NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **334**

# IMPROVEMENTS IN DATA AQUISITION TECHNOLOGY FOR MAINTENANCE MANAGEMENT SYSTEMS



TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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AREAS OF INTEREST

- Administration
- Maintenance
- Construction and Maintenance Equipment
- (Highway Transportation)


**TRANSPORTATION RESEARCH BOARD**
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. DECEMBER 1990

## NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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# FOREWORD

*By Staff*
*Transportation Research Board*

This report contains descriptions of maintenance field-data collection requirements, assessments of alternative "high-tech" data acquisition technologies and procedures, and general system designs employing various technologies for six maintenance data collection scenarios: (1) daily reporting of labor, equipment, and materials use and task accomplishments; (2) material and equipment inventory management and control; (3) roadway feature inventory updating; (4) inputs to short-run scheduling; (5) bridge inspection and maintenance; and (6) monitoring of remote snowplows under dangerous conditions. Maintenance engineers and managers willing to experiment with some of the new emerging technologies for improving the collection and use of data from various maintenance operations will find this report extremely interesting and thought-provoking.

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Accurate and timely data acquisition and reporting are key components to an efficient maintenance management system. These systems can provide quality information that is essential to field managers for allocating limited resources, improving crew performance, and developing cost-effective methods for highway, bridge, and equipment maintenance. Presently, the methods for entering data into maintenance management systems are laborious, requiring, in many cases, the field manager to record work accomplishment using field books or a variety of forms. The information must be checked for obvious errors and entered into a computer by a timekeeper or computer technician. "One-time quick and easy" data acquisition entry and verification systems will permit direct input into maintenance management system computer files. Such a system will reduce work loads and improve and encourage the accurate entry of data.

Most maintenance management systems generate a variety of reports that include measurements of productivity, cost of performing individual activities, and expenditures for given periods. The field manager should be able to extract the data from the system in a timely fashion to correct particular problems or make effective maintenance decisions.

Therefore, more efficient and accurate mechanisms for acquiring and transmitting field data need to be adopted to assist the maintenance field manager in job performance and thereby improve performance of the state highway agency. Some potential improvements include, but are not limited to, the use of portable or hand-held computers, the ability to accept data from locational and navigational systems, and the incorporation of automatic distance measuring and recording devices or other direct data acquisition systems such as voice recognition or bar-coding techniques.

Under NCHRP Project 14-10, "Improvement in Data Acquisition Technology for Maintenance Management Systems," The Urban Institute was assigned the objective of identifying and evaluating the latest technologies to effectively and efficiently acquire, record, field-verify, transmit, and receive field-related data for maintenance management systems. Emphasis was to be placed on the needs of first- and second-level maintenance field managers.

At the time of publication of this report, the NCHRP is contemplating a continuation project to conduct demonstrations of some of the six scenarios described in this report. For further information or to check on the status of any continuing efforts, readers should refer to the latest NCHRP Summary of Progress or contact the NCHRP staff directly.

## CONTENTS

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William A. Hyman, Senior Research Associate, The Urban Institute, was the principal investigator. Ancel Dan Horn, Managing Director, Satellite Systems International, Ltd., was the co-principal investigator. The other authors of this report are: Omar Jennings, Vice President Engineering, Satellite Systems International, Ltd.; Frederick Hejl, Principal Engineer, Bergstralh-Shaw-Newman, Inc. (now with the Transportation Research Board); and Timothy Alexander, Partner, Space Development Services.

Ken Donow and Neil Benedict were technical contributors and Arlee Reno, Ed Shaw, and Jeffrey Garmong provided technical review. In addition, The Urban Institute wishes to gratefully acknowledge a large number of individuals in the Maryland Department of Transportation, the Virginia Department of Transportation, and the District of Columbia Department of Public Works who hosted field visits and participated in an equipment demonstration held in the Fairfax Residency of the Northern Virginia District Office. Particular thanks is extended to George Wittman of the Maryland Department of Transportation, C.O. Leigh of the Virginia Department of Transportation, and Jay Watkins of the District of Columbia Department of Public Works. Also, Dorothy Weberling of the Virginia Department of Transportation helped arrange the equipment demonstration.

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# IMPROVEMENTS IN DATA ACQUISITION TECHNOLOGY FOR MAINTENANCE MANAGEMENT SYSTEMS


## SUMMARY

Advances in technology and telecommunications offer potentially significant savings in the time and effort required for highway maintenance field managers and others to acquire information required for maintenance management.

Current methods are often unnecessarily time consuming, labor intensive, and inaccurate. Moreover, current methods do not offer field managers a quick and efficient means of extracting useful information from the maintenance management system.

Useful information to support field operations would include the comparative efficiency of different maintenance methods, urgent and emergency work orders; equipment and material availability and location; budget balances for different maintenance activities, and needs data for short run scheduling.

A fundamental problem in the past has been the inability to locate maintenance accomplishments accurately. Reporting of maintenance accomplishments and resource use is oriented toward the maintenance management unit as opposed to a maintenance site. Satellite global positioning systems (GPS) offer a way to more accurately locate maintenance work. Being able to identify where maintenance work takes place will not only improve the use of budgeted maintenance resources, but also will help in identifying maintenance needs which are analyzed in pavement management systems (PMS). Moreover, geographical information systems (GIS) are coming on line throughout the country. GIS will require that much data collected be referenced to latitude and longitude, which GPS receivers can do.

This research has determined the requirements for field data acquisition equipment and systems, evaluated alternative technologies and telecommunications for acquiring data, and developed preliminary system designs for data collection pertaining to six areas: (1) crew card data collection—daily reporting of accomplishments and use of labor, equipment, and material by maintenance activity and by worksite; (2) equipment and material inventory management and control—maintenance depot and warehouse inventory management systems; (3) roadway feature inventory updating—procedures for updating information on the maintainable features of the road and bridge network; (4) inputs to scheduling—collecting and combining maintenance deficiency data from various sources (daily patrols and site visits, condition and distress surveys, citizen complaints, and annual work programs) to aid in short run scheduling of labor and equipment; (5) bridge inspection and maintenance—more automated methods of collecting bridge inspection data and maintenance recommendations; and (6) heavy snow equipment monitoring—a way to keep track of equipment and driver status of snow plows and blowers operating in remote locations in dangerous storm conditions.

The system designs entail modular, integrated systems that generally employ "plug compatible," commercially available equipment.

*Crew Card Data*

Crew leaders have traditionally filled out daily cost reports, sometimes known as crew cards, to describe completed work and the labor, equipment, and materials used.

A number of technologies, including keyless data entry, could replace the use of the paper form. A technological solution would require light-weight, portable equipment that is easy to hold and carry. The equipment would be rugged, work in high humidity, operate in a broad temperature range, run on rechargeable batteries, and have convenient communications and data transfer. The equipment would be required to prompt the user for inputs, verify data entry, and provide the capability of "date and time stamping" the data. It should also interface with a GPS receiver or a distance measuring instrument to provide accurate locational information.

A detailed technology assessment revealed that laptop portable computers, hand-held portable data entry terminals, and electronic tablets (clipboards) are commercially available and can essentially meet these requirements at costs of $2,000 per unit, and as little as $300 per unit for some data input devices if certain requirements are relaxed. In addition, bar code readers can be plugged into each of these (or may be an integral part) so that field supervisors could potentially collect crew card data by simply scanning a bar-coded menu or form, eliminating the need for most paperwork and arithmetic. Electronic tablets offer another type of keyless data entry, which may be equally effective.

### *Equipment and Material Inventory Management and Control*

State agencies should give strong consideration to implementing a bar code data acquisition system for keeping track of such physical assets as vehicles, equipment, tools, and office furniture. Such systems, widely used in other industries, are easy to implement and can be expected to provide significantly improved accounting of physical assets as well as cost savings of faster, more accurate inventories.

A comprehensive inventory management system involving materials in addition to equipment would require further study, but if private industry is a guide, cost recovery could be achieved in a year.

### *Roadway Feature Inventory Updating*

Thirty-eight states are now supporting the development of automated methods using GPS receivers to establish a roadway feature inventory data base. These inventory data could serve as an important part of a GIS platform that supports pavement, bridge, and maintenance management. GPS receivers used with the type of equipment suitable for collecting crew card data can help update roadway feature inventories.

If a state does not implement a GIS, more accurate roadway feature inventories and updates could be achieved using distance measuring equipment.

### *Inputs to Short Run Scheduling*

While patrolling, traveling to and from work sites, and during maintenance operations, crew leaders and their superintendents search for maintenance deficiencies and problems. Improved ways are needed to record maintenance deficiencies seen in the field and combine them with citizen input and the condition of maintainable elements stored in the data base. Maintenance field managers also combine this information with planned work targets and available resources to schedule work from week to week.

The maintenance manager's usual practice is to note needed work on a paper form or, in some cases, to fill out a work order, which is often inconvenient to do while driving. Furnishing an inexpensive voice-activated tape recorder ($100 to $200) to maintenance field managers would enable them to take verbal notes of problems while moving in their vehicle and complete more accurate needs reports at the end of the day. Notebook-size computers, laptop computers, and electronic tablets ($600 to $2,000, depending on the equipment) may provide a more automated and cost-effective way to collect and retrieve maintenance deficiency data during day-to-day maintenance work. A GPS receiver or distance measuring instrument could provide fairly precise locational information at added cost.

This research has developed a design for a data collection system that can combine maintenance deficiency information from various sources for more effective short run scheduling.

*Bridge Inspection and Maintenance*

Standard bridge inspection and reporting of maintenance needs can potentially be enhanced using portable data acquisition equipment. Electronic clipboard(s) in conjunction with digital still cameras and GPS receivers may be a practical way to collect, store, and retrieve condition and appraisal data, handwritten notes, and pictures of bridge problems requiring repair.

*Heavy Snow Removal Equipment Monitoring*

Operators of snow removal equipment in remote locations suffer from fatigue of working long hours and face hazardous weather including blizzards. From time to time vehicles and drivers become disabled in accidents. It is desirable to be able to monitor snow removal equipment to keep the fleet operational and to rescue injured equipment operators.

States are increasingly turning toward automated monitoring of storms and snow and ice control operations. The technology and telecommunications examined in this study suggest that it is practical to use navigational equipment (LORAN or GPS), other sensors, and a transmitter to periodically send equipment and driver status information by satellite to a central monitoring facility.

Implementation of any of these systems would require field testing and more detailed analysis. Implementation must fully take into account the operating environment, work culture, management objectives, and the cost and benefits. In general, each state highway and transportation agency can expect to find one or more applications of these data acquisition technologies which can lead to significant cost savings.

CHAPTER ONE

# INTRODUCTION AND RESEARCH APPROACH

## THE PROBLEM

Maintenance field supervisors often confront burdensome and laborious paperwork because of reporting requirements of maintenance management systems. Filling out forms and field books and performing arithmetic computations distract from their primary responsibilities in the field. Data reporting methods are prone to inaccuracies for a variety of reasons including imprecise ways to locate maintenance accomplishments. Moreover, highway maintenance organizations often use timekeepers, clerks, or computer technicians to check for obvious errors and enter information into a computer. Thus, there is a need for "one-time, quick and easy" data collection, entry, and verification systems for directly entering information into maintenance management systems.

Current methods for entering data into maintenance management systems lack an efficient way for managers working in the field to receive feedback and other valuable information. Most maintenance management systems generate a variety of reports that include productivity measures, costs of performing individual activities, and expenditures for given periods. Ideally, a maintenance field manager should be able to extract this kind of information in addition to urgent or emergency repair needs, equipment and material availability, as well as pavement and bridge inventory, condition, and inspection data.

