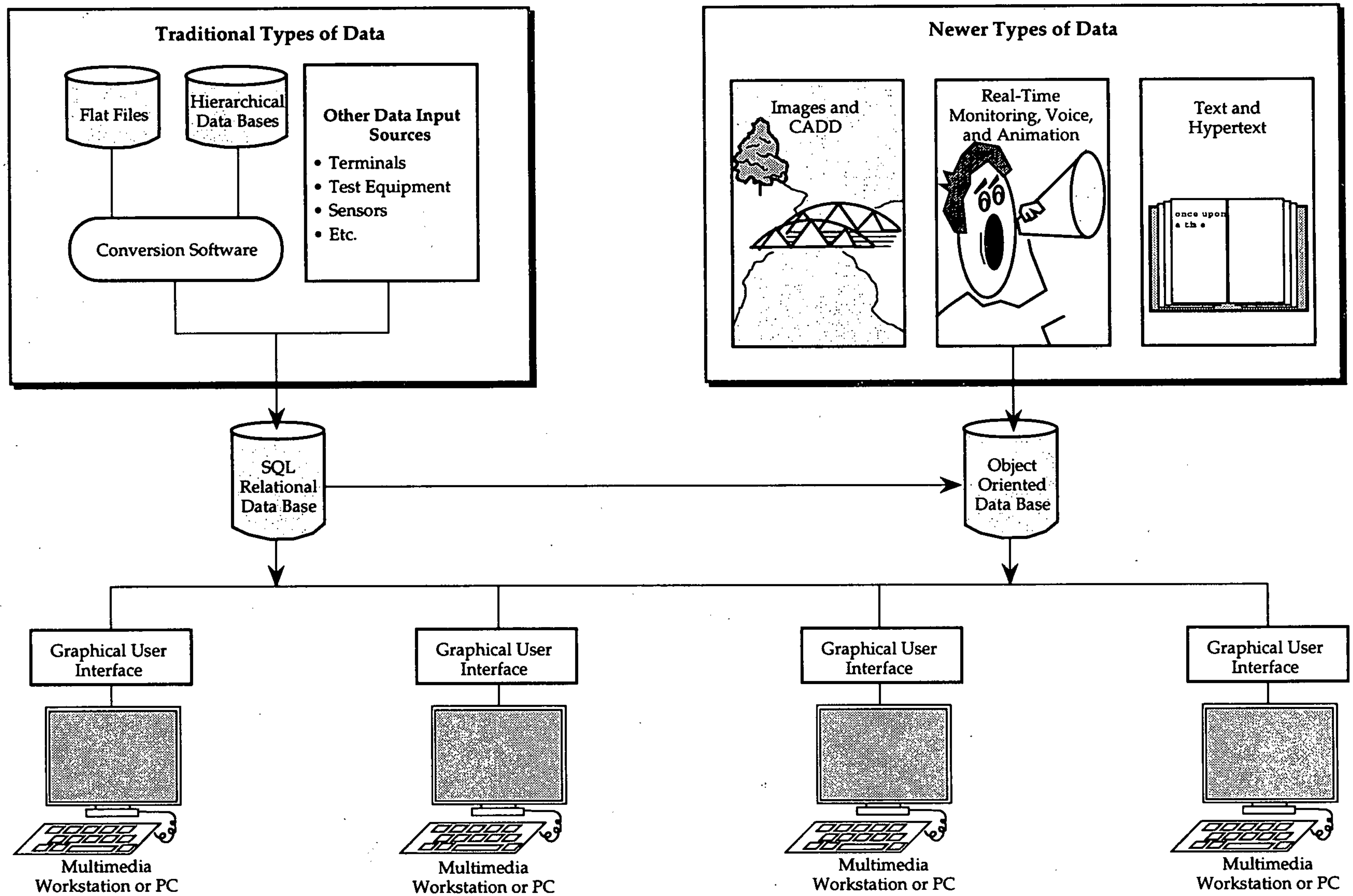
The hub will permit the retrieval of any of these types of data, as well as provide traditional data-sorting capabilities such as those found in a relational database (e.g., to call up all asphalt pavements on principal arterials with a condition index less than 3). A currently workable framework that integrates these capabilities appears in Figure 12. In the future, hybrids of relational and object-oriented databases will emerge, as well as other innovative database structures.

The public and the private sectors are implementing many systems that have functionality similar to the model MMIS described here. For example, Union Pacific Railroad implemented a pilot project for rail, track, bridge and signal facilities management. It integrates GIS, photologging, and relational databases that serve different management functions *(14)*.

As another example, the database management strategy for the $4.9 billion Central Artery Project in Boston, Massachusetts, employed the use of object-oriented databases to store maps, photogrammetry, plansheets, graphics, and other data needed for the project. This project shows the feasibility of a fundamentally object-oriented database management strategy serving a large, complex and dynamic organization involving many vendors and users *(15)*.

The hub handles only the minimum amount of data necessary to serve data-sharing needs of satellite hubs and terminals. Most importantly, hub software does not have human "users" per se. Its "users" are the analytical programs, data-reporting tools, and data-entry tools that exist at the terminals at the end of the spokes. The hub computer provides electronic services for client computers, primarily the collection, organization, translation, and summarization of data that individual management systems, especially the Maintenance Management System, need in order to perform their own functions.

Figure 12. Integration of Different Types of Data



The hub is not just a computer, however; it is an organizational unit with a whole set of duties related to its prime objective of facilitating data sharing. These duties include

- Construction, maintenance, and updating of the corporate database, the main repository of shared data.

- Construction and maintenance of telecommunication linkages and software to

  - Extract data;
  - Satisfy electronic requests from the software operating on the terminals;
  - Enforce all security provisions; and
  - Serve various management systems.

- Execution of quality control procedures on all data supplied to the corporate database by the terminals.

- Monitoring timeliness and quality of data.

- Provision of data collection services.

- Construction and maintenance of computer hardware and software utilities for such purposes as

  - Data summarization;
  - Maintaining audit trails;
  - Production of maps;
  - Dynamic segmentation (translation of road segment data between different conventions for segment endpoints); and
  - Translation among different data formats and coding conventions.

- Consensus-building on the setting of standards for

  - Data coding;
  - Timeliness;
  - Missing values;
  - Precision;
  - Accuracy;
  - Geographic references;
  - Time and date references; and
  - Underlying data item definitions.

- Establishment and maintenance of data linkages with various systems such as

- Accounting;
- Payroll;
- Materials; and
- Infrastructure management systems.

- Support services such as

  - Consulting and problem-solving on data process issues related to management systems and the shared data;
  - Hardware/software procurement and installation;
  - The negotiation of quantity discounts; and
  - Maintenance of data owned by terminal users at the request of those users.

- Ensuring compatibility among future enhancements to hardware, software, and the central, satellite and terminal databases.

Most of these duties can be considered "high-leverage" activities in that they serve a large number of users and applications but have relatively small staff requirements relative to the total number of users. The main exceptions are potential data collection or software development services on behalf of specific users. Where possible, it may be very cost-effective to establish a pricing system for such custom services, so that a department wishing software development services can ask for competitive bids from outside consultants as well as from the hub unit. This concept, now being used in several states for highway maintenance services, appears to be effective in establishing a desirable incentive system, which encourages innovation and cost control.

4.3 Terminals

Each terminal of the hub-and-spoke system is a data collection station, a management system, or a portion thereof, or a related outside system. The information systems on the terminals could be developed in-house or by outside vendors, or could be off-the-shelf packages. Most transportation agencies already have a lot invested in these systems or will spend large amounts of money on modifications in order to adopt the MMIS. If the hub system handles all generic data, then the terminal systems handle all specialized data and analysis. Examples of terminal systems were listed previously in Figure 11.

■ 4.4 Satellite Hubs

Because of the large data volumes used in routine maintenance management, there may be a role in certain agencies for satellite hubs. Such hubs can be of two types:

1. Functional satellite hubs such as a hub located in the central office serving only maintenance management, equipment management, sign management, CADD, document imaging, etc.

2. Local satellite hubs, such as a hub located in a district office serving maintenance, bridge management, traffic counting, and other functions for the district and all of its residences and depots.

Satellite hubs have two major purposes:

1. To share data among terminals, at a level of detail less than that used within each terminal system, but greater than that used by the central hub. Most of the data items would not be of any use to terminals other than those directly served by the satellite hub.

2. To provide a data conduit between all its terminals and the central hub, perhaps providing data subsetting, summarization, and analysis capabilities.

The satellite hub's capabilities are analogous to those of the central hub, including the organizational capabilities of data quality control, graphics production, hardware/software support, and custom development of software. However, economies-of-scale that can be achieved by the hub and costs will partially dictate the distribution of responsibilities between the central and satellite hubs.

■ 4.5 Characterization of Data

Data Elements

Successful data design for the next-generation MMIS depends to a great extent on the proper placement of data items in the hub, satellite, or terminal systems in order to best meet user needs for data access:

- Each item should be placed as far down in the organizational hierarchy as possible to the level where it needs to be shared.

- At higher levels of an agency, most activity data items are needed in three forms:

  - Comprehensive summary data at an appropriate level of detail,
  - Sample data to provide information where it is not economical to develop summary data, and
  - Exception data to highlight problems or deviations from norms.

- Different parts of an agency may have different definitions for the same data item. For instance, the geographic location of pavement deterioration may be expressed with a different road segmentation scheme than traffic counts. The hub database software must provide the means to translate from one definition to another where needed. When this is not possible, the staff of the hub unit will need to obtain agreement among users of the definitions of the shared data.

Hub and Satellite Data Dictionaries

An essential part of the next-generation MMIS is a data dictionary, maintained at the central hub. Each satellite hub also requires a data dictionary. A data dictionary provides detailed specifications and attributes of every type of data shared through the central or satellite hub, as the case may be. The following are among the key elements:

- Variable or object name (long and short spelling);
- Type of data (numeric, character string, object);
- Level of detail (temporal, organizational, spatial);
- Accuracy (e.g., mean, variance, missing data, locational accuracy of geographic coordinates);
- Unit of measurement, if applicable;
- Width, decimal point, and format – if applicable;
- Range of data or selection criteria;
- If packed (compressed) data, specifications for unpacking;
- Keys for principal linkages (e.g., locational, organization, temporal, and cost);
- Index or file type (e.g., .DFX);
- Schedule of data transfer from spokes;
- Access and security provisions; and
- Audited versus unaudited data.

Truth-in-Data

Systems should guard against inappropriate use of data. For example, geographic coordinates may have an inherent accuracy of 100 meters 95 percent of the time suitable for planning purposes, but may be unsuitable for design, construction, and maintenance operations. Traffic counts may be a synthesis of area-wide data and may not pertain to a location of interest. Budget balances available through field office terminals may be unaudited, preliminary estimates rather than balances approved by the accounting branch.

The database should contain data to describe the level of detail and accuracy of data, sometimes referred to as "metadata." Information from the data dictionary can offer an overview of the suitability of data for a certain use or user, but may not provide sufficient detail and insight to ensure against misuse of information. Sufficient supplementary data on the level of detail and accuracy of data should be stored with each piece of data to permit full disclosure of its usefulness and reliability.

4.6 Locational Reference Systems

At a minimum, there should be a location reference system of prescribed precision and accuracy (within 0.01 miles 99 percent of the time) for different ranges of cumulative **elapsed distance** over the ground from known locations in the physical environment (mileposts, reference points, or ends of control sections). Distance ranges might be 0.01, 0.1, 1.0, 10.0 and 100.0 miles or kilometers. The precision and accuracy should reflect the statistical variation of the most accurate distance-measuring equipment expected to be used, which is likely to vary with the distance (for example, a measuring tape or laser range finder for 0.01 miles and an in-vehicle DMI for longer distances).

Elapsed distance from known points gives an indispensable measure of "ground truth," provides a linkage among data pertinent to highway features, and is the way human beings relate to distances in their physical environment. There should be a graphic capability for displaying roadway features according to this reference system in the form of a linear log, straight-line diagram, map, etc.

A highly desirable, complementary, but not essential reference system is a **geographic coordinate system** of two measures of prescribed precision and accuracy (e.g., within root-mean-squared spherical error of 10 meters 95 percent of the time, as one example of how to prescribe precision and accuracy):

1. With respect to survey control points that are tied to a national or international geodetic reference system (e.g., NAD 83).

2. With respect to the discrepancy (difference) between elapsed distance from a physical reference point and the **computed** distance along the roadway alignment, where the computed distance is inferred from the digital cartographic base map that serves as the GIS and which is founded upon the geodetic reference system in paragraph 1 above.[3]

This coordinate system will support a GIS useful not only for a broad range of transportation analysis but also for related environmental and land use planning (e.g., hydrologic, geologic, and seismic analyses, type and density of land development). If the GIS system were to be used for multiple purposes (as is typically the case), questions of the appropriate level of precision and accuracy would need to be addressed for the combination of the anticipated applications.

There are significant cost implications of this decision, as shown schematically in Figure 13.[4] Typical resolution of location for maintenance management today is on the order of 0.01 mile, or about 50 ft or 15 m, and is often measured using mileposts or vehicle odometers. For integrated system applications, however – in which an integrated MMIS may exchange information with pavement management, bridge management, congestion management, safety, and other geographically-based management systems – finer resolutions may be needed (e.g., to correlate routine pavement maintenance with locations of pavement distress). Accuracy requirements for geographic coordinates can consist of either the most stringent precision and accuracy needed for any activity, or may vary with the activity (whichever is more cost effective). If a geographic coordinate reference system is used, the agency should have a GIS or other capability for displaying spatially related features and attributes.

The two reference systems described above are **actual reference systems** that have "ground truth." Agencies have many **nominal reference systems** that do not have "ground truth." For example, a milepost system may have markers whose distances between them have been shrunk or enlarged due to highway construction and significantly misrepresent actual distances.

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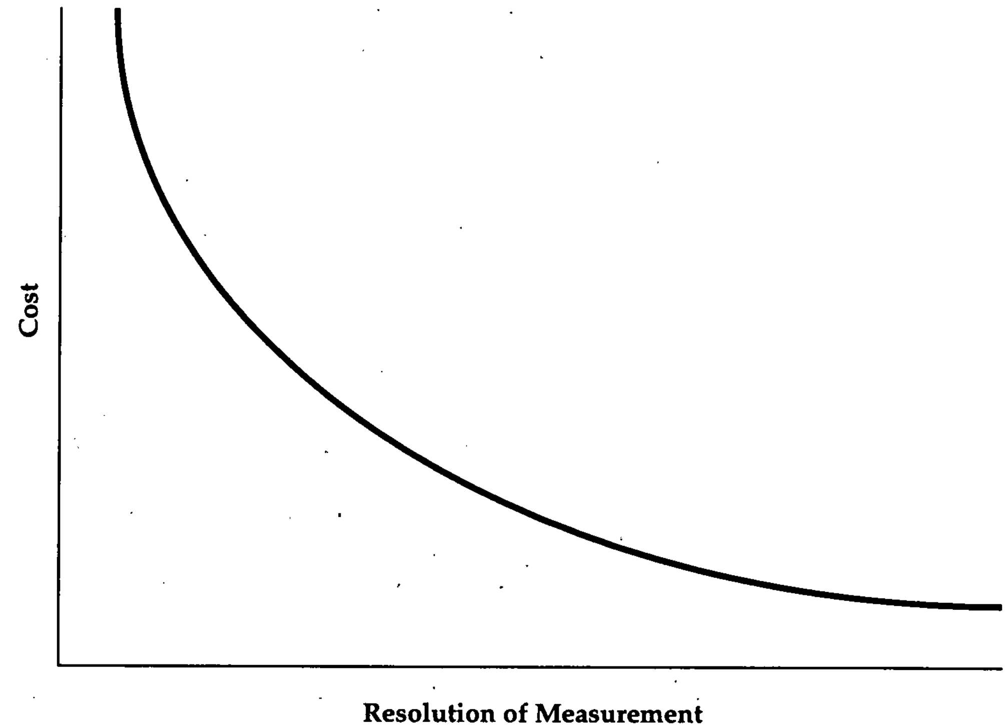
[3] Calculation of the discrepancy between elapsed distance from a known reference point and the computed distance along the same alignment displayed on a digital map probably requires the establishment of standard reference alignments over roads that climb from one elevation to another. There may be a need to set up a national committee to establish standards for determining the accuracy of digital cartographic maps. The committee would need to address all the issues discussed in this section plus the establishment of standard reference alignments that can both be easily found in the physical environment and be calculated precisely from a digital map. Examples of standard reference alignments might be an S-curve of prescribed radii and an L-curve whose head and foot have prescribed lengths and whose elevation rises 100 meters from beginning to end.

[4] The curve is schematic, since market conditions are now changing the cost vs. precision data available.

Figure 13. Cost-Precision Relationship for Global Positioning System



Many agencies have developed geographic coordinates derived from electronically scanning maps that have a nominal accuracy with respect to its resolution, scale, and a few survey control points, but unknown accuracy with respect to many or most important physical features.

Software is essential for converting

- Between the two actual reference systems representing elapsed distance from physical reference points and geographic coordinates tied to geodetic reference system. This is achieved if **field measurements** of the prescribed precision and accuracy are taken of the geographic coordinates of each physical reference points for the elapsed distance reference system (e.g., mileposts, stations), or enough such points to ensure desired precision and accuracy levels are achieved when combined with conversion software.

- Among schemes for representing elapsed distance.

- Among different geographic coordinate systems (e.g., latitude and longitude, state plane, NAD 83).

If all these conversions are possible, then it is possible to convert from any geographic or elapsed distance reference system to any other.

■ 4.7 Local Data Reservoirs

Each terminal connected to the hub (or satellite hub) needs data storage capacity. Storage capacity may reside in a hard disk within each terminal or in a server on a LAN. The local reservoir is organized in a manner that parallels the hub database, but contains only the data items used locally. It is replenished on a daily and weekly basis during off-peak hours, under an automatic procedure electronically coordinated and scheduled with the hub, as reflected in the data dictionary. The local reservoir system can use relatively low-speed phone lines, standard protocols, and inexpensive telecommunications equipment requiring relatively little maintenance.

Although data will be stored redundantly (repeated on the hub and each local system), the necessary hard disk space has become quite inexpensive in just the past 2 years. Software to manage the local reservoirs and handle all telecommunications, scheduling, and coordination with the hub can be developed by the hub unit and supplied in identical copies to every local system. Only the data dictionary would vary among locations. To further lower barriers to connection with the network, the hub unit should offer installation and support services for the local reservoirs.

■ 4.8 Local Application Programs

From time to time, and sometimes frequently, new application programs and associated databases are developed to meet specific local or functional needs. Initially the databases for these "home-grown" application programs will not be a part of the hub database, and indeed may never become part of it. The next-generation MMIS needs to accommodate "home-grown" application programs that will inevitably emerge and to support their access to data. As each new program is implemented, it is necessary to determine what portion of the databases driving these application programs will also reside on the hub and what portion will not.

5.0 New Technologies

5.1 Emerging Technologies

Emerging technologies for data gathering, communications, analysis, and display have significant potential to enhance the maintenance management practice. New data collection technologies enable more accurate and objective information to be gathered, often at a lower cost and greater speed. Advances in data communications and computer hardware and software are allowing improved access to information and the ability to link disparate databases. They are also providing a powerful array of tools for people at all organizational levels to make better use of available data. Figure 14 provides an overview of different technologies and their potential uses in maintenance management. Four major technology trends are described below.

5.2 Geographic Information Systems Technology

Geographic Information Systems (GIS) technology is commonly defined as "a computerized database management system for capture, storage, retrieval, analysis, and display of spatial data or information defined by its location." The generic GIS has three major components: (1) data,

Figure 14. Technology Options for MMIS

Integrated Roadway Inventory	Inspection/Condition/ Assessment	Work Support	Work Schedule/Activity Reporting	Equipment and Inventory Management
• GPS • GIS • CADD • Video Logs • Photo Logs • Portable Data Entry Terminals • Map Conversion (Scanners, Conversion Software) • Bar Coding • Radio Frequency Identification Tags • Metal Detectors • Electronic Distance Measuring Instruments	• Video Logs • Photo Logs • Portable Data Entry Terminals • Acoustics (Distress Identification) • Radar (Structural Conditions) • Eddy Currents (Structure and Distress) • Infrared Thermography (Temperature) • Profilometers, Roadmeters (Pavement Roughness) • Deflectometers (Structural Conditions) • Reflectometers (Visibility of Signs, Markings)	• Real-Time Video Monitoring • Vehicle Tracking • Data Communications (Cellular Telephone, Satellite, Microwave, UHF) • Sensors (Hazard Identification, Snow/Ice Conditions) • Display of Real-Time Weather, Temperature, Snow/Ice, Vehicle Location Data	• Bar Coding • Portable Data Entry Terminals • Voice Recognition • Electronic Scales • Electronic Fuel Gauges • Radio Frequency Identification Tags	• Portable Data Entry Terminals • Bar Code Scanners • Voice Recognition • GPS • Distance Measuring Instrument • GIS with Shortest Path/ Vehicle Routing Capability

(2) software, and (3) the locational referencing schema. Each of these components can range from the most basic to the most sophisticated geoprocessing capabilities.

Wisconsin DOT has implemented in its districts a pavement management system (PMS), which is composed of three interlocked expert systems *(16)*. The PMS operates on a GIS platform, and the expert systems help make network level decisions concerning pavement maintenance and improvements.

The data can consist of a simple flat file containing a locational key or a more sophisticated, relationally structured database with multiple indices maintained in multiple formats across departments. The software could be a simple system for selecting, displaying, and reporting or it could be a complex system, which allows for interactive query and editing, real-time update and feedback, and integration with other decision-support systems. The locational referencing schema could be a simple classification by district or a complex combination of raster imaging, object-oriented entities and vector-based topological referencing.

The most basic GIS would consist of a simple data file containing a key field that identifies a geographic location using basic database management software for selecting, sorting, and reporting. Roadway inventories, often referenced using the route and milepost as the key, are examples of data files, which have historically been used for basic geographic information. The most sophisticated GIS would integrate most DOT data.

North Carolina DOT is developing a GIS platform for its key highway decision-support tools, including all those management systems required by ISTEA *(17)*. The GIS is intended to serve all major parts of the department including traffic, engineering, roadway design, bridge design, environmental analysis, and maintenance.

Several GIS software packages are available that have relevant and useful features for maintenance management. As prime markets for GIS, DOTs are major targets of product differentiation, sales, and innovation. The relational tools in some GIS software packages not only allow the powerful and flexible representation of highway networks and map graphics, but also enable some kinds of analysis that are particularly, if not exclusively, associated with highway transportation. In general, GIS is capable of the following:

- Drawing maps of roads and maintainable elements;
- Associating highway features with map entities for display;
- Entering and querying data interactively with a map;
- Network and spatial analysis;
- Geocoding;
- Real-time highway monitoring;

- Relating independent databases using geographic key or index;
- Integrate video and photolog data; and
- Three dimensional modeling.

While continued advances in spatial information processing and display technologies are assured, significant organizational challenges remain with respect to GIS implementation. Among the most important are

- Short hardware and software economic life cycles;
- Increasing importance of systems maintenance costs;
- Costs of training; and
- User acceptance.

In addition, choices made today regarding data collection strategies, approaches, and update cycles will have important implications for the ultimate benefits of GIS. Development of a GIS strategy that considers the full range of future applications and users of the GIS data may imply a long development cycle and large up-front costs, which must be traded off against the opportunity costs of a smaller scale effort.

According to the *NCHRP Research Results Digest 180,* the planned or current GIS applications in state DOTs include highway inventory, pavement management, bridge management, safety analysis, routing, and executive information systems *(18).* A summary of the survey results indicate that about 80 percent of the 173 applications mentioned in the state surveys were maintenance-related systems. However, only 35 percent (60 applications) were described as operational or under implementation.

■ 5.3 Global Positioning Systems Technology

Global Positioning Systems (GPS) technology is the common term for a U.S. Department of Defense satellite and control system designed to be visible to a receiver at all times on a global basis. One can buy a receiver that uses the transmissions from the GPS satellites to determine the receiver's location within roughly 17 m (military or undergraded civilian code) to 100 m (degraded civilian code). With a supplementary base station, accuracy can be improved to 5 m for normal maintenance operations and to 1 cm for survey measurements.

The GPS was designed primarily as a navigation system, allowing aircraft and other vehicles to know their latitude, longitude, and altitude frequently (once per sec) and to measure speed and direction of motion in real time. In DOTs the applications of principal interest have been survey and mobile acquisition of highway and highway feature points, vectors and attributes. GPS provides two important capabilities which are relevant to development of an integrated MMIS: (1) surveying and mapping applications, and (2) roadway feature inventory applications. These capabilities would facilitate location and tracking of maintenance features, as well as recording of maintenance activities.

■ 5.4 Highway Inventory and Inspection Technology

High-accuracy reference networks are being established by the U.S. Geodetic Survey in cooperation with state mapping and transportation agencies. New Mexico, Texas, Tennessee, Virginia, Wisconsin, and many other states are using GPS to establish networks of precise survey benchmarks designed specifically to support highway applications.

The Ohio State Center for Mapping built a prototype vehicle, called GPS Van that could map state and federal highways and record images of crucial transportation features *(19)*. Stereo video cameras, synchronized with locational data, were designed and tested to collect and locate a visual record of roads, bridges, signs, and other features in the Tennessee and Virginia DOTs.

Traditional roadway inventory databases that support maintenance management are linear representations of roadway features, using distance measuring instruments. Mobile GPS locates features according to longitude and latitude instead of elapsed distances from known reference points such as intersections or mile posts, thus yielding accurate information on the road's location with respect to geographic features and other roads, and making it possible to relate the road inventory to zone systems (e.g., districts or census tracts) and other features which may not be anticipated when the inventory is first built.

The state of Montana completed a demonstration of a relatively inexpensive GPS receiver, a data logger, and a supplemental base station to establish roadway inventories to accuracies of roughly 17 m *(20)*. The information was processed in the office and entered into a GIS software package. Similarly, a field demonstration of differential GPS (consisting of a GPS reference station and a roving receiver) conducted in Arizona DOT by the Urban Institute for a roadway sign inventory showed that locational accuracies of 5 m can be achieved *(12)*.

While approaches to vehicle-based GPS data collection and database development are fluid and changing, there appear to be two distinct emerging branches in this development path. On the one hand are high-end, powerful single-platform approaches, which address a wide range of operational mapping and GIS inventory problems like the one developed by the Ohio State Center for Mapping *(19)*. On the other hand are lower-cost, incremental approaches to developing a GPS-based field inventory like that taken by the Montana DOT *(20)*.

The importance for maintenance management of advances in locational technology cannot be underestimated. The crux of accurate reporting of accomplishments and resource utilization is linking this type of information to specific highway assets or maintenance work sites. GPS devices, which are now commercially available for $1500 or less, can be an important enabling technology that provides the ability to accurately and efficiently report, store and retrieve data on the location of maintenance work, roadway inventory, and (if appropriate) the type of maintenance work (e.g., force account versus contract). The technology, in fact, may enable maintenance personnel to become "surveyors," using portable field equipment to identify highly accurate control points.

Nearly all highway agencies have developed inventories of roadway and bridge features and other elements that require maintenance. The inventory of maintainable elements usually takes the form of a linear log or representation of the roadway with notations as to the start and end point of every maintenance item. It is possible to calculate from this information the extent of each maintainable item to help in formulating annual maintenance work programs. Inspection and condition surveys provide the foundation for evaluating the current and future health of roads and bridges, and for determining what work is required, both in the short and long run.