Road maintenance organizations need to adopt more efficient and accurate ways to acquire and transmit field data to assist the maintenance field manager. Improvements in data acquisition methods to serve the maintenance field supervisor must take into account standard operating procedures, organizational setting, field environment, work culture, existing data base, and current or emerging decision support tools such as pavement management, bridge management, and geographical information management systems.

Accurate and timely data acquisition are essential for an efficient maintenance management system. Improved information from the maintenance management system can help field managers allocate limited resources, improve crew performance, and develop cost-effective methods for highway, bridge, and equipment maintenance (*1*).

A wide variety of commercially available technology and types of telecommunication offer potentially effective ways to address these problems. Among the data collection technologies are laptop and hand-held computers, electronic tablets, voice recognition systems, portable facsimile machines, locational and navigational systems, and automatic identification technologies such as bar coding and radio frequency identification.

Among the newer telecommunication technologies are cellular telephone, satellite links, special mobile radio, and wired digital data circuits. These augment older technology such as telephone lines and conventional two-way radio.

Data acquisition technologies and telecommunications can be integrated into practical systems that can substantially boost the productivity of the field supervisor and improve maintenance management generally.

Generic systems can be designed that are applicable to a large number of agencies and maintenance settings, such as has been done in this report. They can address the requirements necessary to ensure that people in the field are comfortable with the technology. However, implementing a practical system requires attention to the specific circumstances and requirements of each agency. The requirements will vary with the type of maintenance activity (e.g., crack sealing, sign repairs); the data collection activity (e.g., daily cost reporting, roadway feature inventory updating); the geographic and climatic setting; the type, number, and size of maintenance depots; the existing and planned decision support systems for maintenance; and the data flows and organizational ties between the maintenance organization and the rest of the highway agency.

## OBJECTIVES AND SCOPE

The primary objective of this research was to identify and evaluate the latest technological means to effectively and efficiently acquire, record, field verify, transmit, and receive field-related data for maintenance management systems.

This research sought to identify or develop integrated, but modular, data acquisition systems applicable to a wide variety of state and local road maintenance organizations. The systems should enable the typical maintenance field supervisor to more easily, efficiently, and accurately collect data required for maintenance management.

Field supervisors should also be able to obtain timely feedback and information from the maintenance management system.

The research addressed data collection for all types of maintenance activities ranging from pavement surface treatments to roadside litter pickup to snow and ice control. The technology assessment covered the full range of existing and practical technologies and communications, and has taken into account improvements likely to occur over the next 5 years.

System designs were developed for six maintenance data collection activities:

1. *Crew card data collection*—Field managers (crew leaders) of virtually all state highway agencies fill out daily cost reports, sometimes called "crew cards," to describe resource use and accomplishments. Crew card data consist of maintenance activity; location of work; date, time, and duration of work; labor, equipment, materials, accomplishments.
2. *Equipment and material inventory management control*—Every state agency must take periodic inventory of its physical assets including maintenance vehicles and equipment. In addition, agencies keep records of purchases of maintenance materials and supplies, and to some degree keep track of their use. It is not possible to track the use of all maintenance materials, because some are scavenged from old jobs. Nonetheless, agencies are accountable for efficient use of both equipment and materials, and, therefore, a cost-effective equipment and material inventory management control system is desirable.
3. *Roadway feature inventory updating*—Efficient maintenance budgeting and scheduling requires an organization to have a roadway feature inventory data base, including maintainable features. The roadway feature data help agencies to determine annual work loads for each maintenance activity and periodic maintenance schedules. Updating the roadway feature inventory is essential for an effective pavement and maintenance management system.
4. *Inputs to short run scheduling*—Many maintenance field managers spot or search for maintenance deficiencies during daily patrols and while traveling to and from work sites. Because the field manager is often preoccupied with a specific activity, sometimes deficiencies and problems are identified but not recorded. Even if they are written down, there may be no means to store the information in the maintenance management system data base. Also, there may be no way to combine these deficiency data with other information on maintenance needs in order to schedule crews and equipment, normally done weekly or biweekly. Other sources of maintenance needs include citizen input, pavement condition and distress surveys, and planned workloads based on the annual work program.

Thus, better ways are required to record maintenance deficiencies and problems spotted in the field and combine them with other needs to aid in short run scheduling of crews.

5. *Bridge inspection and maintenance*—Road and bridge maintenance are complementary activities. But bridges, which are composed of a deck, substructure and superstructure as well as many subcomponents, impose maintenance requirements different from road requirements. Every state is responsible for inspecting all its bridges frequently enough to ensure safety, and the inspections often result in maintenance recommendations. The inspections and maintenance recommendations often depend on intensive data collection. An inspector frequently prepares supplementary reports containing detailed written descriptions and photographs of problems. For these reasons bridge inspection and maintenance deserve special attention concerning data collection.

6. *Snow and ice control*—Snow and ice control operations are an important concern of many states and are fundamentally different from other maintenance activities. The technology and telecommunications, which are of interest in this research, immediately suggest ways to improve the monitoring of snow plow operations. In order not to conflict with research being carried out under the Strategic Highway Research Program, this research has concentrated on a single facet of snow and ice control monitoring, namely, that of tracking the location and operating status of snow plows and snow blowers during storms, especially in remote locations.

Originally, this research focused on data flows to and from the first level field manager. Field visits and telephone interviews revealed, however, that higher level maintenance managers frequently design and institute procedures that seek to minimize or eliminate paperwork for the first level field manager and their crews. Data recording and tabulation are often performed by clerks and timekeepers and approved by the second level maintenance manager. Some of these procedures are extremely efficient, although not as accurate or as complete as they could be. Consequently, the research addressed data collection for not only the first level maintenance manager, but also the second level.

## RESEARCH APPROACH

The principal phases of the research were to establish the field data gathering and transmission requirements of current maintenance management systems, to perform an assessment of commercially available technologies and telecommunications, and to develop system designs for the six data collection activities listed previously.

### Requirements

To develop the requirements, the initial phase, nine field visits were made that focused on the reporting and informational needs of first level field managers and their supervisors. The field visits were in Maryland, Virginia, and the District of Columbia and covered virtually all categories of maintenance activities, including pavement and shoulder maintenance, signs, roadway striping, mowing, bridge maintenance, and snow and ice control operations.

Structured telephone interviews of maintenance managers were also conducted in nine states. These managers have an overview of their maintenance management system and the state's input data needs and practices. The managers were located in Illinois, California, Missouri, Arizona, Pennsylvania, Maryland, Virginia, Iowa, and Minnesota.

The definition of requirements, moreover, resulted partly from the research team's analysis of factors that might encourage or discourage a maintenance field manager from using various technologies. Among the factors analyzed were ease of use, holding, and carrying; ruggedness and environmental resistance; usability at dusk or in the dark, minimal reading and writing requirements; data entry verification and checking; provision of a paper audit trail; and ease of data retrieval communication and data transmission. Each maintenance activity was examined to determine potential improvements in the accuracy of reporting locational information, data entry accuracy, and informational turnaround time between the field manager and the maintenance management system. In addition, the research team distinguished among the requirements those that pertained to (1) specific technologies, (2) integrated but modular data acquisition systems, and (3) an improved data acquisition system functioning within a typical maintenance management system including the distributed data processing environment.

Consideration was also given to the requirements imposed by maintenance data collection in different geographic regions of the country. This was to take into account the variations imposed by the environment, traffic, and terrain.

Feedback needs were characterized in two ways. The first treats first level field managers as autonomous and evaluates their need for information as being independent of others' needs. The second acknowledges that data originate from the first level field manager, but feedback for performance monitoring, productivity enhancement, and control is provided to the field managers by higher levels of management.

In practice, it was found that, although it was possible to establish some requirements during the initial phase of the study, it was necessary to frequently update them, mainly in response to advances in related research areas, rapid technological change, and new product introductions that occurred throughout the project. For example, during the course of this study, a prototype hand-held electronic tablet/computer emerged, underwent market testing, and moved to full production and commercial availability. This data acquisition device proved to be promising for field data collection and induced the research team to consider an expanded set of requirements that, beforehand, would not have been judged to be practical.

Also the potential locational accuracy of devices that use the civilian code for the NAVSTAR satellite global positioning system improved significantly as a result of analytical and software developments that occurred during the course of this study, and then declined when the federal government degraded the civilian system. At the outset of the research, a practical benchmark of locational accuracy appeared to be approximately 40 ft (13 m) for estimates of longitude and latitude obtained in stationary measurements with a single GPS receiver. Near the conclusion of this study, discussions with experts revealed that by 1993 or sooner, it would be possible to achieve 33 ft (10 m) accuracy or better in a van traveling at highway speeds, and a meter or better with stationary measurements assuming the use of a supplementary base station, differential processing and corrections, and no degradation in the civilian code. Shortly, thereafter, the Department of Defense instituted "selective availability" for the civilian code of the GPS system and degraded the locational accuracy of a single point positioning device to a prespecified level of about 330 ft (100 m) for 95 percent of the time. Differential processing with a supplementary base station at a known reference point can still achieve high degrees of accuracy. Also, the government is developing procedures that may provide civilians selected access to the GPS military code which, with surveying equipment, can achieve locational accuracies of less than a centimeter. Furthermore, the Soviet Union's GPS system may become available to users in the United States with no degradation and provide more accuracy than the degraded civilian system of the United States (*2*).

### Technology Assessment

The second phase of work involved a thorough evaluation of data acquisition technologies and telecommunication options. An extensive literature search included an evaluation of relevant citations in the Transportation Research Information System (TRIS) and the National Technical Information Service (NTIS) data base. The search examined source books on different technologies. The focus of the search, however, was on trade periodicals covering such technologies as bar coding, voice recognition, and hand-held portable data entry terminals, GPS (*3, 4, 5, 6, 7*). On the basis of the literature review, a list was compiled of approximately 150 vendors and acquired vendor literature describing product characteristics and performance. Each technology was evaluated, and summarized, with regard to the requirements for the data collection devices. In order not to lose sight of the advantages of the data collection procedures currently in use, the technology assessment included an evaluation of the strengths and weaknesses of paper forms.

Also undertaken was a parallel, but more general, assessment of the telecommunication options. These include ground-to-ground radio links, cellular telephone, wideband networks, satellite links, and UHF radio frequency transmissions (*10, 11, 12, 13*).

An important part of the technology assessment was an equipment demonstration held with the assistance of vendors. The demonstration was conducted at the Fairfax Residency of the Virginia Department of Transportation. First and higher level maintenance managers from the Virginia and Maryland Departments of Transportation were given an opportunity for hands-on evaluation of various input devices. The devices demonstrated were hand-held portable data entry terminals, bar-code scanners, a portable GPS receiver, an electronic tablet, and a speech recognition system. In addition, one of the vendors used a laptop to simulate how the electronic tablet would be used to collect data, and another demonstrated microcomputer software for inventory management.

### System Designs

The third phase of the project was to develop system designs for each of the six types of data collection that were the object of this study: crew card data reporting, roadway feature inventory updating, equipment and material inventory control, inputs to scheduling, bridge inspection and maintenance, and snow plow monitoring.

The system designs identified the inputs and outputs, the data collection devices including possible alternatives, the feedback and data flows, and the training and implementation requirements.

Most of the system design effort focused on data collection for the first level field managers. However, some attention was given to establishing a geographically referenced roadway feature inventory that incorporates maintainable elements. Without such a data base in place, it does not make sense to introduce devices into the field for updating roadway feature inventory information using GPS.

CHAPTER TWO

# FINDINGS—REQUIREMENTS

Data collection systems to serve maintenance field managers should ideally satisfy a broad range of requirements to be generally useful to state and local agencies. Although it is desirable that such systems work in all agencies, systems too general in their applicability are too expensive. Customized or tailored systems are often more cost effective. Therefore it is desirable to specify requirements for maintenance data acquisition systems that, on the one hand, fit enough situations to be generally useful; and, on the other, it should be possible to fine tune requirements to unique circumstances, work environments, data collection tasks, and maintenance activities.