Several technology options are available to support the development of highway base maps, establishment of roadway feature locations, and determination of feature characteristics and conditions. Some of these technologies may be used in combination with GIS or GPS; others are used on a stand-alone basis. These options include

- Digitized Maps;
- Distance Measuring Devices (Odometers, Electronic Distance Measuring Instruments);
- Photologs;
- Sensors, Detectors and Special Instrumentation (video camera, sonar, laser, infrared, radar, eddy current, optical scanners, radio frequency transponders);

- Profilometers/Roadmeters; and

- Deflectometers.

Much of this equipment is available for measuring characteristics and condition of pavement, bridges, and other roadway features. For example, surface deterioration and distresses of roadway elements can be determined by analyzing data collected using photologgers, video cameras, sonar detectors, profilometers and optical scanners. Subsurface characteristics may be inferred using ground penetrating radar, infrared thermography, eddy currents, and ultrasonic sensors.

Technologies for pavement condition assessment are important to maintenance management. Pavement condition and distress information is needed to determine what maintenance or other pavement treatments are required for each section of the highway. Connecticut DOT, for example, uses videologs for recording pavement condition information*(21)*. A pavement evaluation engineer in the office views the road and rates its condition subjectively. Software already exists to directly tie videodiscs to management information systems to give quick direct access to visual information. Videodiscs are also being used to store detailed bridge inspection information.

5.5 Work Scheduling, Reporting, and Inventory Management Technology

A variety of new technologies can potentially facilitate maintenance scheduling and work order production and daily activity and cost reporting. These technologies include

- Laptop, palm-size, and notebook computers;
- Hand-held portable data entry terminals;
- Barcode scanners;
- Electronic clipboards or tablets with handwriting recognition; and
- Voice recognition systems.

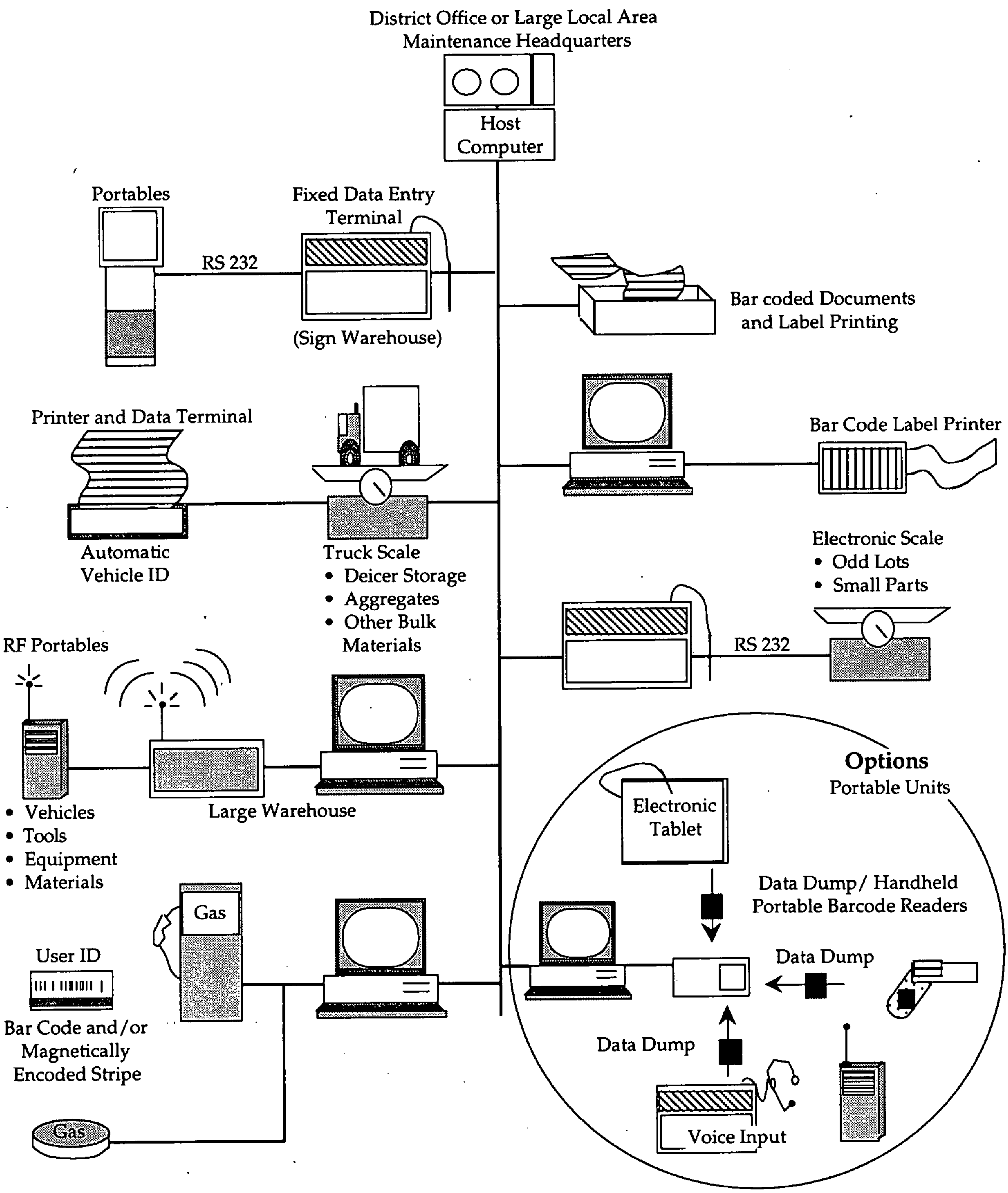
This equipment can be used in conjunction with a distance measuring instrument or a GPS receiver in order to attach location tags to maintenance data being collected.

These data collection devices show promise of significantly reducing laborious and time-consuming data collection tasks field supervisors must perform. They can provide a means for quick access to the maintenance management system database to obtain the latest information on budget balances, planned versus actual accomplishments, equipment and material availability and so on. Accuracy of the data can also be improved through prompting, verification, and error checking of entries.

The Urban Institute recently completed the second phase of an NCHRP study on advanced data acquisition technology for maintenance management systems *(12)*. Practical problems using this technology for maintenance management were investigated during field demonstrations and tests in the Maryland, Connecticut, and Arizona DOTs. Issues addressed include acceptance by field workers, cost-effectiveness compared to existing paper procedures, and ability to conveniently attach location tags to the data that may be used in GIS.

Some of these technologies can also improve material and equipment inventory management and control. Road maintenance organizations use a wide range of materials and equipment for maintenance. Thus one often finds that maintenance yards and warehouses are filled with a surprising array of supplies and equipment. Demands for accountability in the purchase, storage, and use of maintenance supplies and equipment have resulted in extensive accounting in many states. Figure 15, taken from *NCHRP Report 334 (9)*, is a schematic of a comprehensive inventory management and control system. The core of the system would be based on barcode data collection and supplemented by other data collection methods.

Figure 15. Technology Options for Materials and Equipment Inventory



6.0 Systems Implementation

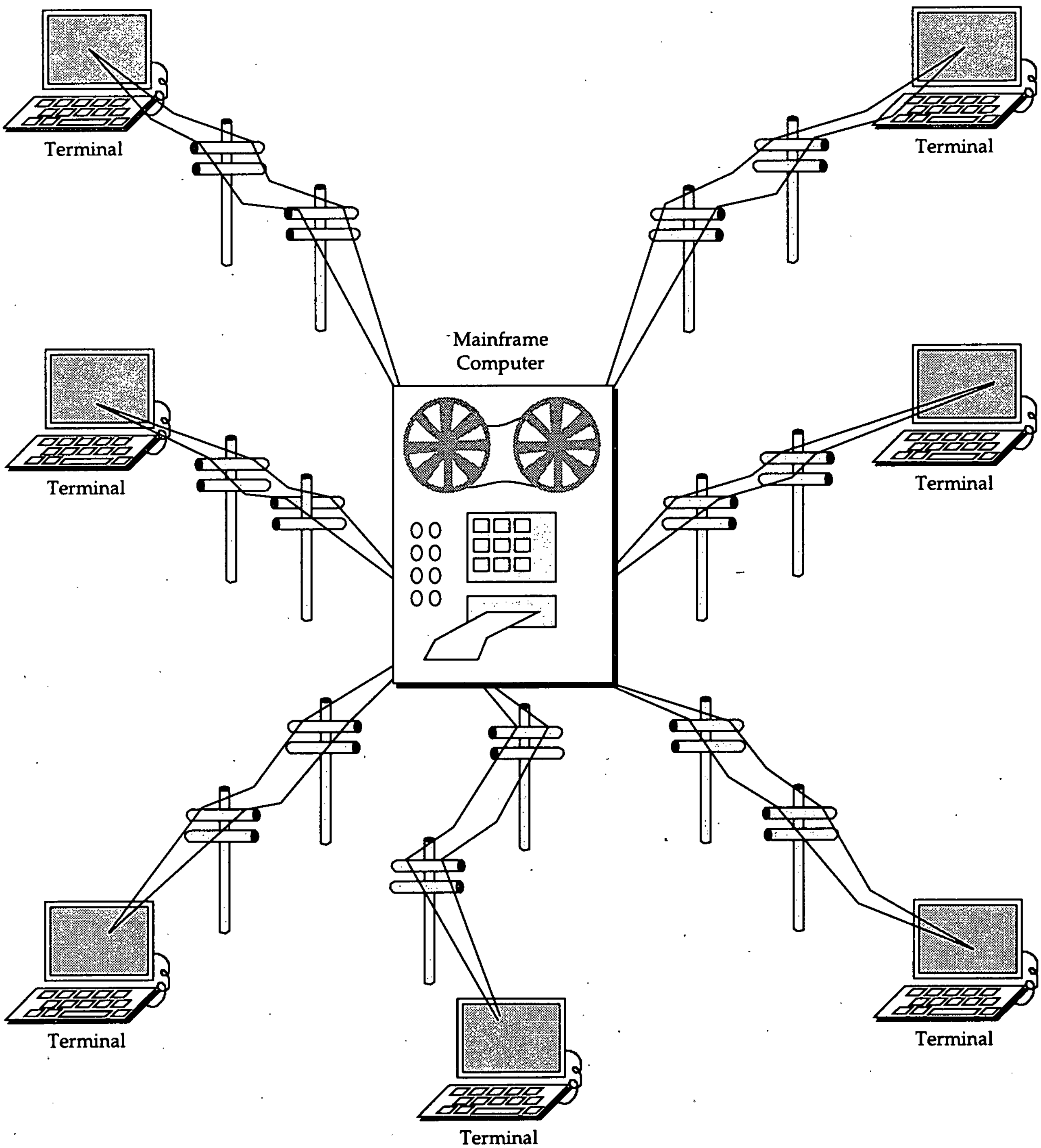
6.1 Alternative System Architectures

The hub-and-spoke theme can be implemented on many different platforms or combinations of platforms. Generally, there is some central computer system (though this may be absent in a distributed database), separate computers or terminals for each user, possibly some shared intermediate computers, and data communication linkages among all these systems. The main differences in architectures are the extent to which computing power is centralized or decentralized, and the role of intermediate computers. Both of these determine the necessary capabilities and usage of the data linkages.

Centralized Mainframe

A configuration built around a centralized mainframe is illustrated in Figure 16. In this scheme, all MMIS software and data reside on a single statewide mainframe, and all users dial in to the mainframe to use the MMIS. This model has high initial hardware and software costs, and high software maintenance costs, but low telecommunication costs relative to the other schemes discussed below. A mainframe can cost upwards of $800,000 initially, and require several full-time staff to manage and maintain. It is very adept at serving large user groups (at least 50) in

Figure 16. Centralized Mainframe Model



highly routinized transactions involving real-time data access where all of the users must simultaneously have access to the same data. This scheme is very inefficient for analytical tasks because of the division of computer processor time among numerous users, but it is very suitable for centralized accounting systems, which are relatively less analytical.

Because of the expense, these systems are overused in most DOTs and new ones are difficult to purchase. In practice, the mainframe tends to become loaded beyond capacity, so the level of service offered to individual users, especially for computationally intensive management analysis, is relatively poor. High software maintenance costs tend to limit the flexibility of these systems to meet changing management needs. For centralized agencies having an existing MMIS on a relatively modern mainframe, a realistic migration path involves making incremental changes to the existing system to add necessary analytical capabilities. This migration path is prohibitively difficult, however, on older mainframes with inadequate processing power relative to usage, or for MMS software that is custom-made and does not use standardized database management systems.

Centralized District Minicomputer

A system employing minicomputers at the district level is shown in Figure 17. This scheme is similar to the centralized mainframe, but it is tailored to DOTs whose maintenance management is primarily at the district level. Hardware, software, and maintenance costs may be slightly higher, on a statewide basis, than the centralized mainframe. Performance for individual users is often better than the mainframe scheme, but data-sharing capability among districts or with headquarters is often poor, especially if district and central computers are under separate management; thus, such systems tend to become isolated and difficult to support because of the isolation. If all of the district minicomputers within a state are standardized, then upgrading an existing MMS to add analytical and data-sharing features is feasible; otherwise, it is prohibitively expensive.