There are three levels of requirements addressed in this chapter. The first concerns the requirements of the maintenance management system. The second level pertains to data collection devices or modules and focuses on the necessary characteristics for field use. The third applies to a modular system of integrated components including telecommunications.

## MAINTENANCE MANAGEMENT SYSTEM REQUIREMENTS

Maintenance management is an orderly approach to planning, scheduling, and controlling maintenance work. Its principal objective is to assist management in providing an efficient and effective highway maintenance program. Management cannot achieve this objective, however, without suitable data collection by field managers. Field managers will resist improving their current methods of data collection unless it clearly benefits them in terms of reduced paperwork, savings in calculations, and significantly improved information that makes their work easier to do.

Maintenance management provides a means of establishing levels of maintenance service; preparing annual work programs based on work priorities and the level of service to be provided; allocating resources as needed to perform annual work programs; scheduling and performing work in accordance with methods and procedures designed to ensure optimum efficiency; and reporting work performance in ways that permit engineers, supervisors, and crew leaders to evaluate performance and to take action to effectively control operations (*14*).

Maintenance management systems vary somewhat among the highway and transportation agencies, but the basic concepts remain the same.

A key requirement of new data collection procedures and devices is that they must serve the major functions of a maintenance management system: work planning, work authorization and scheduling, work reporting, and work evaluation.

### Work Planning

Work planning involves the development of an annual maintenance work program, a performance-based budget, and a maintenance work calendar. The annual maintenance work program defines, calculates, and documents the kinds and amounts of work estimated to be required to provide a desired level of service. The development of the maintenance program involves identifying maintenance work activities, road and bridge feature inventories, quantity standards representing levels of service, and performance standards. The performance-based budget calculates the cost of performing the maintenance work program in terms of labor, equipment, and material costs as well as total costs. The maintenance work calendar procedure distributes the annual work load to reduce the peaks and valleys in resource requirements.

An important part of the information needed for work planning is an accurate inventory of maintainable features. The inventory is needed to calculate quantity standards that are used to develop preliminary estimates of annual workloads for the different maintenance activities. An accurate inventory, therefore, is one of the requirements of maintenance data acquisition.

Accuracy requirements for roadway feature inventories and updating are 50 ft (16.7 m) or better. Twenty-five to 50 ft are generally satisfactory for features on rural highways, but greater accuracy—less than 3 ft (approximately 1 m)—is desirable in dense urban areas in order to locate driveways and other features small distances apart. Accuracies of less than 33 ft (10 m) are technically, though not necessarily economically, feasible using mobile (kinematic) data collection and 3 ft (1 m) or less using stationary measurements assuming there is a base station at a precisely known point and differential processing (*7*).

### Work Authorization and Scheduling

A requirement of maintenance data acquisition systems should be to facilitate work authorization and scheduling. Different methods are used to authorize work. Some agencies use authorized work orders or crew day cards. Each represents one crew day of work on a particular activity and authorizes the maintenance supervisor or foreman to schedule one day of work on the activity using the standard crew size, equipment complement, and materials established in the performance standards. Other agencies simply provide each supervisor with a hard copy of their work program. A few agencies are able to display annual work programs and more detailed schedules on personal computers.

Effective use of the maintenance work force demands effective scheduling and fairly uniform workload throughout the year. Information on the deficiencies of maintainable items (pavements, signs, rest areas) is needed to schedule work. Crew leaders as they travel from site to site and their superintendents, as they check on crews, typically gather this information. Citizens also notify local headquarters of problems. Superintendents are responsible for integrating these data with the long term (quarterly, semi-annual or annual) work plans to produce weekly or biweekly crew work schedules. In most instances, this is a manual process where the supervisor lays out a work schedule for a 2-week or semi-monthly period. The intent is to plan ahead for enough work for the resources available. Some agencies are beginning to use the personal computer for work scheduling.

### Work Reporting

Work reporting for maintenance management involves submitting the work effort in terms of labor, equipment, materials, and accomplishments. Labor is reported in hours, equipment by hours or miles driven, and materials by appropriate units of specific materials used. Accomplishment is reported in a unit of measure that appropriately represents the work done on the activity, such as tons of bituminous mix for pothole patching and shoulder-miles for blading unpaved shoulders. The work activity is reported for each activity by management unit. In addition, some agencies report the work effort by road section, milepost, or bridge number. The day and the number of hours required to perform each activity are usually reported.

Currently, work reporting is done on crew day cards or some other type of work order, on dual purpose forms that serve both cost accounting systems and maintenance management systems, or directly on work scheduling forms.

The reported information is entered into an electronic data base by various methods. Most agencies are using remote desktop terminals for direct input, although a few may still be using key punching.

The greatest potential for improving field data collection lies in reporting the location of work activities and roadway features more accurately. Locational information will be increasingly important as states implement geographic information systems and integrate maintenance and pavement management systems. At present, locational information is imprecise. Hand-held devices that use the satellite global positioning system (GPS) were achieving accuracies of 40 ft (13 m) until "selective availability" was instituted, as mentioned above.

Additional improvement in data collection will result if the data are tagged with the date and time it is collected. This permits more accurate reporting of the time engaged in different activities.

Consequently, the following requirements are sensible for crew card data collection: location accuracy of 50 ft (16.7 m) or less, regular and overtime labor in hours and minutes, equipment miles or equipment hours and minutes by activity and location, quantity of materials by activity and location, and accomplishments by activity and location. From this information the data input device or the host processor should be able to quickly calculate the total costs for each activity each time it is performed.

Standard operating procedures of state and local agencies indicate that a single set of requirements will not adequately address the main ways data are collected. Requirements should reflect the fact that maintenance field managers generally obtain their work orders in generally two different ways. Most field managers report daily to a staging area where they receive their work orders, crew, and equipment. When they return to the staging area at the end of the day, they report their resource usage and accomplishments. However, some maintenance managers who work in highly rural or remote locations may essentially work out of their homes.

The communication requirements for these two sets of maintenance managers differ. At the minimum, the first group should be able to automatically transfer their data to the host computer at the end of the day, and obtain feedback and extract other information the next day. Field managers would benefit even more if they could extract data in real time from the maintenance management system.

The second group will require home, public, or in-vehicle cellular telephone links to transmit and receive data using a modem or a facsimile machine.

#### Work Evaluation and Access to the Data Base

Work performance evaluation is required to ensure proper execution of the maintenance program and achievement of designated levels of maintenance and standards of performance. Typical evaluation reports include accomplishment and productivity analysis reports and quantity standard (level of service) analysis reports.

Work evaluation has traditionally been a problem for highway and transportation agencies because of the time it takes to enter the information into the computer, process it, and return it to the maintenance manager. Also both random and systematic errors in work reporting frequently go undetected resulting in unreliable reports.

Maintenance management systems currently serve upper level managers more than field managers. The data base should be more accessible to field managers. Information useful to the field manager would include emergency or urgent repair needs, availability and status of equipment and vehicles, budget balances by management unit and maintenance activity, and cost-effectiveness of different approaches to maintenance. Indeed, the maintenance management system should offer two types of feedback which strengthen local control and accountability. The first one assumes that the maintenance manager is an autonomous professional and serves his or her needs directly. The second provides feedback that reflects the goals and objectives of the local maintenance office of which the field manager is a part.

These feedback requirements pertain to crew card data collection. Other types of data collection will require different types of feedback. Data collection systems for updating roadway feature inventories should be able to extract information from roadway inventory data base. Similarly, a materials and equipment inventory control system should enable a stockkeeper to determine unit costs, status of purchase orders, the location and quantities of equipment and materials on hand, and vehicles in the repair shop. Bridge maintenance managers should be able to extract information from the bridge inventory, inspection, and appraisal data bases.

**Table 1. Maintenance management system requirements.**

- Addresses one or more MMS functions
  - Work planning (roadway inventory feature updating)
  - Work authorization and scheduling
  - Work reporting (accomplishments, labor, equipment, materials)
  - Inventory management and control
  - Work evaluation
- Augments work reporting with
  - Date and time of work
  - Location of work
    - < 50 ft (16.7 meters) generally
    - < 3 ft (1 meter) for dense urban areas
- Data transfer
  - Daily uploading at staging area
  - Remote location (cellular, home or public phone)
- Data retrieval and feedback for
  - 1st level field manager
  - Higher level management
  - Emergency and urgent repairs
  - Equipment/material availability
  - Budget balances by management unit and activity
  - Cost-Effectiveness of different maintenance approaches
  - Planned versus actual work

#### Summary of Maintenance Management System

Requirements for field data collection systems pertain most directly to work reporting, which in turn provides the information to plan, authorize, schedule, and evaluate maintenance work. Other important data input requirements concern roadway feature inventory data and the current inventory of vehicles, equipment, and materials. Table 1 summarizes the data collection system requirements that stem from the maintenance management system.

### MODULES—DATA COLLECTION DEVICES

Maintenance field managers will be faced with handling a new data collection device if they give up filling out paper forms. Acceptance of the new device will depend on friendliness, ease of use, and ruggedness as well as the tangible rewards of reduced paperwork and ready access to the maintenance management system data base.

The equipment should be portable and light weight, not exceeding 6 lb and preferably considerably less than 2. It should be compact in dimensions and, thus, easy to hold and carry. It should require as little dexterity as possible for data entry. Keyless data entry is preferable to keying in data, unless lengthy text must be entered. To key 12 characters of data into a computer terminal takes approximately 6 sec on average and has a substitution error rate of 1 character in 300. Keyless data entry (bar coding, radio frequency identification, touch screens) of 12 characters typically takes less than 2 sec and has a substitution error rate as high as 1 character in 15,000 and as low as 1 in character in 36 trillion entered (*15*).

When keying in data, the percent of time data entered on the first try (first time success rate) will vary with the number of characters entered. The fewer the number of characters, the higher the first time success rate. With prompting and error checking, success rates by the second entry attempt will approach and may exceed 99 percent.

Although it is desirable that all maintenance workers be literate and able to write, the need to read and write in the field should be minimized. Data entry procedures should ideally require no extra reading or writing. Besides simplifying the data entry task, this would be advantageous where maintenance crews are of widely varying educational levels and countries of origin.

The data collection device should be rugged. It is not uncommon for field data collection equipment to be able to endure repeated drops of 5 to 6 ft onto concrete.

Such equipment should also be impervious to water, dirt, and dust. Waterproofing is desirable. For protection against humidity, electronic field equipment should have at least the following characteristics: operating—5 to 95 percent relative humidity at 104 F (40 C), nonoperating—90 percent relative humidity at 104 F (40 C), condensation—operates without damage and recovers within 15 min.

Field data devices need to withstand severe temperatures, sometimes both high and low extremes. A reasonable temperature range that permits storage in vehicles under most circumstances is −40 F to 137 F (−40 C to 75 C), and a reasonable operating temperature range is −4 F to 131 F (−20 C to 55 C).

Field devices also need to be usable at dusk and in the dark.

Data collection devices must function in varied traffic conditions. For example, the success in using voice recognition technology will depend partly on its ability to screen out background noise due to traffic. Data collection equipment should also work in a broad range of geographical conditions, including flat, rolling and mountainous terrain.

Another requirement is a suitable source of power to support field use. Battery life should be at least 8 hours, and batteries should be rechargeable using a recharger that fits in a cigarette lighter receptacle in a vehicle.

Although field data should be reported daily, the field device should be able to store enough data so that a week's worth of information can easily reside in the field device. Data storage capacity should allow for extenuating circumstances that cause the field manager to transfer data less frequently than each day. Generally, at least 8 kilobytes of random access memory (RAM) should be satisfactory, although 16 to 32 kilobytes of RAM is better. Field units that require software programming would benefit from having erasable programmable read only memory (EPROM) or electrically erasable programmable read only memory (EEPROM).

To aid in uploading the data to a host computer, the unit should have a simple means of directly transferring data, such as a RS232 port or docking device. A diskette or removable memory module is a workable means of data transfer, but may be susceptible to damage and dust. It is also desirable for it to have a built-in data modem. Another possibility is an acoustic coupler that attaches to a phone mouthpiece, although acoustic couplers are not always reliable.

Software necessary to operate the device should ideally be compatible with as many types of computers as possible. Therefore, MSDOS-compatible units are attractive. Many field devices use some variant of BASIC as a programming language. If a proprietary language is required, it should have simple utilities to aid programming.

Field devices, especially portable data entry terminals and computers, should be capable of prompting the user for the correct input data. The device should be programmable, so that it prompts the user to furnish a set of data in a specific sequence and according to specific conditions. It should provide verification of correct entry by making sure the data lie within proper bounds and offer other error checking procedures. The device should also provide audible and visual cues of correct entry.

**Table 2. Summary of requirements for field data collection devices.**

- Portable
- Light weight; less than 6 pounds
- Easy to hold and carry
- Avoids need for reading and writing
- Keyless data entry preferable to key entry
- Endures drops to concrete of at least 6 feet
- Humidity
  - operating: 5 to 95 percent relative humidity at 104 F (40 C)
  - non operating: 90% relative humidity at 104 F (40 C)
  - condensation: operates without damage and recovers in 15 minutes
- Temperature:
  Storage: -40 F to 137 F (-40 C to 75 C)
  Operating: -4 F to 131 F (-20 C to 55 C)
- Usable in dusk and dark
- Unaffected by noise
- Operates in different terrain
- Battery life
  - 8 hours minimum
  - Rechargeable in cigarette lighter adapter
- Memory
  - Minimum 8 kilobytes RAM, 16K to 32K desirable
  - Programmable
- Communications
  - Direct: RS232 port or removal memory modules
  - Telephone: Data modem and/or acoustic coupler
- Uses software utilities to ease programming
- Prompting for data entry
- Data entry cues (visible and/or audible)
- Error checking and data entry verification
- Attachable printer
  - portable
  - desk top printer
- Cost per device $400 to $2000
- Internal clock
- Provides a means for entering location data
  - Manual or automatic entry in field

Many maintenance field managers may wish to retain a paper copy of field data. It should be possible to connect the field device either to a portable printer in the field or to a printer in the office where the maintenance field workers start and end their days. A paper copy of field data may be important to maintain an audit trail and to protect against legal suits.

The cost of a data collection device should be in the range of $400 to $2,000, depending on its capabilities. The more flexible the equipment, both in terms of function and ability to perform in different environments, generally the more expensive it will be.

Data collection devices should include an internal clock to "date and time stamp" data. Ideally, a data input device should be able to connect another device that provides location reference points, such as longitude and latitude.

Table 2 summarizes the requirements of field data collection devices for maintenance field managers.

## INTEGRATED SYSTEMS

The work statement for this research project specified that consideration should be given to integrated but modular components to provide for incremental improvements and flexibility in meeting the needs of management systems. An integrated system would include a means to both collect data in the field and retrieve data from the maintenance management system.

To meet the test of practicality and technical feasibility, components of a data collection system should be commercially available.

Components should be plug-compatible or modules of a commercially available integrated unit. For example, one should be able to plug together a laptop, a fax modem, and a cellular

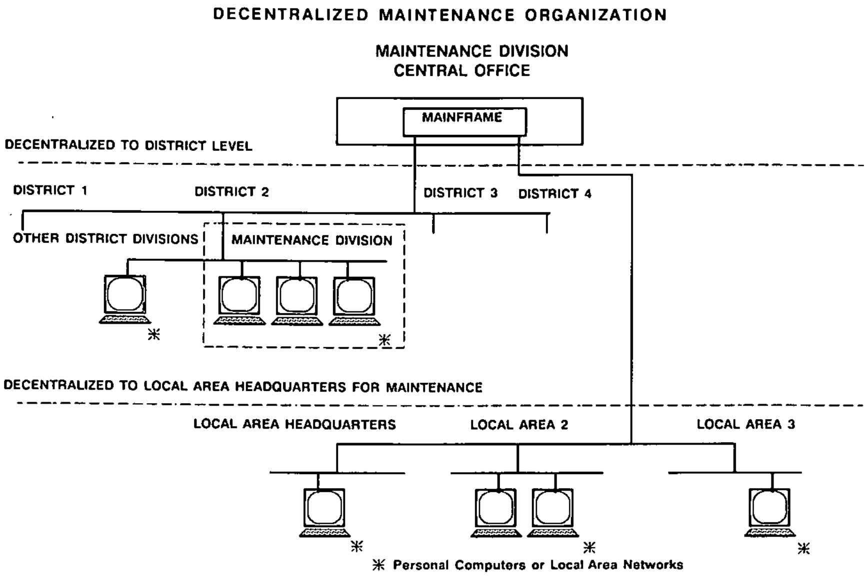



*Figure 1. Data processing in decentralized maintenance organizations.*

telephone, even though a maintenance field manager may wish to use these devices separately. Alternatively, some of these devices may be an integral part of an off-the-shelf unit, such as a "portable office."

Requirements should address the what, where, when, speed, frequency, accuracy, and reliability of data transmission. The type of data that needs transmitting will depend on the data collection activity; for instance, whether it is crew card data, equipment and material inventory data, or bridge inspection and maintenance data. Crew card data will consist of relatively short strings of characters and letters. Transmission requirements for this type of data will generally not exceed one kilobyte. However, if digital pictures of bridges are transmitted, the requirements could exceed 500 kilobytes of data for each picture, assuming a charged couple device (CCD) camera is used with a resolution of 200 × 250 pixels. Transmission speeds will be as low as 300 baud for older rural phone lines and up to 9600 baud for good circuits.

There should be provision for data flows between the field and the local area maintenance field office as well as the central office. Highway maintenance organizations at the state level are increasingly decentralized. Distributive data processing is widespread, and field data collection needs to link to local office terminals, whether they are directly on-line to the mainframe computer or part of a local area network (see Figure 1).

Currently, maintenance field managers furnish crew card data daily. However, depending on the agency, typically they require more than 1 day and up to 2 weeks to retrieve information from the maintenance management system. Most states are not able to offer turnaround of information in a day or less. Integrated systems for field data collection should be capable of providing field managers with information at least daily and ideally in real time. Retrieval of data should be possible from the nearest maintenance office, from home, in the field, or from a vehicle. At present, maintenance field managers do not have this capability.

Because, maintenance field managers are not accustomed to electronic transmission of data, such procedures should be simple to encourage acceptance. Unless the procedures are simple, the prevailing work culture may generate resistance.

Table 3 summarizes the requirements of integrated systems.

**Table 3. Summary of requirements for integrated systems and maintenance management.**

- Modular/plug compatible
- Commercially available modules
- Capable of two way data flow between field and office
- At least daily turnaround of input (real time is ideal)
- Retrieval of data feasible from:
  - office
  - home
  - public phone
  - vehicle or field
- Simple transmission procedures
- Automatically performs calculations

CHAPTER THREE

# FINDINGS—DATA COLLECTION DEVICES AND TELECOMMUNICATION OPTIONS

At the end of a long day, after filling out a daily work report, many maintenance field managers go home, sit down in a chair, pick up a technological marvel, and snap on the TV from across the room.

That familiar hand-held device that turns on a TV, changes the channel, and raises and lowers the volume, is not much different from the hand-held computers with radio transmitters that send inventory data to central processors in retail stores, warehouses, and manufacturing plants across the country.

The consumer electronic age has produced startling advances that people now take for granted. Similarly, there are a wide range of data acquisition technologies used in the retail, wholesale, and manufacturing sectors and telecommunications that can make it easier for maintenance field supervisors to report the work they have done, receive useful information, and strengthen maintenance management generally.

Yet today, field supervisors still fill out many different kinds of forms to provide data to the maintenance management system. Instead, they may just as well use a portable computer, an electronic tablet (clipboard) or some type of keyless data entry, for example, bar coding. Direct data entry from the field is more accurate. Field data entry can also reduce the need for clerks and timekeepers who frequently compile this type of information and free this type of personnel for more valuable purposes.

Not all of these technologies will work in every agency, environment, and application. However, the options are so numerous, that at least one approach will offer an agency significant cost savings in some aspect of maintenance management.

This chapter describes the technologies and telecommunications that have the most promise in improving the ease and accuracy of field data collection. Figure 2 lists the technologies described in this chapter and three important characteristics. The first is whether the data entry can be manual or automatic. The second is whether it affords error checking, and the third is whether it is suitable for providing feedback to the field. For example, a crew card requires manual data entry, generally no error checking, and no feedback; whereas, a hand-held computer with a bar-code reader permits manual or automatic (keyless) data entry, can check errors, and is able to receive information and, thus, provide feedback from the maintenance management system.

Figure 2 is also suggestive of interchangeable data collection and telecommunication systems. Different combinations of data collection devices, field data links, and local office communication tools can be combined into workable systems. The field data links include hand delivery, regular and electronic mail, direct wire links, special mobile radio, satellite, and cellular and regular telephones.

Office communication tools include a stand-alone facsimile machine and a computer terminal. Depending on the type of data collection device the field supervisors use, information may be communicated from a local office to the field through key entry, a data modem, a fax modem, or an optical scanner.

For example, if a field supervisor uses an electronic clipboard to collect maintenance data, an engineer in the office can send a picture of a maintenance problem to the field supervisor via fax modem. The photograph could be stored on an optical disk or in some other electronic medium. If the picture is not electronically

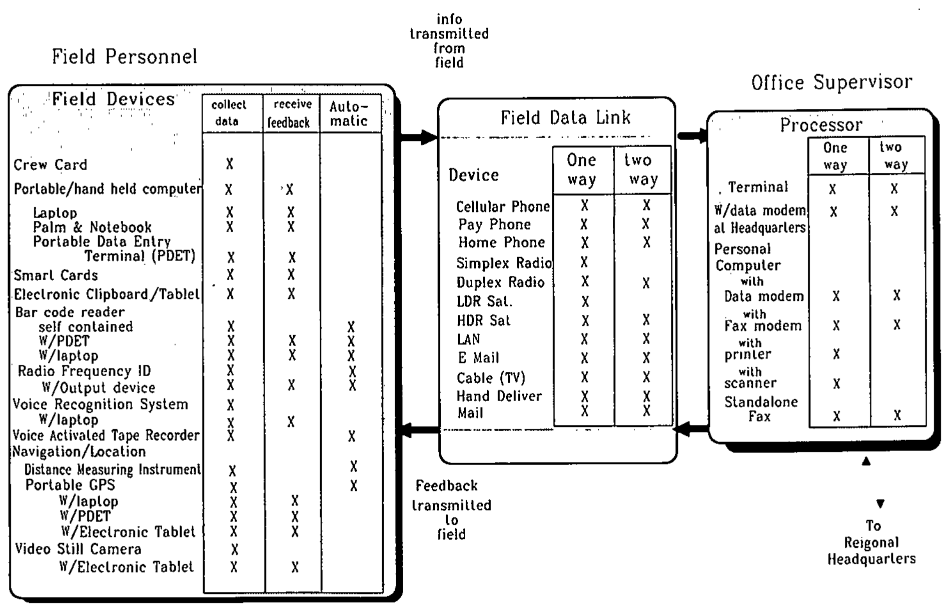



*Figure 2. Data acquisition matrix and processing options.*

stored, the person in the office can use an optical scanner to digitize a photograph, enter it into a computer, and then send it using a data modem. Still another possibility is to fax the picture, provided the electronic clipboard has a built-in fax modem to receive the photographic image or the field supervisor is carrying a plug-in fax modem.