Centralized Client-Server

A halfway point between centralized and distributed computer systems is a client-server system, as shown in Figure 18. Here, a central database is resident on a central computer, but the server computer's only role is to act as a collection and distribution point for data. The computer is fully dedicated to the database management task, so all reporting and analytical software is resident on the client workstations or on local-area network servers acting as clients. This scheme is a natural for any agency that has established a corporate database, or is contemplating doing so. Since

Figure 17. Centralized District Minicomputer

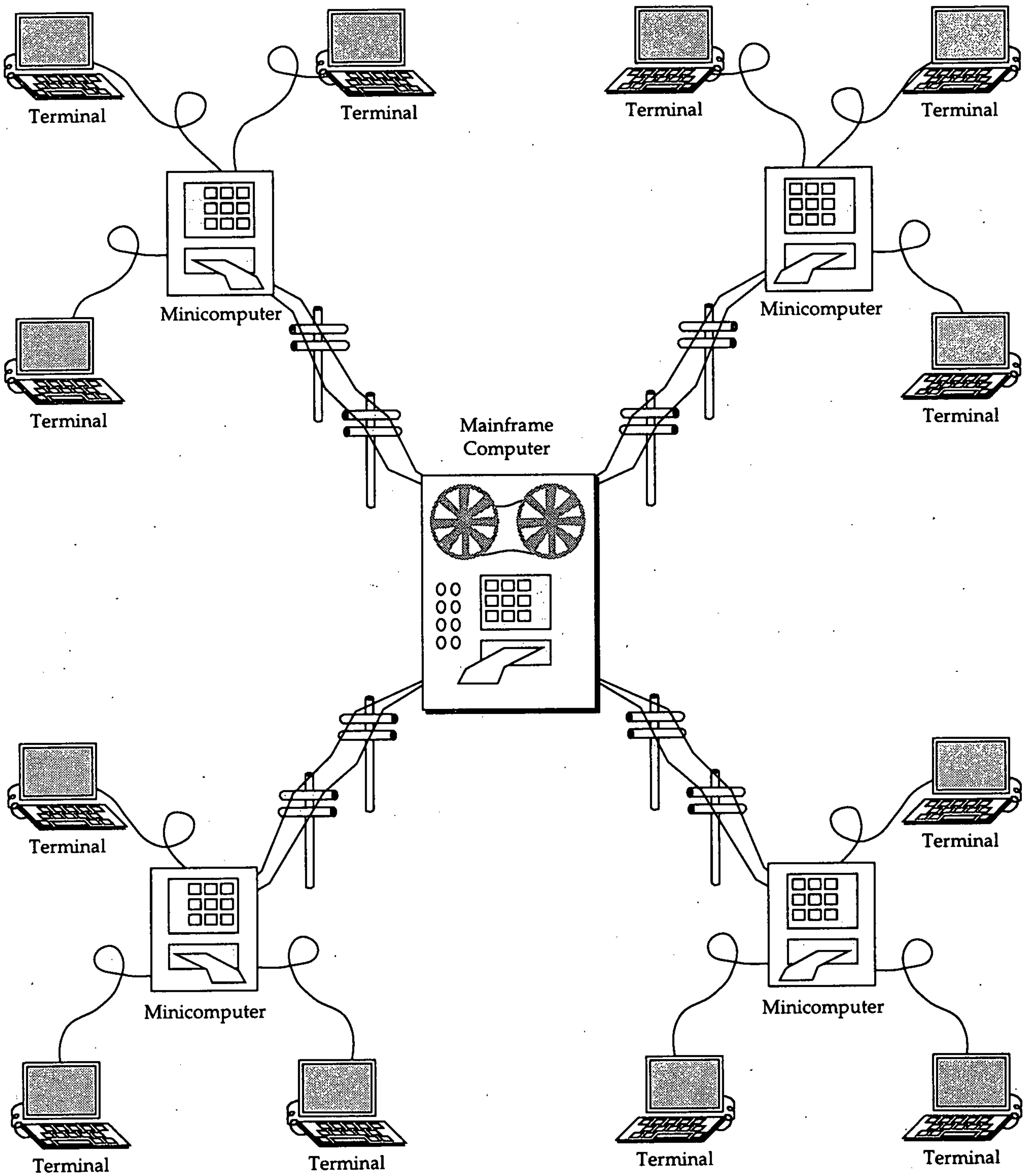
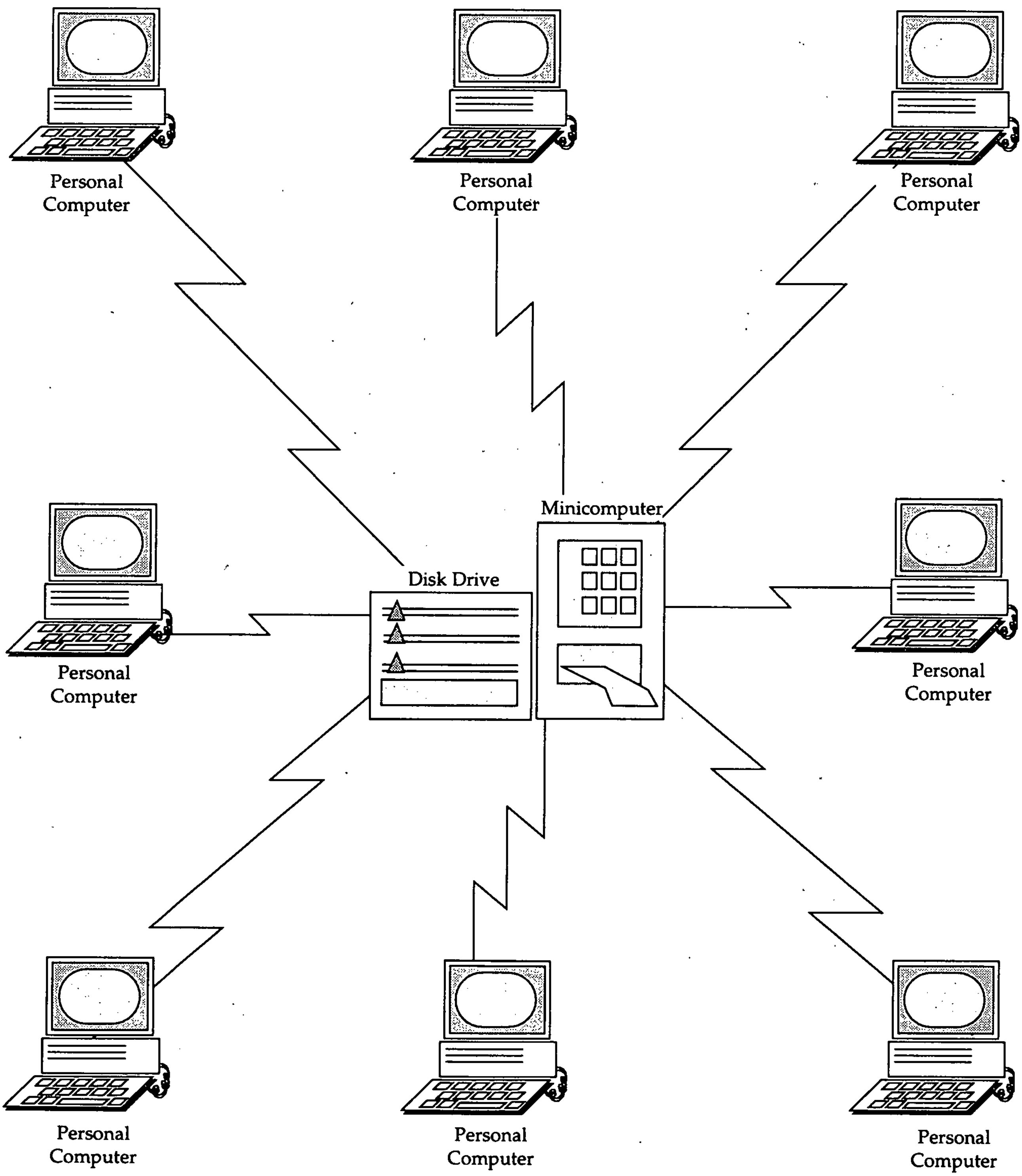


Figure 18. Centralized Client-Server



setting up the data transfer mechanism for an MMS is difficult and costly, using the corporate database as a centralized maintenance data server would save substantial development and support costs. Even if it is necessary to establish a totally new maintenance data server, hardware and software costs are relatively low. Telecommunication costs are relatively high, usually requiring a wide-area network, which can cost upwards of $10 thousand for each location. Since most of the intelligence of the MMS resides on individual client workstations, standardization of software is very important; but maintenance of PC-based software is relatively inexpensive. The level of service offered to users is quite good, and data-sharing attributes are excellent. Since the server's role is limited, a mainframe is not necessary; instead, a minicomputer or engineering workstation houses the central database, at a cost of $80 to 200 thousand.

Decentralized Client-Server

Similar to the centralized client-server scheme, this scheme (Figure 19) includes the addition of local-area networks, which act as clients, relative to the central database server; and as servers, relative to individual user workstations. The networks can thus be described as satellite hubs. This configuration has higher hardware and software costs than the centralized client-server model, but it has lower telecommunication costs. It is especially suitable for agencies that have already networked their district offices, or who intend to do so: the local-area network, including its system administrator, is a substantial part of the cost. A local-area network typically costs $20 to 25 thousand for the server, software, equipment, and training, plus $3 to 4 thousand per workstation (for personal computers with standard office software). Administration of each network requires roughly 0.05 full-time staff per workstation. For agencies where decentralized decision making is predominant, this model puts most of the data flows where the action is.

Distributed Databases

These systems (Figure 20) do not require any centralized computer; instead, each workstation automatically accesses the data it needs directly from the data's source workstation through automated protocols, at the moment when the data are needed. Data storage costs are low, but each workstation must be relatively powerful, and the network must provide high data-transfer speeds, if performance from a user perspective is to be acceptable. Such systems are relatively inflexible because database changes must occur simultaneously on every workstation. The software is also relatively expensive. A cost per workstation of at least $20 thousand can be expected.

Figure 19. Decentralized Client-Server

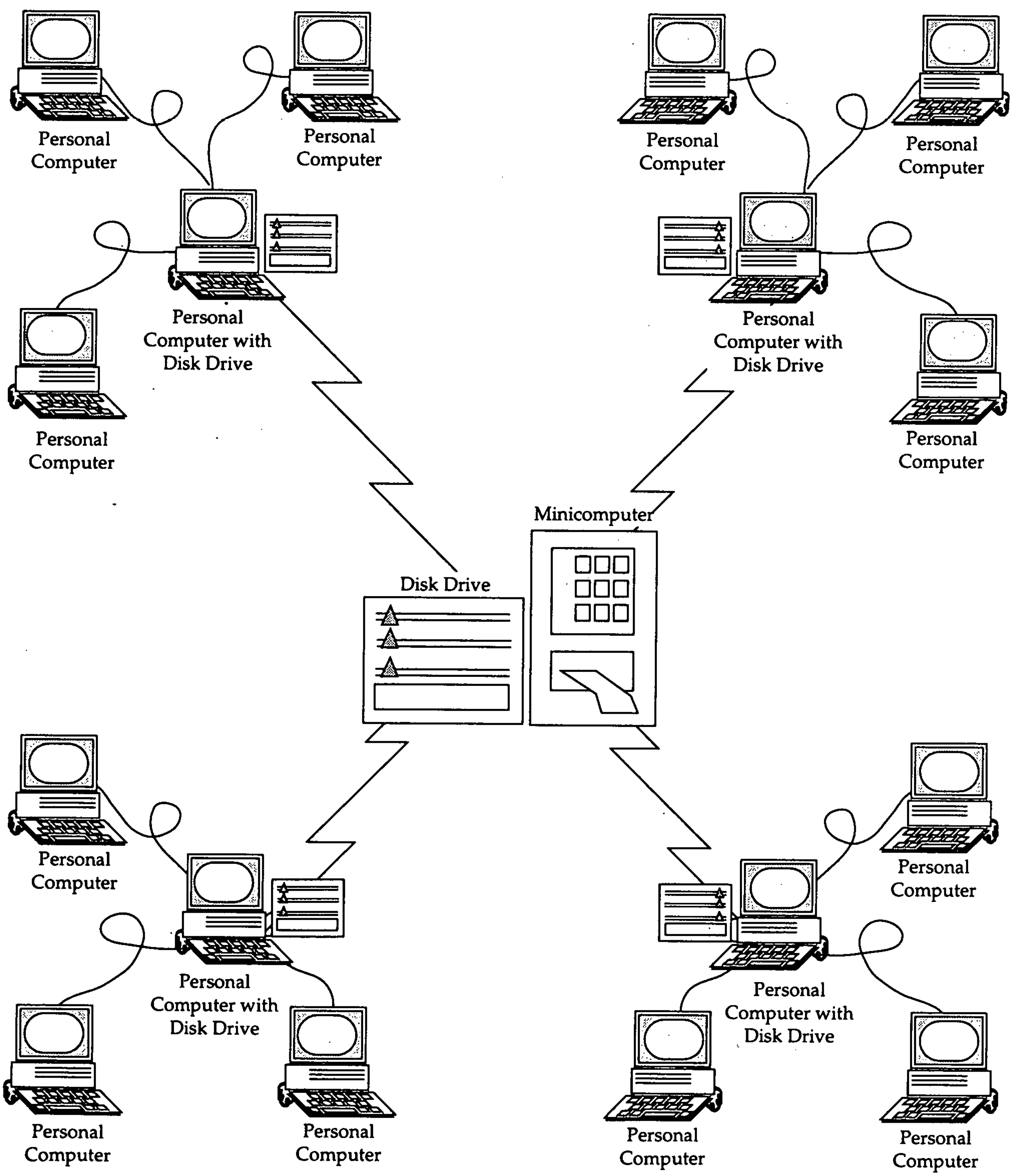
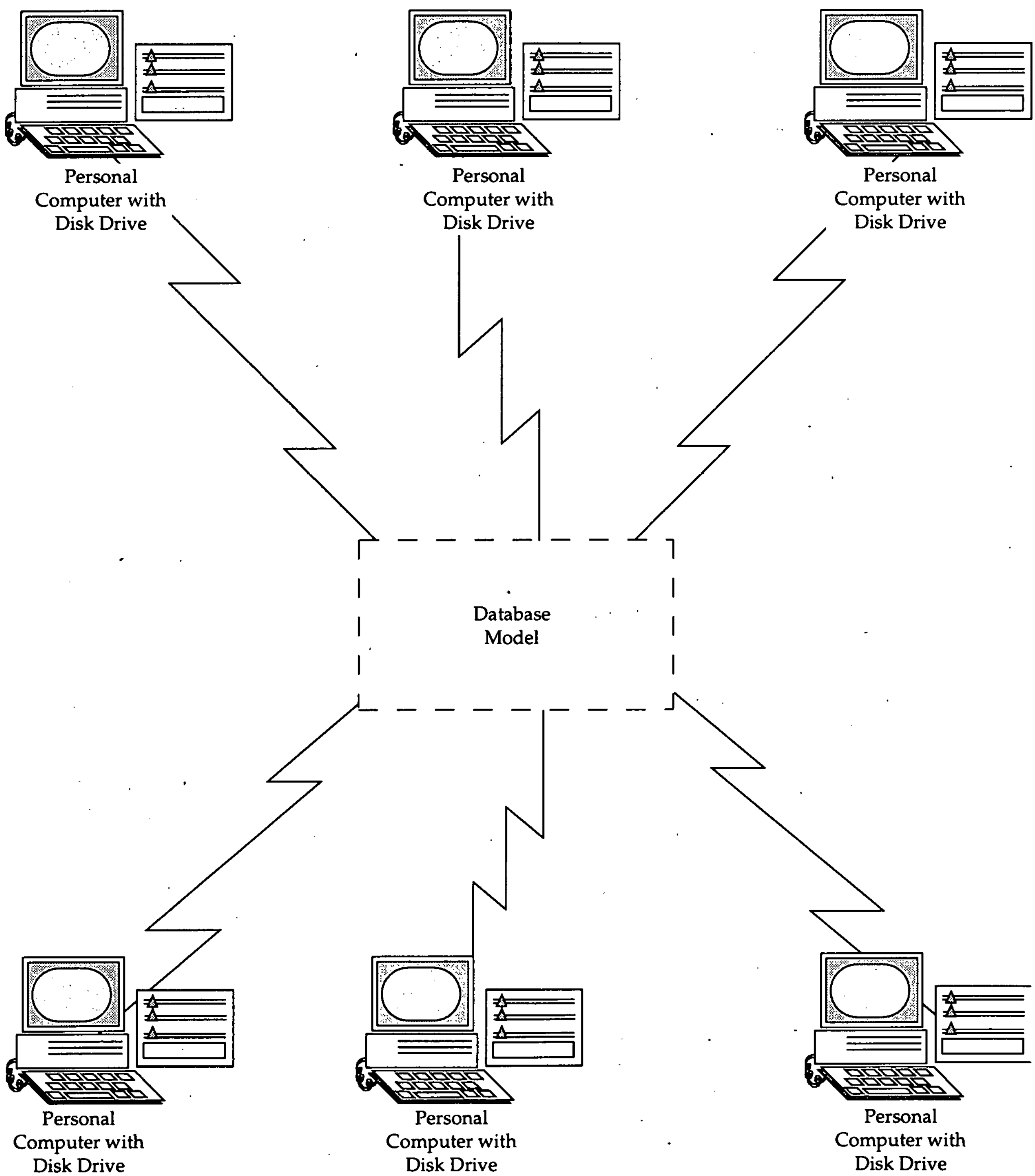