## FEASIBILITY OF INTEGRATION

This study seeks to identify integrated but modular systems that permit easy data entry and feedback. The various technologies and telecommunications can fit within the generic system design in Figure 3. The reader should bear in mind this generic system design while considering the suitability of a particular data collection device or type of telecommunication for a particular data collection activity (e.g., crew card data collection or bridge inspection).

As stated earlier, the study concentrates on plug-compatible technologies that are already commercially available. Most of the technologies can be purchased as part of integrated "boxes" that are suitable for one or more maintenance data collection activities.

## PORTABLE DATA COLLECTION DEVICES AND TECHNOLOGIES

This section describes the technologies that offer maintenance field managers efficient data acquisition. Table 4 summarizes how different technologies satisfy the requirements. The technologies differ in their accuracy, error checking abilities, and ability to input and extract information from the maintenance management system. They also differ in the volume and scope of data they can handle. Some are best suited for collecting a limited set of information, for example, just the traditional crew card data. Others are more flexible and could be used to acquire a myriad of data.

The review of data collection devices presented here is a snapshot of technology at a particular time. New and improved devices for collecting field data are emerging at a rapid pace. Technically and economically feasible data collection technologies of tremendous variety are described regularly in trade publications and technical journals, and new product announcements occur monthly.

The technologies, described below, fall into the following categories: (1) portable and hand-held computers—laptops, palm-size and notebook-size computers, hand-held portable data entry terminals, and smart cards; (2) electronic clipboards; (3) keyless data entry—bar coding and radio frequency identification; (4) voice systems—voice recognition, voice-activated tape recorders, and voice synthesis; (5) distance measuring and navigational equipment—distance measuring instruments and satellite geographical positioning systems; (6) facsimile machines; and (7) miscellaneous equipment.

Before turning to the different types of technologies and telecommunications, it is worthwhile to carefully consider the advantages and disadvantages of paper forms, which are currently the nearly universal method for collecting maintenance data. All other data collection devices and communications need to be compared to current data acquisition technologies which involve paper.

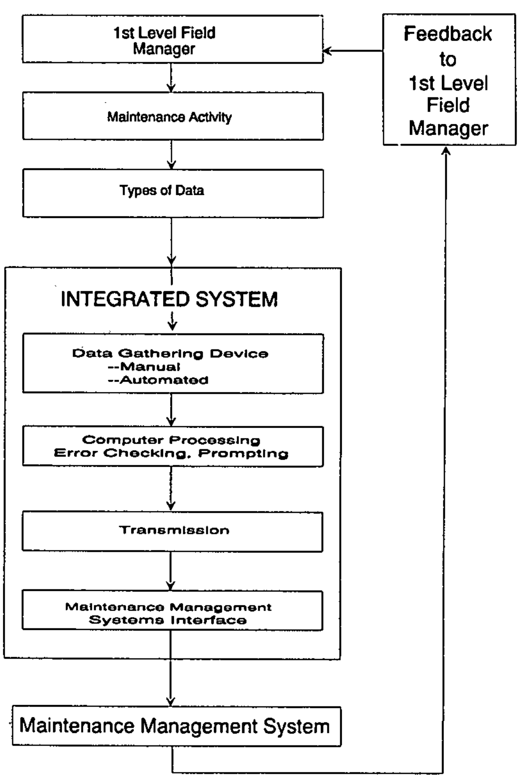



*Figure 3. Framework for a generic system.*

## PAPER DATA COLLECTION METHODS

Paper is a very friendly medium that people use every day. It comes in all sizes. Multiple sheets come in pads; single sheets affix to a clipboard. Paper is cheap. Once a form has been designed, the user can print it in large quantities. Forms with carbons are also available, so that one can make multiple copies and create an audit trail. Personnel can photocopy paper easily and send a copy by facsimile machine.

Paper is also a communications and storage medium. It can be carried or mailed, stored in stacks on a desk, filed in a cabinet or archived in storage boxes.

Data entry is easy using pen or pencil. By preprinting certain information, such as the crew expected to show up for work and time spent making handwritten entries, can be reduced. A well-designed paper form can include some provisions for error checking, for example, requiring the columns and rows of an allocation of labor hours to tasks to sum to an identical total. Users can correct errors by striking out or erasing information and rewriting it.

Some paper forms are quite durable, such as the heavy crew cards used by such agencies as the Maryland Department of Transportation. These cards do not bend as easily as notebook paper and are more resistant to moisture and dust. In practice, paper proves to be quite durable rather than destructible. Even if folded, creased, or crumbled, paper can be straightened out, and the information on it will usually be legible. Paper is also convenient to carry and handle. It is light and fits in a pocket or thin folder.

Table 4. Ability of data acquisition technologies to satisfy requirements.

| Requirements of Field Devices | Laptops | Palm Notebook Computers | Handheld Computer (PDET) | Electronic Tablet (Clipboard) | Bar Code Scanners | Radio Freq. I.D. | Voice Recg. | Voice Tape Recorder | Dist. Meas. Instr. | Portable GPS | Portable FAX |
|---|---|---|---|---|---|---|---|---|---|---|---|
| • Portable | x | x | x | x | s | | x | x | | x | x |
| • Light weight; less than 6 pounds | x | x | x | x | s | | x | | | x | x |
| • Easy to hold and carry | x | x | x | x | s | | x | x | | x | x |
| • Avoids need for reading and writing | | | s | s | x | x | x | | | x | |
| • Keyless, data entry preferred | | | | s | x | x | | | | | |
| • Endures 6 drops to concrete | r | r | r | r | s | | r | | | | |
| • Waterproof, moisture resistant | r | r | r | r | s | x | r | r | x | x | x |
| • Temperature: | | | | | | | | | | | |
| Storage: -40 F to 137 F | r | r | r | r | r | x | r | r | x | x | r |
| Operating: -4 F to 131 F | r | r | r | r | s | x | r | r | x | x | r |
| • Usable in dusk and dark | x | x | x | x | | x | x | x | x | x | w/light |
| • Unaffected by noise | x | x | x | x | x | x | s | x | x | x | x |
| • Operates in different terrain | x | x | x | x | x | x | x | x | x | | x |
| • Battery life | | | | | | | | | | | |
| - 8 hours minimum | x | x | x | x | s | | x | x | | x | x |
| - Rechargeable in cig. lighter | x | s | s | x | s | | | | | | |
| • Memory | | | | | | | | | | | |
| - Minimum 16K | x | x | x | x | s | s | x | | x | s | |
| - Programmable memory | | | | | | | | | | | |
| • Communications | | | | | | | | | | | |
| - Direct: RS232 or removable memory | x | x | x | x | s | | x | | x | x | |
| - Telephone: Data modem and/or acoustic coupler | x | x | | s | | | | | | | |
| • Software utilities to ease programming | x | x | x | x | x | | x | | | | |
| • Prompting for data entry | x | x | x | x | s | | x | | | | |
| • Data entry verification cues (visable and/or audible) | x | x | x | x | x | | x | | | | |
| • Error checking | x | x | x | x | s | | x | | x | | |
| • Attachable printer | | | | | | | | | | | |
| - portable | x | x | x | x | s | | | | x | | bulletin |
| - desk top printer | x | x | x | x | x | x | x | | x | x | |
| • Cost per device $400 to $2000 | x | x | x | x | x | | | | x | x | x |
| • Internal clock | x | x | x | x | s | | | x | x | x | x |
| • Provides a means for entering location | | | | | | | | | | | |
| - Manual or automatic entry in field | x | x | x | x | x | | x | | x | x | |

**x = widely available**
**s = some modes of operation; some models**
**r = ruggedized equipment**

*Figure 4. Laptop computer.*

A major disadvantage of paper is that not only must a maintenance field manager record data, but also that person or a clerk or timekeeper, usually, has to transcribe it and perhaps perform additional calculations. In contrast, direct entry into a computer saves time, avoids transcription errors, and speeds calculations.

Physical storage requirements are vastly reduced when paper use is cut drastically. Once information is stored electronically, many users can retrieve it immediately if the data base management system has a responsive user interface. Paper is not ideal for entering or extracting data from a maintenance management system, whereas transmission of data to and from a computer data base can provide virtually instantaneous entry and retrieval.

Paper forms have minimal potential for automated error checking, whereas a computer can check to ensure entries are from the allowable set of possibilities.

## PORTABLE AND HAND-HELD COMPUTERS

### Laptop Computers

Transportation agencies have used portable laptop computers (Figure 4) for a wide variety of purposes including construction management, bridge inspection, collecting pavement condition and distress data, and establishing and updating roadway feature inventory data. The California Department of Transportation (Caltrans) is furnishing laptops to more than 600 maintenance personnel to enhance data entry procedures for its maintenance management system. Maintenance field supervisors will be able to enter crew card data, time and attendance information, and obtain and record other types of information.

Laptop computers are versatile, lightweight (5 to 15 lb), compact, and powerful and can perform almost any function that can be operative on desktop personal computers. The versatility of laptops means that a maintenance field manager can not only enter data but also use the laptop for word processing (notes, memos, and reports), spreadsheets, and other purposes depending on the software used.

Data are stored internally on random access memory (RAM), 3.5-in. floppy disks, or, in many models, on hard disks. Data are usually transferred to a host computer by disk, although direct transfer by telephone and modem is not uncommon.

A computer programmer must design the layout of the data entry forms which appears on the display screens. Most data entry software allows the user to select a data entry screen from a menu. The software can prompt the user through data entry tasks or allow the user to enter data at will. The software should check for errors and missing information. Programmers can also design data entry screens readable in more than one language, for example, Spanish in addition to English. Data entry software normally is developed on another computer, compiled, and then loaded into the laptop.

Laptops have ports for plugging in peripherals such as modems, portable printers, bar-code readers, and optical scanners. Some laptops have internal fax modems for transmitting and receiving facsimile copies. Many laptops permit one to plug in expansion boards, although an expansion chassis may be required to accommodate them, which adds several pounds of weight to the unit. Expansion boards exist for highly specialized functions, voice recognition, for example. Thus, in principle, a single laptop with expansion chassis, or a heavier portable personal computer, can support a wide variety of functions including key data entry, bar-code scanning, facsimile transmission, and voice recognition.

An important advantage of laptops is that they can be used to collect and to retrieve information and to display it in an easy-to-read fashion. Daily crew assignments can be transmitted to laptops electronically. Laptops can also provide maintenance supervisors with direct access to the maintenance management system data base, including budget balances, equipment availability and status, urgent repair needs, and productivity measures. Alternatively, a maintenance manager, before going out into the field, can download a data file stored in a mainframe or personal computer into a laptop and display it later.

A drawback of laptops is that they require two hands to use and a reasonably stable place to set the computer. Laptops require some dexterity and the ability to at least "hunt and peck," if not type, to enter data. Some maintenance crew leaders may find the keys too small for comfortable use.

Display screens of many laptops are more readable in the dark than paper forms. Screens are normally encased in pop-up tops. Plasma or back-lit liquid crystal display (LCD) screens are easier to read in the dark than a simple LCD screen, but plasma screens require more power and, consequently, reduce battery life. Many laptop manufacturers use less readable liquid crystal display screens to lengthen the time a battery can be used without recharging and to reduce cost. Light emitting diodes (LED's) are occasionally used for single line displays but have poor resolution.

The battery life of most laptops is in the 8 to 12-hour range without a hard disk and 2 to 4 hours with one. If the battery runs out, the data in random access memory will be gone. If the main battery is backed up by a second battery, the user gets another chance. To eliminate the possibility of total battery discharge, a maintenance field manager can carry an extra one or recharge the battery through a cigarette lighter adapter.

Laptops are available in hardened weather resistant cases, but most commercially available laptops will only withstand so much abuse and exposure to severe weather conditions. The normal operating temperature range is from roughly 9 F to 105 F (5 C to 35 C) and storage temperature in the range from −4F to 149 F (−20C to 65 C). Dust and dirt will eventually damage laptops if they are unprotected. Laptops work well under good weather conditions, and in unsuitable weather, one can operate them inside a vehicle. Maintenance field managers must use common sense in caring for laptops and the data in them to assure reliable operation. Data need to be backed up regularly, an extra battery should be carried, and the laptop should not be stored in an excessively hot or cold vehicle or exposed to rain or very dusty conditions.

Even with these features, maintenance field managers will have mixed reactions to laptops. Personnel accustomed to paper crew cards and traditional ways of reporting data may be resistant to laptops. Laptops will prove intimidating to many who have no prior exposure to computers. Two days of training, assuming menu-driven applications, or encouraging a maintenance person to become familiar and comfortable with it at home will normally overcome most resistance.

States have increasing expectations of their field managers, and more and more field managers readily accept innovations including data entry using laptops. Indeed, many organizations are fostering a receptive attitude toward trying new and better ways of working and the field supervisors are responding accordingly.

*Figure 5. Notebook size portable computer.*

### Palm-Size and Notebook-Size Computers

The inexorable trend toward smaller and smaller electronic products has resulted in the recent introduction of notebook- and palm-size computers. Palm-size computers were not intended for outdoor field use, but for the business traveler. They are more suitable for recording brief notes, maintaining a phone or address directory, keeping track of appointments, and providing profiles on prospective clients. They were not designed for rugged, outdoor environments, but they might actually prove workable for maintenance data collection, especially if they were made more rugged. Their low cost relative to laptops ($300 to $600 versus $1,000 to $5,000) recommends their further consideration.

As the name implies, palm-size computers are much easier to carry and hold, because they are about the size of a large hand. Notebook computers are a little larger. They are suitable for simple data entry tasks, one finger at a time, but with practice and skill can be used for word processing. The smaller size of their keyboards makes typing a little challenging. Their screens are smaller and generally less legible than laptops. A few high-performance notebook-size computers are quite versatile and can even accommodate bar-code scanners. Figure 5 shows one such notebook-size portable computer (dimensions 9 in. × 5 in. × 3 in). Manufacturers of palm- and notebook-size computers try to provide the same basic functions that a laptop offers but more portability at much lower cost. Thus, many palm- and notebook-size computers are programmable, have removable memory cards, and permit downloading and uploading data.

### Hand-Held Portable Data Entry Terminals

Portable data entry terminals (PDET), used in a number of manufacturing, wholesale and retail applications, are a different breed of hand-held computers. These types of portables are widely used for inventory management and control. They are employed in forestry, warehousing, and grocery stores for stocktaking. These hand-helds thus have direct applicability for material and equipment inventory in highway maintenance yards and warehouses, and can also be used for field data collection.

Many PDETs fit in one hand, weigh 1 to 2 lb, have an alphanumeric keypad, a display, function keys, and ports for downloading and uploading data as well as plugging in peripherals such as printers, modems, and bar-code scanners. In fact, many PDETs have built-in bar-code scanners and/or modems. Some are rugged, hermetically sealed against dust and moisture, and can withstand operating and storage temperatures that equal or exceed the most environmentally rugged laptops. Costs vary from around $300 per hand-held unit to several thousand dollars, depending on the specific capabilities. Figure 6 shows a waterproof hand-held terminal immersed in water.

Many of these hand-held units use proprietary software, often some version of BASIC. Software utilities are available to speed programming. Many portables are also MSDOS-compatible and can easily transmit data to and from a host personal computer or upload further to a mainframe. Portables may use removable memory, a direct link, data modem (Figure 7), an acoustic coupler (Figure 8), or a docking device to transfer data (Figure 9). Some portables have a radio transmitter that will send data to a host computer within a reasonable range (generally one mile or less) (Figure 10).

PDETs appear suitable for reporting basic crew card information. As long as the types and quantity of data entry are focused and limited, these hand-held units are a practical data entry device. A suitable application would be crew card data collection involving the maintenance activity, recording of accomplishments, and labor, equipment, and material used. If written text or more extensive data are required, including time and attendance information, a laptop may be more practical. Most PDETs have internal clocks that can stamp data with the date and time. Locational data may be entered manually or automatically via locational or navigational equipment. Scanning bar codes on a paper map, linear roadway inventory log, or even on signs, mileposts and bridges is another way to gather location information.


*Figure 6. Waterproof portable data entry terminal.*

*Figure 8. PDET with acoustic coupler.*

*Figure 7. Built-in data modem.*

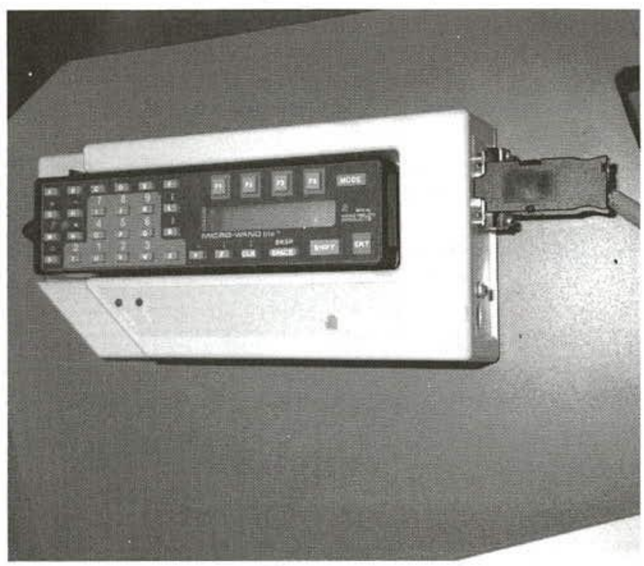


*Figure 9. Docking device for hand-held portable terminal with integrated bar code scanner.*

Maintenance field supervisors can also use PDETs to obtain feedback, provided they have a convenient telecommunications link such as a built-in modem and a display large enough to communicate pertinent information.

In sum, many PDETs are practical, integrated units able to perform many functions of interest to maintenance field supervisors. They can also be used as an integrating device through their plug-in capabilities.

#### Smart Cards

Smart cards look like credit cards, but contain integrated circuitry. Manufactured for specific functions, smart cards vary in their capabilities. Some simply store transactions and others are virtual hand-held computers.

The most common type is a debit card such as those used in France to make public telephone calls. Credit for future calls is stored on the card. The smart card is inserted into a payphone to make a call. Upon completion, the balance on the card is reduced by the cost of the call. Debit cards have been used in experiments to enable welfare clients to receive benefits from automatic teller machines (ATM), and to enable sailors in the navy to receive paychecks on shipboard ATMs (*16*).

One possible use of a smart card is to record equipment maintenance history and to upload that information to a host computer. A highway agency might require that a smart card be kept in the glove compartment of every vehicle or attached to each piece of heavy equipment. Every maintenance event would be electronically recorded on the smart card along with what was done. Inputting and outputting data would be accomplished by a separate device. Periodically the information would be transferred to the main computer.

A prototype super smart card—a credit-card-sized computer—has recently been developed which has a data entry keypad, liquid crystal display, a 3-V paper-thin lithium battery, and metal contacts for data transfer by an external device. Large-scale integrated circuits on a single chip provide the super smart card its "intelligence." The single chip contains an 8-bit central processing unit, 16 k bytes of programmable read only memory (PROM), and 8 k bytes of random access memory (RAM). The card bends 20 mm lengthwise without harm and withstands repeated impacts from mechanical imprinters used for credit cards. This super smart card was designed to be a portable electronic bank into which a person could deposit cash from an issuing institution and from which one can withdraw funds for retail purchases (*16*).

A similar smart card could be customized and manufactured for crew card data collection. But manufacturing smart cards for the maintenance field supervisor of one state probably would not yield sufficient economies of scale to be cost effective at the present time. Only if a number of states were to jointly buy enough smart cards would they become cheap enough per unit to warrant their use. During the next 5 to 10 years the market will drive the development and application technology so that, in all probability, a suitable smart card will be available to maintenance managers at low cost.

Smart cards are most advantageous in situations where it is desirable to store transaction information outside an organization's data processing and storage system. A data collection system that does not have an umbilical cord connected to the mainframe computer might enhance acceptance by field supervisors who, on the one hand, must report accomplishments daily and, on the other hand, relish their independence.

*Figure 10. Portable terminal with radio transmitter.*

There is also a danger that a person may lose a smart card and all the data stored on it. Smart cards will be a reliable way to collect road maintenance data only if there are rigorous procedures to ensure that the data stored on them are uploaded frequently enough to protect against unrecoverable loss. This problem is not unique to smart cards. If any portable computer containing important information were lost, the data might not be recoverable.

Despite its convenient carrying size—it fits easily in a wallet—some maintenance field managers may find a smart card's keypad awkwardly small and data entry procedures complicated if the keypad has only numeric keys, a limitation of the prototype mentioned above.

### ELECTRONIC CLIPBOARDS AND DATA ENTRY TABLETS

Manufacturers have been introducing electronic clipboards and tablets in order to help businesses and governments reduce paperwork and eliminate storage of paper records. Maintenance field managers are accustomed to filling out forms mounted on a clipboard. An electronic clipboard or tablet is similar, but it offers innovative ways to enter data.

*Figure 11. Electronic tablet (clipboard).*

One electronic clipboard looks like a regular clipboard tablet and the user writes on a paper form laid over a digitizing tablet to enter data. Another clipboard, a full function computer, looks like an etch-a-sketch toy and has an electronic pen attached which is also a bar code wand (Figure 11).

A typical electronic tablet allows one to enter data by writing in block letters in spaces programmed to receive the information. A pattern recognition algorithm figures out the letter or number written. Initially it may take a person an hour or two of experimentation writing, so that the electronic clipboard will recognize most of the information the first or second try. The clipboard immediately displays the entry, as it is understood. If the entry is wrong, one strikes it out and rewrites it. The internal computer can be preprogrammed to check for omissions and to ensure that each entry is in proper range. It can also be programmed to receive data in a specific order. The electronic clipboard shown in Figure 11 has many features that are designed to reduce handwriting errors.

For example, the clipboard can be programmed to require an answer to be picked from a list of options. To make a selection, one touches the pen tip to the appropriate option displayed on the screen.

Options can be represented by icons instead of a list of written alternatives. As an example, if one had to record equipment use, the clipboard might display icons representing a pickup, backhoe, compactor, and so on. For each piece of equipment used, one touches the pen to the appropriate picture.

A calculator pad can be displayed by touching the pen to a preprogrammed spot on the screen. Numbers are entered by touching the pen to each of the keys on the pad instead of writing them in.

The screen can display a full function QWERTY keyboard that can be used for data entry, again using the tip of the pen. The computer, if programmed accordingly, will provide a default selection.

This electronic clipboard can be preprogrammed to display easily understood data entry forms. The software programmer can reserve space on each form for drawings and for a signature that is stored electronically. A field supervisor can sign off, make written supplementary notes or comments concerning a data item, or annotate a data entry with a drawing.

This electronic clipboard has a built-in modem for telecommunications, memory cards, ports for a printer, a bar code wand, and other peripherals. Plugging a regular keyboard into it will turn it into a laptop computer.

There are both positive and negative ergonomic features of these devices. The clipboard with the full function computer has a feature to facilitate left-handed or right-handed use. The orientation of information on the display screen can be changed to fit right-handed or left-handed people without changing the orientation of the clipboard itself. A person can hold or support an electronic clipboard with one hand and write with the other. Clipboards weigh between 3 and 5 lb, the heavier ones being more tiring to hold for a long time. An electronic pen is just as easy to hold and use as any other pen. In some ways, it is easier, because the tip has only to be tapped against a part of the screen to enter data.