Figure 20. Distributed Database



■ 6.2 Support Requirements

Support of the hub data-sharing function of the agency (which would serve all of the management systems, not just MMIS), plus support of the MMIS itself, should require 5 to 10 full-time staff in a medium-size state DOT. This does not include the MMIS users, whose number should not be significantly affected by the next generation of MMIS. Since most states already have an MMIS with a support staff, the change in staff size would be expected to be less than this estimate. The duties of the support staff are:

- **Database Management**, including overseeing the operation of the database manager, solving problems, and helping users with questions.

- **Maintenance of Data Transfer Mechanisms.** This is often done by contract, and can cost 10 to 35 percent of the original price of the equipment, per year.

- **Monitoring of Data Timeliness and Quality.** Providers of data must commit to a schedule of updates and quality standards. It is the responsibility of the hub to monitor schedule compliance and expected data quality.

- **Mediation of Standard-Setting Processes.** Achieving compatibility of standards among users will often require changes in user procedures or standards, which they may find inconvenient. Usually such changes are determined by a process of negotiation among providers and users of the data. Hub personnel can serve the useful role of mediating such negotiations.

- **Fast, Flexible Response to Changing User Needs.** This is a critically important issue. Management needs routinely change, and as a result, management perceptions that their needs are adequately met depend to a great extent on the responsiveness of the hub. A system architecture that provides the hub with only flexible off-the-shelf database management software (i.e., does not put the hub in charge of application software) ensures that there are no technical hurdles to quick-response changes on request.

- **Failsafe Backup Procedures for Data Storage and Transfer.** All computer users are aware of the importance of data security and data transfer reliability, but few routinely take the time to guarantee themselves these features. The hub unit can assume this responsibility and thereby ensure the overall reliability of the system.

■ 6.3 Shared Communications

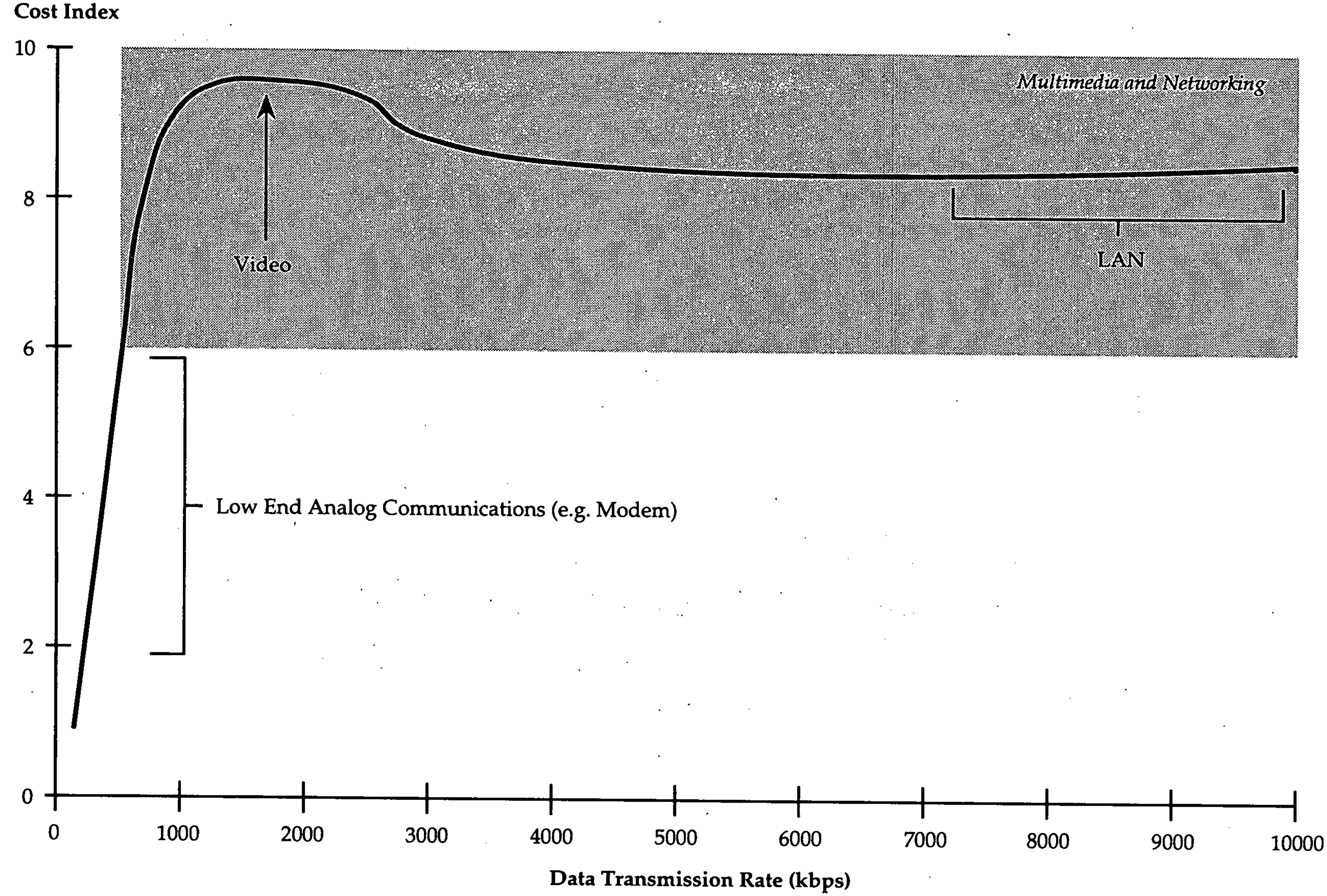
Communications is an integral part of the MMIS system configuration built around the hub-and-spoke approach. Minimum requirements and specifications that will ensure effective shared communications need to address the following:

- **Compatibility with Hub Equipment and Software.** The telecommunication linkages (both hardware and software) between terminals and the hub need to be fully compatible. Hardware and software are needed between the computer storing the hub data and the data communication links as well as compatible hardware and software interfaces at the terminals. Hardware may consist of a mainframe front-end processor, a network interface computer, modem, etc. The software must include a common method of "handshaking" involving a common protocol that permits computers to share information. A protocol involves packaging a message into a frame beginning with a "header," followed by a "trailer" and containing information such as address and error detection support.

- **Minimum Data Rates and Access Time.** The network needs the speed and capacity to transit the volume of data expected to move between the hub (satellite hubs) and terminals. The most desirable minimum data rates are partly a function of cost. Low-speed, low-capacity data lines may effectively serve certain purposes, while high-speed data rates and capacity may be essential for other purposes. Because large amounts of data can be stored for subsequent low-cost/low-speed transmission, there are price/performance tradeoffs in transmission speed illustrated by Figure 21. There are also critical issues concerning potential bottlenecks; for example, the data rate on a Local Area Network (LAN) far exceeding that of a telephone line connecting the LAN to the hub computer.

- **Reliability.** Network reliability for types of data needed only daily, weekly, or monthly is very different from the reliability required for real-time emergency maintenance operations. When data transfer requirements are only daily, weekly, or monthly, sneakernet options (mailing or hand-carrying diskettes) provide extremely robust backup against network breakdown. Nearly real-time operations, where reliable data transfer must be accomplished in less than an hour or even a few seconds, must have backup linkages that are appropriate to the risk and cost of a breakdown. MMIS capabilities intended for disaster and emergency management need considerable redundancy that provides for very low access times.

Figure 21. Price/Performance Tradeoffs



■ 6.4 Communications Linkage, Hardware, and Software

Hardware and software requirements for the next-generation MMIS depend upon the functions to be served, state of technological advance at the time of implementation, and economic considerations that influence the types of hardware and software an agency wishes to support:

- **Functionality.** Centralized functions, such as those carried out by a headquarters hub, will have different hardware and software requirements than decentralized functions of district offices, warehouses and depots, field crews, and various suites of sensors used in real-time monitoring of the physical environment and traffic incidents. Requirements also vary with the functionality of MMIS in terms of ability to store and transfer traditional types of data, support a GIS, and store and transfer text, images, and voice.

- **Technological Advances.** In the future, technological advances will obscure many of the hardware building blocks and the separate types of software we can identify as requirements today. One reason is our inability to accurately forecast technological change. Another reason is that technological improvements result in integration of many hardware and software components or permit software to emulate certain hardware functions or vice versa. Thus a piece of hardware or a software package that seems necessary today, may in 20 years not be a separate identifiable requirement.

- **Economics.** Requirements depend partly on economic considerations, which vary from agency to agency. For example, agencies with different policies toward leasing and buying equipment and different perspectives toward minimizing short- versus long-run costs are likely to have different hardware requirements.

Table 1 presents typical telecommunications, hardware, and software requirements for the central hub and the users connected to it. Requirements for the hub-and-spoke system are meant to be only suggestive, recognizing that there are many current and future network, hardware, and software solutions to implementing it. Two network options are identified in Table 2, and illustrated in Figures 22 and 23. The first involves a centralized hub computer with a front-end processor and direct phone or other linkages to user terminals. The second involves a hub computer functioning as a server on a headquarters LAN. The headquarters LAN is directly connected via bridges and gateways to local users on local LANs or Metropolitan Area Networks (MANs, which serve real-time metropolitan incident management and IVHS applications).