Electronic clipboards vary in their ruggedness and resistance to moisture, dirt, dust, and extreme temperature variations. The most lightweight models seem more appropriate for indoor use. Other models are suitable in temperate outdoor conditions, and extremely durable units do exist for military use in stressful field conditions.

Costs of electronic clipboards vary with their capabilities and ruggedness. The cost range is currently about $1,500 to $4,000—more for specially encased models. Costs should drop considerably over the next 5 years.

During this research project the full-functioned electronic clipboard was demonstrated to maintenance field supervisors. It was programmed to receive some of the data normally collected on crew cards and on bridge inspection forms. Each maintenance field supervisor was given some hands-on experience. Some maintenance managers were very favorably impressed, others moderately so, and one felt it was not suited for maintenance field data collection.

Electronic clipboards appear to be a promising data entry device, with usefulness and practicality comparable to laptops, but with different advantages and disadvantages. Among the greatest advantage of the one that was demonstrated is the ability to enter data by simply tapping the screen with the pen and the ability to draw on the clipboard. This type of clipboard may be well suited for bridge inspection.

Another advantage of this clipboard is that an optical scanner can be used to read in a map and display it on the screen, as occurred during the demonstration. Location information can be entered by tapping the pen against the appropriate spot on the map.

Electronic clipboards do contain digitizing tablets. Digiting tablets solely intended for data entry are also commercially available and are being used in roadway feature inventory data collection. A template with an icon for each type of feature is laid over the tablet. When passing a particular feature, a person in a van taps the appropriate icon (*17*). A number of local governments in New Hampshire have also been using a digitizing tablet attached to both a laptop and distance measuring instrument to collect pavement condition and distress data (*18*).

## KEYLESS DATA ENTRY

### Bar Coding

Today, everyone has some exposure to bar coding. Virtually every product sold in supermarkets is marked with a universal product code. The Department of Defense requires contractors to put bar codes on all items, the U.S. General Services Administration requires bar codes on all deliveries to supply depots, and the automotive industry has a similar requirement. These and other industries use bar coding extensively for inventory management and control. Commercial enterprises also use bar coding for document tracking, including express mail, keeping abreast of work in progress, and recording time and attendance. A curious fact about bar codes is that they were imprinted on millions of products around the world long before the world was ready to use them. Industry experts have called them the most significant data entry device since the advent of computers.

What are bar codes and how do they work? A bar code uses lines of varying width and the spaces between them (also of varying width) to give a visual representation to 1's and 0's, the binary language of computers.

In a bar code, a narrow line (the bar) may represent the binary digit 1, while a wide bar (or sometimes a white space between the bars) may represent the binary digit 0. Groups or patterns of bars and spaces, constituting the 1 and 0 numerical vocabulary of computers, represent numbers and letters.

Bar coding is attractive for data collection because it is proven, quick, easy to use, often relatively low cost, and applied in wide variety of indoor and outdoor environments. As stated earlier, a maintenance field supervisor can expect to read a bar code correctly on the first pass at least 85 percent of the time, and obtain a successful read on the second pass 99 percent of the time. Bar code substitution error rates (switching one character for another) are less than 1 mistake in 15,000 to 36 trillion characters entered (*15*).

A bar code label can be put on nearly anything, from vehicles to hardhats to bridges. Odd lots of small items can be weighed using electronic scales, put in plastic bags, and marked with a bar code label. Preprinted, pressure sensitive adhesive labels are commercially available in paper, plastic, anodized aluminum, and other materials. Some are highly resistant to weather, tampering, and wear and tear. Bar code labels properly selected to fit the environment in which they are used can last 3 to 20 years.

Metal labels can be nailed or screwed onto posts, and bar codes can be engraved into metal. Wide or narrow reflective tape can be applied to a sign or pole to create the pattern of bars that are readable by a bar-code scanner at some distance. Dust, dirt, or snow can inhibit scanning, but bar codes with laminates (vinyl, mylar, polyester, or other polymers) are also available and easy to clean. Even if a bar code is not readable by a scanner, the bar code number (printed below the bar code) can be entered using a paper keyboard (Figure 12) or by entering the number into a computer manually.

Bar codes can be printed or manufactured serially (numbered sequentially forwards or backwards) or they can be generated on demand—one prints the labels as they are needed. Printers of varying sizes and portability exist. Some are industrial purpose printers that are fixed in place. Others rest on a desk top. Still others are hand-held portable printers.

While the universal product code, for point of sale transactions in supermarkets, is most familiar to the public, other codes have widespread use. The Plessey code is used for grocery store shelf markings. Code 3 of 9 (also known as Code 39) is a common code for industrial and commercial applications. Code 2 of 5 (or Interleaved 2 of 5) is widely used in warehouse inventory handling, airline ticketing, and baggage and cargo handling. There are literally dozens of different bar codes, many designed for specific applications. Each has its own advantages and disadvantages. In general, desirable features of bar codes include a self-checking code and readability from right-to-left and left-to-right. Hand-held devices exist for checking the readability of different types of bar codes (*19*).

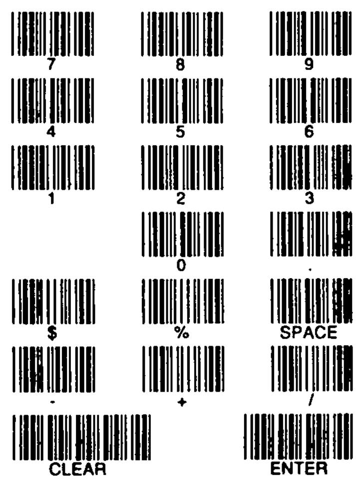



*Figure 12. Bar code keypad.*

There are two basic types of bar-code scanners, contact and noncontact. A contact scanner directly touches or nearly touches the bar code as it is being read. A noncontact scanner reads a bar code, generally in the distance range of 0.25 to 24 in., depending on the scanner. There are, however, scanners with special optics that permit reading at up to 15 ft and have potential applicability to reading bar codes on roadside features. The cost of the scanners and applying and maintaining labels may preclude this practice.

Contact wands come in a variety of forms including pens, a thick credit card, or tips that are an integral part of a hand-held computer terminal. Noncontact wands are often found in the shape of a gun, many of which are ergonomically designed—easy to hold and handle.

Scanners can be plugged into an RS232 port of computer terminal or inserted into an "RS232 wedge" between a regular keyboard and a desk top terminal. Scanners may also be part of a hand-held portable whose information is downloaded periodically, or part of a hand-held terminal with a radio frequency link to a host computer.

Bar-code readers should provide both audible and visual cues of a successful scan. Scanners usually beep and most noncontact scanners emit a beam which aids the user. Many bar code readers incorporated into portable terminals have light emitting diode (LED) or liquid crystal displays (LCD) which inform the user of the data being entered, errors, or other prompts. These two types of displays have different advantages in outdoor conditions. Compared to the LCD, the LED is easier to read in the dark, is harder to read in bright sunlight, wears out a battery-powered scanner sooner, but is less sensitive to temperature changes.

Bar-code scanners that have a keypad are desirable because

*Figure 13. Credit card sized bar code scanner with keypad.*

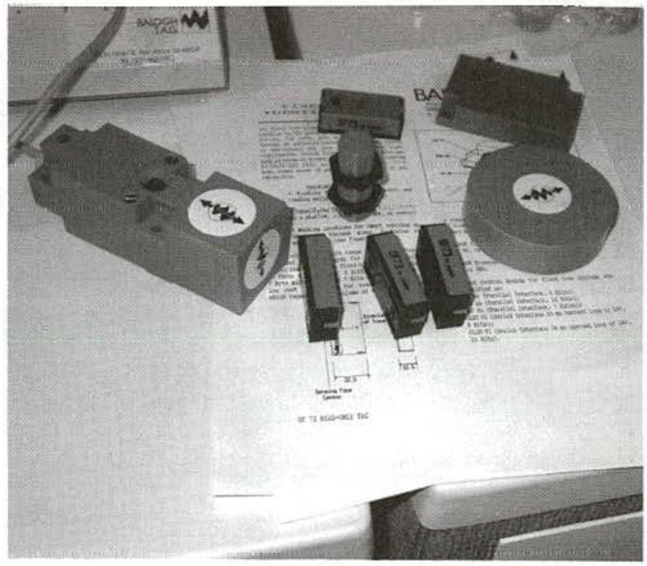


*Figure 14. Radio frequency identification tags.*

the keypad provides another way to enter data if the bar code is unreadable. One battery powered, programmable wand that costs under $500 per unit is the size of a credit card 5/16 in. thick and has a numeric data input keypad with special function keys, a display, a built-in clock, and enough memory to scan several thousand bar codes before data must be loaded into a host computer (Figure 13).

The keys in smaller devices, such as these, may pose some difficulty in entering data if maintenance field workers are wearing gloves, have large hands, or are unaccustomed to small accurate finger movements. The desire for simplicity, ease of use, and low cost may recommend a scanner without keypad. Alternatively, a portable terminal with large "chicklet" size keys can facilitate data entry.

Bar-code scanners vary in ruggedness. Some are practical for field use and are designed to withstand considerable impact, to resist water, and to endure temperature variations comparable to the most environmentally resistant laptops or hand-held computers. Under extreme weather conditions, a maintenance field supervisor can restrict use to inside a vehicle.

Some portable data entry terminals with scanners have an attachable or built-in modem for telephone data transfer, and some terminals have a small plug-in printer.

Field supervisors can be trained in about 10 min. to successfully scan bar codes. However, more complicated protocols suitable for collecting crew card data, taking equipment inventory, and so forth, would require more extensive training, perhaps on the order of a half day.

Of all the approaches to data collection that were examined, bar coding appears to be the most reliable for inventory management and control. Its applicability to field use for such purposes as crew card data collection is more problematic and requires a thoughtful implementation tailored to specific operating environments and agencies. It may be possible to place bar codes on roadway features, which can facilitate updating of selected roadway feature inventory data. For example, bar coding may have some applicability to bridge inspection and maintenance. A maintenance field manager or bridge inspector scanning a bar code affixed to a bridge would be able to identify its location and provide a positive electronic record of having visited the site on a certain date and time, assuming the scanner has a built-in calendar and clock.

Bar coding is an ideal tool for tracking work in progress by using a simple menu. For example, a menu can be designed showing a series of bar codes printed next to a sequence of steps that may be performed in bridge deck repair. Upon completing each step, the field supervisor can scan the bar code representing its accomplishment. Bar codes can also be used to ensure that work takes place in a prescribed sequence of steps. A hand-held computer with built-in scanner can be programmed to read bar codes in a certain order. If the bar codes are read out of order, the computer will prompt the user to return to the missed step.

In the equipment demonstration conducted during this project, vendors demonstrated a wide variety of bar-code scanners. Also demonstrated were the use of a dummy bar code menu for collecting crew card information (see Chapter Four) and inventory data collection software on a microcomputer system. There was a strong favorable reaction of maintenance field supervisors and higher level maintenance managers to bar coding. Maintenance personnel perceived bar code scanners as easy to use, hold, and carry in addition to being environmentally resistant and requiring no reading or writing.

#### Radio Frequency Identification

Radio frequency identification (RF/ID) technology is often suitable in severe environments where bar coding will not work well. RF/ID tags are affixed to items on which one might otherwise put a bar code. The tags are encased to keep out moisture, dust, and dirt. They come in various sizes and shapes, for example, a cylinder an inch or two in diameter or a rectangular box half the size of a wallet (Figure 14). They are attached with adhesives, bolts or nails, depending on the nature of the tag. RF tags are fairly tamper resistant, but not totally immune to vandalism. Although RF tags are not currently cost effective for extensive use, they could be placed on mileposts, traffic signals, or perhaps even in the pavement, and could be read from a moving vehicle containing an antenna and transceiver.