Table 1. Communication, Hardware, and Software Requirements (Central Hub and Spokes)

Architecture Options/ Added Capabilities	Communications Between Hub and Spokes	Hardware		Software	
		Hub	Spoke	Hub	Spoke
Option 1: Hub headquarter's computer with direct links to terminals	Phone line	- Mini or mainframe computer - Suitable memory - Front-end processor - Printer	- PC or workstation - Suitable memory - Modem - Printer	- SQL relational database - Groupware	- SQL relational database - Groupware
Option 2: Headquarter's LAN with hub server and links to local LANs	HQ LAN; phone line interconnection with local LANs at each spoke	- Server with suitable memory - Terminal - Printer	For each user on headquarter's LAN or local LANs: - PC or workstation - Suitable memory - Printer	- SQL relational database - Groupware	- SQL relational database - Groupware - Bridge software for each LAN
Added GIS capability		- Extra memory for cartographic database - Plotter	- Extra memory for cartographic database - Plotter	- GIS software meeting spatial data transfer standards	- GIS software meeting spatial data transfer standards
Added multimedia capability (text, imagery, voice)	Direct linkage via basic ISDN (64 kbs) or broadbased ISDN	- Optical storage - ISDN modem - ISDN PBX (or equivalent)	- ISDN modems - Extra memory (optical storage)	- Object oriented database	- Object oriented database

Table 2. Communication, Hardware, and Software Requirements (Satellite Hub and Spokes)

Architecture Options/Added Capabilities	Communications Between Satellite Hub and Spokes	Hardware		Software	
		Hub	Spoke	Hub	Spoke
CADD	Local LAN (or Bus)	- Server - Memory (optical storage) - Printer - Plotter - Bridge to connect to headquarter's LAN	- Workstations - Object/relational data storage and transfer	- CADD software - Object/relational data storage and transfer	- CADD software
Videologging	- NA	- High-resolution monitor - PC/workstation - Optical storage - High-resolution color printer	- NA	- Suitable software	- NA
Document Imaging	- NA	- High-resolution monitor - PC/workstation - Video disk player - Optical storage - High-resolution color printer - Scanner	- NA	- Suitable software	- NA
Warehouse, Materials, Inventory, and Equipment Maintenance	Options: - RS 232 - RS 449 - RF data communications - Removable memory - LAN - Bus - Inductive loop and transponder	- Mini, PC, or workstation - Memory - Printer	Options: - PC/workstation - Barcode data entry terminal - Voice recognition - Pen-based computers - RFID - Smart card readers - Magnetically encoded stripe reader	- Object/relational database	- Software suitable for each data entry terminal/device

Table 2. Communication, Hardware, and Software Requirements (Satellite Hub and Spokes) (continued)

Architecture Options/Added Capabilities	Communications Between Satellite Hub and Spokes	Hardware		Software	
		Hub	Spoke	Hub	Spoke
Field Data Collection	Office Data Transfer: - RS232 or - Removable memory In Vehicle Options: - Cellular telephone data communication - Radio data communication - Satellite data communication - etc.	- PC/workstation - Memory - Printer	Portable field data collection equipment options: - Barcode data entry terminal - Voice recognition - Pen-based computer - Palm top/notebook/laptop computers - GPS receiver end distance measuring instrument	- Differential GPS processing software - Object/relational data storage and transfer	- Software suitable for each field device
Real Time Environmental Monitoring	Options: - LAN - Direct cable - Telephone communications - Radio data communications - Satellite data communications - etc.	- Monitor - PC/workstation - Memory - Printer/plotter - Receiver/medium	- Roadside sensors - Video cameras - Transmitter/modem	- Processing software	- Data transmission software
Real Time Incident and Emergency Management	Options: - Fiber optic - Cellular telephone - Radio data communications - Satellite data communications - Other IVHS communications (infrared; FM subcarrier) - etc.	- Monitor - PC/workstation - Memory - Printer/plotter - Other IVHS infrastructure, such as Traffic Management Center hardware	Roadside sensors: - Video cameras - Transmitter/modem - In-vehicle digital map displays (IVHS) for dispatch vehicles	- Processing software	- Data transmission software

Figure 22. Implementation of Hub and Spoke System on Centralized System Using Signal Bus Architecture

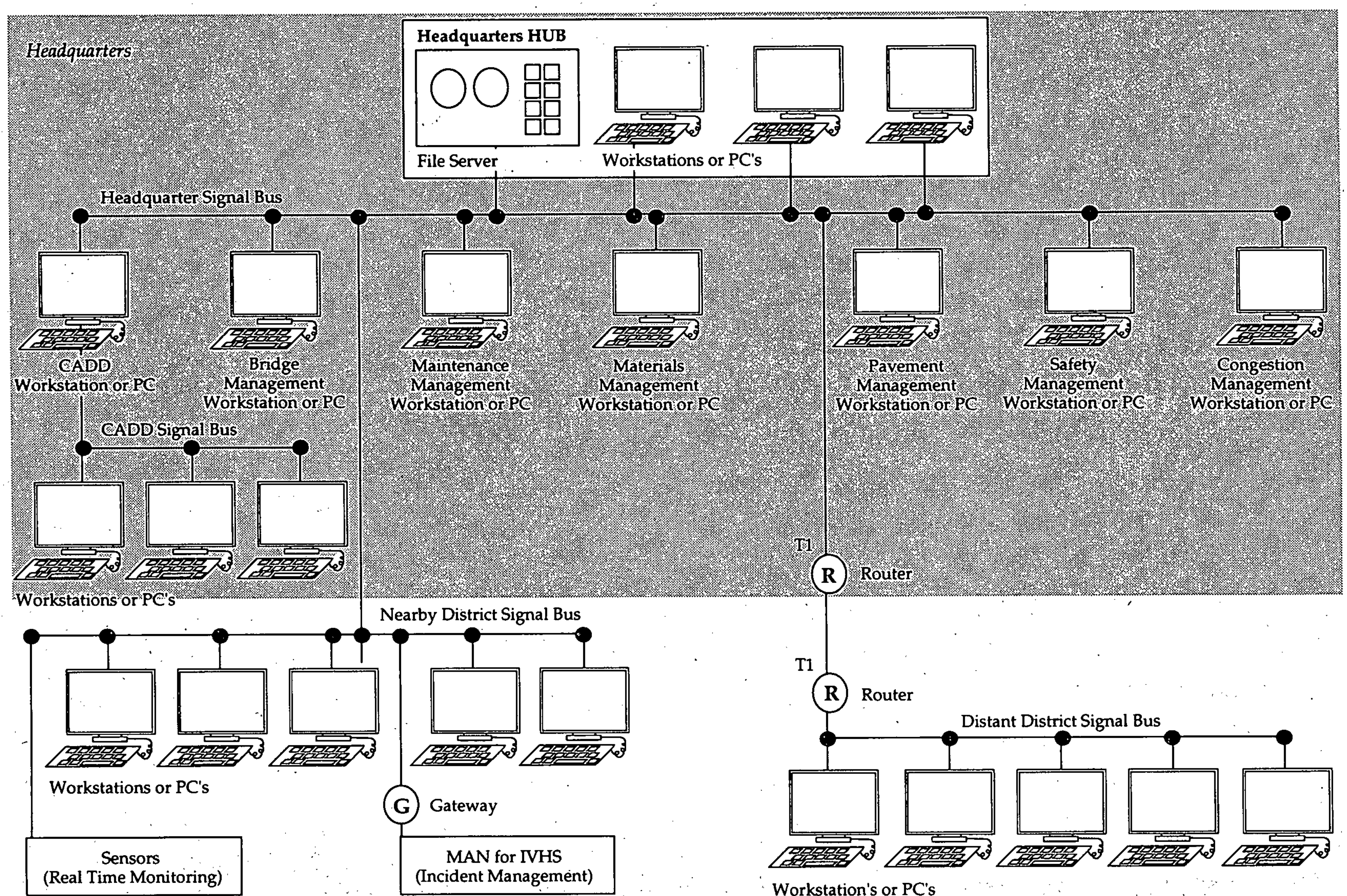
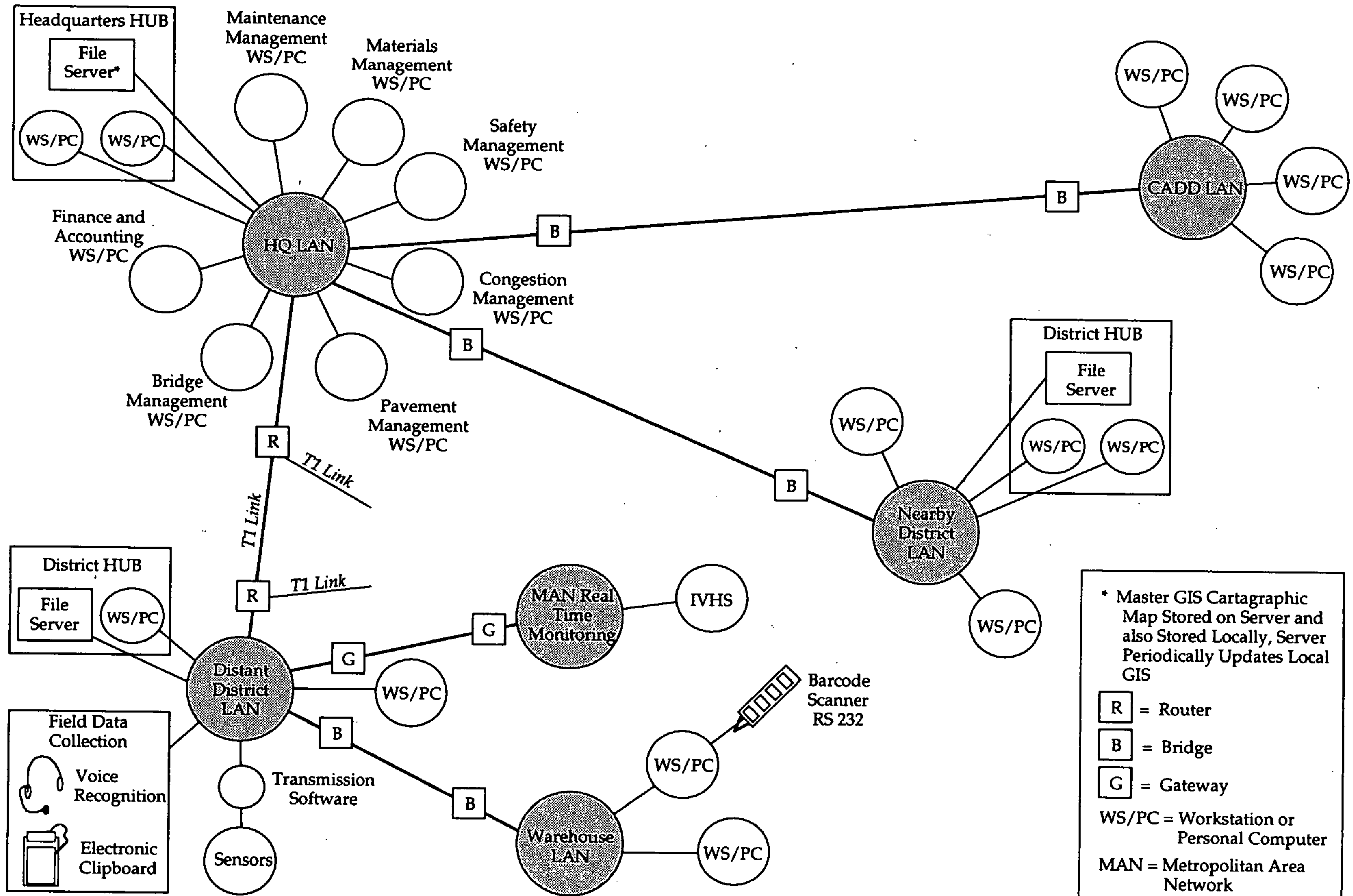


Figure 23. Decentralized Implementation of Hub-and-Spoke System on Local Area Networks (LAN)



Note that the software and hardware requirements for the hub-and-spoke system are presented in incremental form. The most fundamental needs are the hardware and software to store and transfer traditional types of data (alphanumeric characters, ASCII, etc.). Added hardware and software is needed if there is a GIS capability. To process large amounts of text, imagery, and voice data, the linkages between the hub and the spoke terminals need to be of considerably greater capacity than the minimum capacity for just traditional types of data. In agencies that need to send only relatively small amounts of imagery, text, and voice on a sporadic basis, the transmission requirements probably need to be at least equivalent to that for basic Integrated Digital Services Networks (ISDN with a 64 kbs channel). The transmission requirements of agencies transferring large amounts of text, imagery, and voice probably need to be at least the equivalent of broadband ISDN. In an ISDN environment, all hardware has to be ISDN-compatible. Many gigabytes of optical storage will be needed and database management software will have to be object-oriented in addition to relational.

Table 2 suggests the telecommunications, hardware, and software requirements for the satellite hubs and spokes, which serve the more decentralized functions. These decentralized functions are

- A Computer Aided and Design (CADD) capability in the headquarters and/or districts;
- A video-logging capability in the headquarters and/or districts;
- A document imaging capability in the headquarters and/or districts;
- Materials inventory management and equipment management capability in warehouses, garages, and depots;
- Field data collection capability to serve maintenance supervisors and crew leaders;
- A capability for real-time monitoring of physical environmental conditions related to maintenance (e.g., weather conditions and bridge scouring, fatigue and seismic stress);
- A capability for real-time monitoring of traffic related incidents requiring deployment of maintenance personnel and identifiable through Intelligent Vehicle Highway Systems (IVHS).

■ 6.5 Migration Paths

A key implementation issue is the sequencing of MMIS improvements from the current system toward a better one. The telecommunications and data-sharing components of the system form its backbone, and must, therefore, be implemented first. Agencies that already have an operational MMS on a mainframe computer will want to keep that system in operation while the new backbone is being put into service.

If the file access functions of the existing MMS software are sufficiently modular, the best strategy is to "insert" the access routines of the new database between the MMS and its files, by modifying the MMS file access subroutines. The old MMS files then become the first generation of the shared database, while ongoing MMS usage is not interrupted. In most cases, it will be necessary to migrate the files to a modem database manager as part of this process.

After this first step, the data-sharing capability will be operation, but still have the old MMS software using it. The next step is to begin developing "workstation packages" for local-office terminals of the new hub-and-spoke architecture. Design of these terminals should be in close cooperation with depot and district managers, and must support both the needs of the new system and the ongoing needs of the old system, which will still be in operation. It is important to begin at the lowest levels of the agency and proceed upward, because the newer system will tend to push data entry and decision making downward in the organization chart. The depot terminal packages should be highly standardized, but should allow controlled opportunities for depot managers to customize their own terminals.

Implementation of district-level terminal packages should not begin until the lower-level packages are fully-implemented (i.e., no depots are still using the old system), because the districts will rely on data present in the new system, but not the old one. Design of these systems is also a participating process. Along with the user packages, satellite hubs should be implemented in the district at this time. When the satellite hubs are operational, it may be possible (depending on the original MMS software) to switch all depot MMS data flows through the satellite hubs to the central mainframe, where the original MMS software is still running. At this stage, the user functionality of the district workstations should be an incremental improvement over the old system; further technological enhancements (such as planning analysis, GIS, GPS, etc.) should wait until the old MMS has finally been taken off-line.

When all depots and districts have converted to the new MMIS, only the headquarters terminal packages remain. Upon their completion, the original MMS software will no longer be in use and may be taken down. The new system will then be ready for modular addition of new technological features. Figures 16 through 20 provide examples of the modular nature of various configurations under the hub-and-spoke approach that be used to lay out planned migration paths.

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APPENDIX A

Current MMIS Decision and Information Needs

■ A.1 Introduction

This Appendix describes the following aspects of current MMIS approaches:

- It categorizes and structures the types of management decisions that are made with respect to highway system maintenance in state DOTs.
- It describes the types of information (both inputs and outputs) associated with each of these decisions.
- With this framework established, it identifies the opportunities to apply this information within an integrated approach to management.

■ A.2 Administrative Functions

Table A.1 presents "administrative models" for the performance of maintenance management functions. This table groups in a practical way the decisions and related information as normally performed within the overall management hierarchy of a typical department. For each function,

Table A.1 Administrative Models

Function and Level	Actions	Inputs	Outputs
Basic Planning Inputs			
Maintenance Engineer/Technical Staff/Standards Panel *Long-term*	Maintenance Road Classes – basis for grouping roads of like maintenance characteristics and demands	Functional classification Highway system Service characteristics	Class definitions Each road section classified
Long-term	Quality Standards – technical description of deficiencies and techniques of correction	Technical criteria Safety criteria Service expectations Condition evaluations	Condition descriptions Levels of maintenance
Annually reviewed	Activity Standards – combined base planning values related to an activity	Engineering judgements Historic information Operations analysis Performance evaluations	Activity definition Accomplishment measure Inventory measure Quantity standards Work methods Production expectations Resources required Operational costs
Reviewed on submission	Activity Exceptions – standard applicable to a specific local situation	Activity standards Local conditions Local resources Performance evaluations	Same as above for local condition
Updated continuously	Feature Inventory – tabulation of maintenance features by individual road section and management unit	Inventory measure from standards Highway inventory database Supplemental counts	Amounts by inventory unit for each road section within management units
By others/field observations *Updated continuously*	Maintenance Condition Identification	Condition identification from PMS and BMS Condition ratings	Importance of activities Relationships among activities Trends
Maintenance staff/data processing	Systems Development	Management improvements Changes in other systems Hardware/software changes	Improvements

Table A.1 Administrative Models (continued)

Function and Level	Actions	Inputs	Outputs
<u>Top Management Planning</u>			
Chief Engineer/ Director/Commission *Multi-year*	Integrated Maintenance/Capital Plan for Pavement and Bridges – development plan for each road section	Current condition Alternatives and costs Deterioration curves Decision rules	Section-by-section plan for program period (and beyond)
Maintenance Engineer/Chief Engineer *Same*	Long-range Maintenance Work Program with Alternative Levels of Effort	Section-by-section plan for program period (and beyond) Alternative levels of 4R Alternative levels of maintenance Expected changes in inventory Expected changes in work methods Expected changes in costs	Maintenance requirements for examined alternatives Optimum maintenance levels Effects on resource requirements Alternate standards/quantities
Director/Commission *Annually*	Maintenance Appropriations	Maintenance requirements for examined alternatives Optimum maintenance levels Effects on resource requirements	Appropriations by broad object of expenditure Appropriation by program groupings
<u>Functional Planning</u>			
Maintenance Engineer *Annually before budget year begins*	Maintenance Work Programs – statewide work program developed from summaries of field prepared work programs	Routine maintenance programs Summarized periodic maintenance programs Special maintenance programs (snow and ice, etc.)	Statewide needs by activity Summarized resource requirements Field level needs by district
Same	Performance Budgets	Statewide work program	Statewide line-item budget Budgets for each district

Table A.1 Administrative Models (continued)

Function and Level	Actions	Inputs	Outputs
Same	Object of Expenditure Budgets	Statewide work program Performance budget Resource availability standards	Statewide objects of expenditure budget District resource requirements
Same	Resource Allocations	Object of expenditure budgets Contract needs Authorized manpower tables	Table of organization Equipment allocations Materials allocations Contracts allocations
Same	Appropriations	Appropriations by broad object of expenditure Appropriation by program groupings Performance and object budgets	Appropriations to field units Approved budgets Approved resource allocations
<u>Operational Planning</u>			
Maintenance Areas/Special Crews/District direction *Annually before budget year begins, initial and final submissions*	Maintenance Work Programs – prepared for each management unit and activity; defines work quantities and resources required by section where applicable; conceptually places work needed in a queue; see Routine, Periodic and Special subprograms below	Activity standards Activity exceptions Feature inventory Maintenance requirements from related systems	Routine maintenance programs Periodic maintenance programs for each section Special maintenance programs (snow and ice, etc.)
Same	Routine Maintenance Work Program – includes routine work and may include non-maintenance work	Activity standards Activity exceptions Feature inventory	Routine maintenance programs
Same	Periodic Maintenance Work Program – generally will include items that can be planned through PMS, BMS or equivalent routines	Activity standards Activity exceptions Feature inventory Maintenance requirements from related systems	Periodic maintenance programs for each section

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Table A.1 Administrative Models (continued)

Function and Level	Actions	Inputs	Outputs
Same	Special Maintenance Work Programs – activities or activity groups requiring specialized planning approaches	Activity standards Activity exceptions Feature inventory Snow road classes and routes Historic storm data Historic materials usage Traffic marking plans Etc.	Work program for special areas Route-by-route plans for snow and ice Route-by-route plans for traffic markings
Same	Seasonal Work Programs – month-by-month work program designed to balance workloads and promote coordination among basic units; singles out a month's worth of work from the queue	Maintenance Work Programs Seasonal limitations Equipment and manpower limitations Contract alternatives Temporary help available	Seasonal Work Program (Work Calendar)
Same	Operational (Performance) Budgets	Maintenance Work Programs Resource costs Appropriations	Line-item budget
Maintenance Areas/Special Crews – Consolidated at district *Every two weeks*	Schedules – short-term (typically two weeks) work plans; selection of a part of the month's queue	Work Calendar Status Reports Field inspections Manpower and equipment available	Activities to be done by day and road section Manpower and equipment required by day
District in consultation with Maintenance Areas and Special Crews *Monthly*	Monthly Work Program – seasonal work program updated based on progress reporting	Work Calendar Accomplishment quantities and/or periodic maintenance completion check-off Resource constraints	Revised work program showing next month's work plus work remaining
Maintenance Areas/Special Crews *Daily*	Work Assignments – daily assignment of manpower and equipment plus instructions	Schedule Activity standards/exceptions Progress reports Manpower and equipment availability Field inspections	Activity Tools and materials needed Exact locations Extent of repairs

Table A.1 Administrative Models (continued)

Function and Level	Actions	Inputs	Outputs
Activity Reporting			
Maintenance Area Crews and Special Crews *Daily*	Accomplishments and Completions – removes work from the queue	Work assignments Observed results	Accomplishment quantities and/or periodic maintenance completion check-off
Same	Resources Used	Work assignments Field observations Tabulations	Labor, equipment and materials used Contractor progress
Same	Condition Updates	Work assignments Condition ratings	Revised conditions New/relocated facilities
Immediate Control			
Maintenance Areas/Special Crews *Daily*	Schedule Status and Quality Control	Daily progress Field observations	Changes within schedule Corrections, added instructions
Same	Problem Alerts	Checks against standards Checks against schedule Checks against Work Program	"Dailies" Schedule changes Additional instructions
As needed	Schedule Changes	Complaints Resource problems Emergencies	Revised schedule and work assignments, either formal or informal
Operational Control			
Maintenance Areas and Special Crews District (independently) *At least monthly*	Progress Monitoring – review of accomplishments vs planned work including resource usage	"Dailies" Status Reports Information from supervisors Complaints Resource problems Emergencies	Problem solving Next Monthly Work Program Training Exceptions or unusual to Maintenance Engineer
District *Same*	Cost Control – expenditures vs planned by activity and by resource	Expenditures status vs budgets Activity priorities	Program revisions Exceptions or unusual to Maintenance Engineer
Same	Quality Control – workmanship and level of service reviews	Field observations Reported completions	Re-work Training Program revisions Exceptions or unusual to Maintenance Engineer

Table A.1 Administrative Models (continued)

Function and Level	Actions	Inputs	Outputs
As needed	Incidents – isolated situations having an impact on normal routines	Nature of incident Resources expended Cost of incident	Program impacts Program revisions Attention Maintenance Engineer
Functional Control			
Maintenance Engineer *Quarterly and as needed*	Program Control – overall monitoring of both progress and performance	Progress Reports Exceptional and unusual cases reported by districts Incident Reports	Program/Budget revisions Corrective actions Special reports to top management
Annually	Evaluate Planning Values – periodic review of all planning values	Analysis reports Special studies Filed observations	Revised planning values Revised procedures System revisions
Maintenance Engineer and Chief Engineer *Quarterly*	Impacts on Related Systems	Changed planning values and criteria Actions outside of those assumed in related systems Procedural matters	Revisions to strategic plans Revisions to Long-range Maintenance Work Program
Top Management Control			
Director/Commission *Annually and as needed*	Results Monitoring – regular information regarding non-cost reporting items (trends)	Results measures such as: Accidents Maintenance condition Levels of service Public complaints	Revision of funding and overall priorities Initiate new or revised programs Personnel changes
Quarterly	Performance Monitoring – performance trends in major functional areas and for major geographic units	Performance indexes Degree to which objectives are met Trends of employed resources Public complaints	Same as above
Annually and as needed	Background Knowledge	Major program components Relationships among components Problem areas Proposed improvements	PR activities Better top management planning

the likely participants, the specific management or control actions included, and the information inputs and outputs associated with these actions are listed. In addition, the typical frequency or time horizon for each management function is noted.

Maintenance management functions can be divided into three categories: (1) **system development**, which consists of defining the structure of systems for planning, reporting and control of maintenance activities, (2) **planning**, which consists of a variety of activities related to identifying maintenance needs, priority-setting, budgeting, and development of work programs, and (3) **control**, which includes work supervision and quality monitoring, reporting of work accomplishments, tracking progress with respect to plans and making course corrections as needed. Functions in each of these categories are briefly described below:

System Development Functions

- **Development of Basic Planning Inputs:** Establishment of maintenance road classes, feature inventories and condition identification methods; the definition of maintenance activities and related standards; and information systems development. These determine the basic structure for maintenance management information systems.

Planning Functions

- **Top Management Planning:** Agency-wide strategic planning and resource allocation decisions including development of multi-year capital and maintenance plans, analysis of alternative long-range maintenance work program scenarios, and establishment of "optimum" levels of maintenance, statewide funding appropriations and associated resource requirements.

- **Functional Planning:** The interface between top management decisions and operational decisions made by field units. It involves "bottom-up" activities such as summarizing and reflecting maintenance needs identified in the field to guide development of agency work programs, and "top-down" activities such as establishing appropriate allocations of resources to field units which balance identified needs, resource availability, and appropriations to expenditure categories.

- **Operational Planning:** The lowest, most direct level of planning for maintenance, involving the development of specific maintenance work programs, schedules, work assignments, and line-item budgets.

Control Functions

- **Activity Reporting:** The reporting of accomplishments, resource usage and potentially updates to condition ratings for maintenance elements.

- **Immediate Control:** Monitoring of daily progress, problems encountered and schedule deviations and making adjustments to schedules and crew work assignments and instructions as needed.

- **Operational Control:** Periodic (at least monthly) monitoring of actual versus planned accomplishments, resource utilization, and expenditures. Monitoring of work quality may also be included in this category. Based on the extent of deviations from plans, revisions to monthly work programs, new training activities and/or exception reports to the state maintenance engineer may be undertaken.

- **Functional Control:** Annual or quarterly monitoring of the maintenance program from a statewide perspective. It includes comparison of planned versus actual progress and performance, a review of planning values, and an assessment of impacts on related systems. Revisions to programs and budgets, strategic or long-range plans, planning values, procedures, or information systems may be made in response to this type of monitoring activity.

- **Top Management Control:** Annual or quarterly review of maintenance results and trends for the purpose of measuring attainment of stated policy objectives such as safety and level-of-service to road users. Management decisions in this category include revision of funding allocations and overall priorities, initiation of new or revised program activities, personnel changes, and enhancements to top management planning methods.

Decisions and Information

Table A.2 takes a more detailed look at the specific decisions and information items which need to be supported within a MMIS. This table identifies elements drawn from the best MMSs currently in use to match specific system components or information with decisions being made in maintenance organizations. While some of these decisions are tied to a single administrative function above, others may be related to multiple categories, such as the development of maintenance work programs to support both agency-wide budget processes and the actual planning and scheduling of work. Key decisions in the table are summarized below, organized according to the three basic categories of system development, planning and control:

System Development Decisions

- Classification of highway sections by service characteristics.

- Development of maintenance activity classifications and work methods.

Table A.2 Decisions and Information

Elements	Decisions	Information	Notes
<u>Basic Planning Values</u>			
Maintenance road class definitions	Classify highway sections by service characteristics	Traffic, functional classification, as-constructed as it applies to maintenance	Group sections by class so that common maintenance levels apply within a class. This may require different classes for service activities vs. repair activities
Quality standards	Match techniques of maintenance or repair to type of defects	Results expected from maintenance operations, costs, safety considerations, and public expectations	Respect such terms as "patch-in-kind" and "bare-pavement" policies
Activity definition and grouping for planning purposes	Define work activities and accomplishment and inventory units	Importance of activity, relationship to other activities, planning and programming characteristics	Develop based on purpose as defined in Quality Standards plus limit list to only important activities
Procedures and techniques	Steps in work method including workmanship factors	Safety requirements, materials requirements, relationships of crew and equipment, selection of exact locations, adjustments expected	Defines what is expected at the jobsite to relate quality standards to work methods
Staffing, equipment and materials requirements	Determine specific resources required for effective methods	Results from various options, need for internal balance or minimization of inherent delays	Often requires on-site methods analysis
Activity costs	Estimate cost of operations	Costs on inputs (resources)	It helps to have rental rates based on criteria consistent with planning abilities, specifically based on hours committed to a job
Production estimates	Estimate operational productivity (daily production)	Results from trained crew performing work according to standard methods and procedures	Best way to set production standards is to selectively measure the results of good crews doing the work

Table A.2 Decisions and Information (continued)

Elements	Decisions	Information	Notes
Quantity standards	How much of the work is needed per inventory unit for a programming period	Varies with activity, see section on work programs	A default value is needed for advance planning and for routine activities plus condition related values for bottom-up planning
Exceptions	Geographic or equipment-related variations for specific management units	Differences in conditions, requirements or base equipment or materials availability	Allows for matching standards to local needs
Feature Inventories	Workloads of management units	Tabulations of workloads (inventory item/measures) by road section and by management unit	Tabulations are geographic for area crews plus special tabulations for special crews crossing area boundaries
Work Programs			
General content for purposes of advance planning and for development of budget and allocations:	Work quantities and resource requirements by activity for each management unit and further broken by road class and/or road sections	Management unit workloads in terms of area and roads assigned plus standard values	The term workloads is used both for quantities by activities/road/road class and for the base assignment of roads to a geographic unit or activities assigned to a specialized unit
+ Set work quantities	Workloads for each management unit in terms of accomplishment units (by activity/road class)	Feature inventories, quantity standards	Normal computations (inventory amount * quantity per inventory unit) apply except as described below
+ Application of standards	Manpower needs for each activity and/or road class for the management unit or special crew	Quantities and production standards	Normal computation is quantity / average daily production = crew days; crew days * man-hours/days per crew day = man-hours/days required
+ Seasonal distribution	Determine periods of year best suited to work and for a balanced workload	Technical considerations, activity flexibility, performance criteria	Develop plan by months that provides balance plus which allows for efficient operation on key activities including sharing of equipment

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Table A.2 Decisions and Information (continued)

Elements	Decisions	Information	Notes
+ Determine manpower needs	Determine numbers of men needed for both permanent and temporary staffing	Computed requirements, seasonal considerations, staffing restraints	Policy decision based on maximum conditions to staff for (see "Contracts" below)
+ Determine contract needs	Define typical work for contract maintenance	From both economic choice of options and to make up for staffing limitations	Some items go to contract because contracts are a more efficient means; others are used to make up for staff limits
+ Other resource needs	Define equipment and materials requirements	Compute from standards, applying availability standards for various classes of equipment	Also required is a plan for use of shared equipment and/or special crews when individual management unit workloads are not sufficient to justify assignments
Variations by type of work developed within the programming period:	This section describes variations in planning criteria. All developments are also within the appropriated amounts and also meet performance budgeting requirements	Ideally, these determinations would come from related systems based on economic analysis	These items are largely viewed as suggestions from in-Department experts in the various areas described with maintenance generally making the final determinations
+ Routine maintenance	Determine program items for routine work (pothole patching, shoulder grading, drainage repairs, cleaning signs, rest areas, etc.)	Based on quantity standards modified as needed by estimates necessitated by other items in the work program	These are the items which should be done quickly and which are outside of the work that can be more specifically planned
+ Periodic maintenance	Specific periodic maintenance work programs developed by activity for specific road sections with individually estimated quantities	Based on condition surveys, outputs from related systems and major items complementary to major work initiated outside of maintenance	Includes ditching, culvert, shoulder work complementing resurfacing activity; major patching and/or leveling; joint and crack repair; etc.
+ Traffic services	Elements for traffic markings, sign replacements, vegetation control, etc.	Based on condition surveys, economic criteria, and items such as herbicide and wild flower programs	The result is a section-by-section plan based on specific analysis for major traffic service items

Table A.2 Decisions and Information (continued)

Elements	Decisions	Information	Notes
+ Snow and ice control	Determine snow removal service classes, route assignments and develop a cost and resources model for winter maintenance	Based on special standards for snow and ice control, history and policy decisions regarding the level of service to be provided	It seems to be best to plan snow and ice control efforts based on past experience but by snow removal classes and routes, relating overall amounts to number of storms or to overall hours of snow activity expected
+ Maintenance projects	Develop projects for maintenance staff to be done during slack periods (see seasonal distribution)	Projects may be maintenance (guardrail replacements, etc.) or minor improvements such as added turn lanes, intersection improvements, etc.	These are defined as projects with activities defined, quantities and resources estimated, and time periods established for the specific job
+ Overheads	Program elements for supervision, leave, training, etc.	Developed in same way as for routine maintenance	This is a means of including these items in the work program
<u>Budget Development</u>			
Performance budgets	Develop dollars required for major work program elements – management units, activity, road class, and road section, where applicable	Resource costs applied to work program	The performance budget is used as the basis for developing appropriations, for evaluating in-period planning, and for evaluating performance
Object of expenditures budgets	Dollars required related to resource classifications and overall requirements for each resource class in order to set cost targets plus to determine organizational capabilities	Resource costs and availability standards applied to work programs	The objects of expenditure budget is used to view program alternatives in terms of their impacts on resource needs

Table A.2 Decisions and Information (continued)

Elements	Decisions	Information	Notes
Appropriations	Formal allocation of resources and the authority to expend those resources; required some time before the actual program period begins	Based on performance budgets, object of expenditure budgets and resource allocations; becomes the spending limitation	This is the formal funds allocation and is generally to broad objects of expenditure and to activity groups; separating this function from the other budgeting function allows for program modifications within a budget period, either from changes in maintenance condition or from changes initiated in related systems
<u>Long-Range Planning</u>			
General content	Proposed maintenance programs and budgets for a three- to five-year period in advance to allow for planning by funding authority and to plan for improvements within the maintenance organization	Proposed changes in maintenance practices, derived changes in resource requirements, estimates of changes in costs and estimated changes in workloads and maintenance condition ratings	The long-range plan is the picture of the maintenance program of the future with a definition of all of the changes in practices, work by others and in resources assumed in the development of the picture
Alternative levels of maintenance	Development of maintenance options relating cost/resource impacts to varying levels of effort from both maintenance and from related programs	Alternative levels of effort for programs affecting maintenance (CIP, PMS, BMS) and economic estimates of impacts; plus alternative levels within the maintenance program	Both internal and external options need to be evaluated with internal elements limited to service items and external effects being those on maintenance from increased/decreased amounts of resurfacing, bridge rehabs, etc.
Relationships with non-maintenance measures	Develop relationships with non-cost measures of results: + condition ratings, + accidents, + level of service (speeds), + user costs, etc.	Use of relationships developed for other functions within the department plus development of actual measures or estimates	These are measures we need in order to establish broad policies. In their absence, these policies will be set by judgments of both political and non-political leadership

Table A.2 Decisions and Information (continued)

Elements	Decisions	Information	Notes
<u>Scheduling</u>			
Work to be done	Decide activities (and locations) of work in the schedule period	Work program (routine, periodic, traffic, etc.) plus field observations, complaints, etc.	The work program and seasonal distribution should give broad guidance in terms of general activities required; this is supplemented by observations and complaints
Time estimates	Allocate crew days to activities and locations	Field estimates of amounts of work to be done at locations and experience with production under similar circumstances	Items in the periodic work programs will have estimates of days required
Resource utilization	Evaluate resources required based on tentative schedule	Standards and work programs	This is the process of making sure that work in the schedule represented relatively equal daily workloads plus that these assignments are with limits on equipment, etc.
Work assignments	Assign individuals and individual equipment units to work items	Knowledge of individual capabilities and equipment availability	The matchups made determine the amount of supervision and instruction required to get the desired results
<u>Crew Supervision</u>	Lead operator or crew supervisor must find/decide on specific location(s), determine extent of repair, follow standard procedures, meet workmanship standards, and report results	Information includes work methods training, equipment operation, knowledge of the standards, schedule elements, instructions from the supervisor and jobsite consultations with the supervisor	This is a vital communications link in any system and the more visual it is the better
<u>Immediate Control</u>			
Field checks	Jobsite checks need to be made for technique and workmanship	Observations and knowledge of standards	All work needs to be checked at the site by the supervisor, usually just a drive-by

Table A.2 Decisions and Information (continued)

Elements	Decisions	Information	Notes
Problem identification	Checks of performance variables: production, quantities, methods, resource utilization	+ Review of incoming work reporting documents + "Dailies" + Consultation with crew	This is a key part of supervision and also needs all the help it can get. The opportunity to correct a problem before it gets large is the intent of this element
<u>Program Control</u>			
Quantities	Monitor quantities required for each activity and activity group, assessing impact of departures on remainder of program	Quantities and completions by activity, road class, section, etc. compared with planned quantities and program impacts	Most of the program should fall in periodic or fully planned segments and can be monitored by completions. Routine maintenance needs quantity monitoring. System needs to indicate where re-planning is needed.
Productivity	Find areas of the program which will, in time, cause problems in other areas	Actual productivity and resource usage vs. planned	This is primarily to find areas where planning is affected by wrong expectations of production
Credibility checks	Make sure that the next time period in the program actually reflects work requirements and that it also shows effective utilization of resources	Program status reports plus work planned for next period(s)	This is one of the main issues in MMSs. Provision needs to be included – with the ability to re-plan – to make sure the next increment in the work program is still valid as a work objective
Analysis of planning values	Review and verification of planning values	Results vs. standards for resource usage, production, quantities, seasonal values	Annual verification of planning criteria, generally done by a standards panel
<u>Cost Control</u>			
Program management	Make sure the cost of operations is within the limitations of budgets and appropriations	Activity costs vs. performance budget items and appropriation limits	This is in part a performance control item, but more important is the ability to see how incidents (snow storms, etc.) will affect the remaining program and to see the needs for re-planning

Table A.2 Decisions and Information (continued)

Elements	Decisions	Information	Notes
Incidents	Special cost information	Aggregate costs for an incident (snow storm, accident, etc.) to a special work order or project number	Provision to get incident costs for reporting to top management and the public as well as to bill others for services provided
Appropriations	Make sure that program accomplishments are in general order and that appropriation limits are not exceeded	Expenses vs. appropriations plus overall program attainment and measures of maintenance condition	This is an attempt to get closer to an end-results type of performance control, relating adherence to appropriations with service level objectives
Level-to-Level Reporting			
Lead operator to area supervisor	Report progress against schedule	Accomplishments, completions, resources used	Daily reporting both verbally and on reporting forms
Area supervisor to district	Progress against program elements on routine, periodic and incident items	Results fed through the MMS plus an assessment of impact on overall work program and needs for re-planning	Monthly reviews with emphasis on quick correction of past problems and agreement on what is to be done next
District to division	Program status, re-planning involved and appropriations status	Emphasis on completions and appropriations control with identification of impacts on other programs (PMS, CIP, etc.)	Monthly reviews with emphasis on how results will affect other parts of overall operations plus status of appropriations
Division to division	Program status as it affects related systems	Impacts on related systems that cause changes in work programs	This is to build in provision for horizontal coordination at the division level
Top management reporting	Provide information for overall program control	Trends, results, problems, changes expected in long-range plans; details on call	Establish contact designed to keep maintenance needs in front of top management and to serve the PR function as well

- Estimation of costs and resource utilization per unit of activity accomplished.
- Estimation of activity production standards.
- Estimation of activity quantity/maintenance condition relationships.
- Development of maintenance feature inventories to determine management unit workloads.

Planning Decisions

- **Long-Range Planning:** Analyze impacts of changes in maintenance practices on resource requirements, workloads, and maintenance condition ratings, analyze alternative levels of effort for maintenance and variations in capital versus maintenance expenditures, and develop long-range (three to five year) maintenance program and budget.
- **Development of Maintenance Budgets:** Analyze budget options with respect to performance and resource needs, and appropriate funds to maintenance activities.
- **Development of Maintenance Work Programs:** Determine work quantities and resource requirements by activity, management unit and road class. Separate analyses of work may be conducted for routine maintenance, periodic maintenance, traffic services, snow and ice control, and maintenance projects such as guardrail replacements.
- Balance workload by season.
- Analyze manpower and contract needs and strategies.

Control Decisions

- **Work Scheduling:** Based on the work program, schedule specific activities, allocate crew days to activities and locations, and evaluate resource requirements. Assign individuals and equipment to tasks. Ensure that work is balanced on a daily basis and that sufficient resources are available.
- **Crew Supervision:** Decide on specific maintenance locations and extent of repairs, ensure proper procedures are followed, and report results.
- **Immediate Control:** Review completed work and identify quality/workmanship or other problems related to production, methods or resource utilization. The intent is to identify and correct problems as soon as possible.

- **Program Control:** Identify and make necessary adjustments in work programs based on progress to date and to ensure credibility with respect to work requirements and resource utilization. Verify planning values based on actual resource utilization, production, etc.

- **Cost Control:** Ensure that actual costs are tracking within limits set in budgets and appropriations and make program adjustments as needed to ensure budget adherence.

- **Level-to-Level Reporting:** Reporting of accomplishments versus plans at different levels of frequency and detail, depending on the levels of management involved. Top management reports would focus on major trends, problems and expected changes for long-range planning. Maintenance area supervisor reports would consist of detailed accounting of accomplishments, resource utilization, and problems encountered.

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Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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Robert M Smith
Research & Asst Matls Engr
Idaho DOT
3311 W State St
P O Box 7129
Boise ID 83707