An RF/ID system is a three part system: a transponder, an antenna, and a transceiver, i.e. transmitter/receiver. A recent highway application is automatic toll collection. The transceiver and antenna can be located in the toll collection facility, and drivers can obtain monthly toll passes in the form of RF tags that are placed on the vehicle. The RF tag can be credited or debited like a smart card. Automatic toll identification systems hold the promise of significant reduction in congestion at toll plazas because vehicles will not have to pay for tolls. An application relevant to maintenance management is to use RF/ID to automatically identify a vehicle and trigger entry to a maintenance yard.

Some RF/ID systems use low frequency radio signals and others high frequency. The former employ low frequency inductive-coupling that operates through most nonconducting materials and thus works in many very difficult or harsh environments. Low frequency systems generally have short upper reading ranges that typically vary from 18 in. to 3 ft, although 15 ft is feasible. A high frequency system may have a range from 30 ft to 150 ft, depending on the efficiency of the antenna. With the ability to read a tag on a bridge, pole, or milepost along the road, this technology has potential applicability to both highway maintenance inventory management and roadway feature inventory updating. However, high frequency microwave transmissions necessary to reach longer distances can be a health hazard (*19*, pp. 145–154).

Radio frequency tags can be further classified in two other ways: (1) active and (2) passive. An active RF tag contains a battery, a transmitter, receiver, internal memory, and integrated circuitry. The tag rests in a quiet state until a radio frequency field from an interrogator (transceiver) intercepts and energizes it. Once the tag receives the trigger signal, it sends the information stored in its memory (*19*, p. 147).

Many manufacturers assert an active tag with a lithium battery will work for up to 10 years or approximately 4 to 5 million read and write operations. A passive system contains no batteries and relies on the power it gets from the interrogator (*19*, p. 147).

Tags can also be grouped into "read only" and "read and write." A passive, read only tag operates much like a bar code. When interrogated, it furnishes its preprogrammed uniquely coded number and other predetermined information. Data tags with "read and write" capability can be updated over the radio frequency link.

RF/ID tags currently cost nearly $20.00 apiece, although in large volumes numbering in the millions, the costs can drop to around $2.00. RF/ID tags are much more expensive than bar code labels, which can cost less than a cent per label for indoor applications and as little as 10 cents for durable outdoor labels.

RF/ID is not the same as radio frequency communication links, which are often used in conjunction with portable data entry terminals. Radio frequency links are discussed further in the section on "Telecommunications."

## VOICE SYSTEMS

### Voice Recognition

Voice recognition technology is advancing so quickly that moderate or low cost voice data entry systems are likely to be available by the mid-1990s. Already reasonably practical, but rather high cost, portable units ($8,000) are available for such purposes as construction inspection. These portable units may potentially be used for material and equipment inventory management and control and for certain highway maintenance data collection purposes, such as roadway feature inventory updating and bridge inspection and maintenance tracking.

Voice recognition systems can understand a preprogrammed vocabulary. Vocabularies of systems may range from 50 to thousands of words, but the costs increase with vocabulary size. For many highway maintenance data collection tasks, a simple system that recognizes 50 to 200 words may be more than sufficient.

Recognition of a word occurs when the digitized signals representing a word fit an electronic template with prescribed accuracy.

A person can enter voice data the first try about 98 percent of the time, and the rest with some repetition. The voice unit will repeat back to the user the data entered to avoid substitution errors. If there is an error, the user can say something like "strike" or "correction," and reenter the data.

Simple voice recognition systems are programmed to receive data in a certain sequence. The system asks the user for each piece of data. The user may enter by voice any one of a predetermined list of responses for each piece of data. Logical operators ("and," "or," and "if. .then" statements) determine the next data item requiring entry. For example, the voice recognition system may first ask the user to enter the labor used for a maintenance activity. Next, if the machine does not recognize the name, it may ask if the person is a new employee, and if so, to enter the employee number.

There are two basic types of voice recognition systems. The first is called "speaker independent" and the second "speaker dependent." A speaker independent system will recognize and correctly understand the speech of any person. A speaker dependent system correctly interprets the speech of just the person it is trained to understand. Speaker independent systems may be too expensive for field use, although one can install a speaker independent system in a central office and provide field links for data entry.

A "speaker dependent" system applicable to road maintenance can be trained to recognize a single voice with roughly one hour of training the machine. If a speaker's intonation or pitch changes considerably for some reason, the machine will need to be retrained to recognize selected words or the whole vocabulary, although voice systems can be quite robust in their ability to recognize words.

Before using the machine in a particular environment, the user must speak a few words into the system so that it will adjust and screen out background noise. Speech recognition systems will work in noisy environments, such as factory assembly lines and construction sites, provided the noise is not too unpredictable and upsets the calibration.

The main advantage of voice recognition over other types of data collection technology is that it leaves one's hands free for other work. There is no need to key in or scan data with a handheld device.

Even so, maintenance field supervisors may find these systems an encumbrance. The field supervisor has to wear a headset that has earphones and a microphone (Figure 15). A wire connects the headset to the voice recognition unit which attaches to a waistbelt if it is a fully portable system. The waistbelt also carries

*Figure 15. Voice recognition system.*

a battery pack that provides 8 or more hours of operating power and may support a radio transmitter. The headset, voice unit, and battery pack together may weigh around 5 lb. In the demonstration conducted for this project no field manager felt interested enough to try the voice recognition system.

A typical voice recognition system is not as rugged as some data collection devices that were examined, although it has enough impact resistance to be useful for entering roadway feature inventory data on foot or from inside a truck. A voice recognition system can be made impervious to rain by enclosing it in plastic. It will operate within temperature ranges similar to many laptop and hand-held portables. Although it is not totally resistant to dirt and dust, it can be kept clean fairly easily.

The data entered into a portable voice recognition system can be transferred easily to a host computer through direct linkage. Normally, the information will be downloaded at the end of a day. A radio link may be used with some voice systems to provide real time input to a host computer.

Current technology and cost would seem to preclude voice recognition from widespread use by all first level field maintenance field supervisors of a state transportation department. But voice recognition does warrant consideration in specialized circumstances where only a few people will be using it and where its application will lead to gathering of highly valuable data or to significant cost savings. Limited uses include a way to record supplemental information for bridge inspection and maintenance, or to record roadway feature inventory information from inside a moving vehicle.

The road maintenance community should stay abreast of this data collection technology. Rapid advances in the accuracy, convenience, size, and cost of voice systems are likely to occur in the next 5 to 10 years.

### Voice-Activated Tape Recorders and Voice Synthesizers

Several maintenance field managers suggested that it would be useful to have a small, battery-powered voice-activated tape recorder that would fit in their shirt pocket or be mounted on their dashboard. Whenever they drove past a problem site they could make a verbal note of it. Frequently, maintenance supervisors do not record and report a minor problem that should be addressed because it is inconvenient to write it down while driving. With a voice-activated tape recorder, maintenance field supervisors can refresh their memories of problems at the end of the day and furnish the information for scheduling future work.

Such tape recorders are inexpensive. Many models cost as little as $100.00. Sturdier models impervious to dust and moisture cost more.

Voice synthesizers are another device that can help people who are simultaneously driving and collecting data on roadway features. A commercially available voice synthesizer has been designed expressly for aiding the collection of roadway feature inventory data. As the driver approaches each inventory event, the voice synthesizer will announce it. Information obtained from distance measuring instruments concerning the location of inventory features can be input to the voice synthesizer. The voice synthesizer will announce the next feature just as one passes it. Auditory input is a good complement to some other data entry device such as a keyboard or data entry tablet.

## NAVIGATION AND DISTANCE MEASURING DEVICES

Substantial improvements are possible in the accuracy for reporting location of maintenance work. Two types of technology offer the largest potential in improvement. The first is distance measuring equipment and the second is a locational device that uses a satellite global positioning system (GPS).

### Distance Measuring Instruments (DMIs)

The distance measure which is second nature to DOTs and maintenance management is elapsed distance in miles, for example 2.45 miles of resurfacing, 3.12 miles of mowable swath, or 6.33 miles of ditch pulling. Many states have invested significant resources to create a network of thousands of physical "mileposts" to serve as reference points for maintenance and other purposes. Highway agencies use elapsed distance to identify the location of maintenance work and in some cases the extent of maintenance needed. Guardrail down, damaged bridges, bent signs, and a host of other maintenance needs are partly characterized by elapsed distance from mileposts and other known points such as intersections and city or county boundaries.

Distance measurements are formal or informal parts of maintenance work estimation and scheduling. Maintenance management standards, not surprisingly, are frequently expressed in linear terms.

Elapsed or relative distance measurements are so fundamental to most DOT maintenance that they have resulted in a closely related set of representations of the road and roadway assets. These representations exist in a variety of forms, such as manually scribed straight line diagrams, oversized "blue line" sheets, a machine stored log, or as in Pennsylvania, a fully computerized linear graphic.

One can classify distance measurement technology in terms of its intended use and accuracy. Survey level data (geodetic benchmarks located to an accuracy of less than 1 cm or plats of less than 1 ft accuracy) are typically provided for maintenance use through other governmental agencies, DOT project plans, or by developers of subdivisions who must furnish construction plans affecting public roads.

DOT inventory units (and some maintenance offices) employ traditional survey technology, for example, optical and digital triangulation equipment, and a variety of other survey instruments, such as quality steel tapes, steel chains, and height gauges, to mark off centerlines or important features from known points.

The backbone of current inventory and maintenance measurement technology is the DOT vehicle equipped with a standard odometer (0.1 mile (528 ft) accuracy). Standard 0.1-mile odometers are available on virtually all vehicles. Odometers are calibrated on 1 mile and 1,000 ft calibration courses found in most maintenance districts.

Because the accuracy of the standard vehicle odometers is the nearest tenth of a mile (528.5 ft), and varies with road surface and tire condition, odometers are inaccurate and imprecise. In addition, measurements require interpolation to obtain locational information. The standard of accuracy for locating and reporting maintenance items in Tennessee, Virginia, and elsewhere is 52.8 ft. Graphic logs and other locational reference devices used by maintenance personnel have an accuracy of about 50 ft (16.7 m) or better. Interestingly, 50 ft is also the width of a standard line of a USGS quadrangle map.

A wide variety of more precise distance measuring instruments are on the market. While some very expensive equipment exists, commercially available units used in highway applications vary from about $100.00 to $700.00, depending on their features and expected applications. The low end equipment is just a more precise odometer than the factory-installed odometers in cars and trucks. Figure 16 shows a distance measuring instrument display-mounted on a dashboard. A more sophisticated one on the market has the following features:

1. A bright display that, with the push of a button, presents measurements in meters, feet, and miles.
2. Accuracy to within plus or minus 1 m and resolution of plus or minus one count at 0 to 60 mph.
3. Ability to measure distance traveling forward or in reverse, plus a capability to adjust for (subtract) movements in the direction one is measuring.
4. Impact resistant case with hermetically sealed control panel to keep out moisture, dust, and dirt.
5. Operational temperature range of −4 F to 158 F (−20 C to +70 C).
6. Transmission encoder which provides 16 pulses per shaft revolution.

The research team's own experience with DMIs indicates that

*Figure 16. Distance measuring instrument.*

once properly installed, they are extremely reliable, and installation is fairly easy. Variations in elapsed distance measurements are likely to be due more to such variables as tire pressure and user behavior than the DMI. When recording inventory features, accuracies of 50 ft or better can easily be achieved at slow driving speeds. At speeds of 40 to 60 mph, it is difficult to relate the location of roadway features to DMI readings. A speed that permits reliable data recording is between 15 and 20 mph.

DMIs clearly have significant potential to improve maintenance inventory and reporting, especially if their costs continue to decline, the traditional reliance on elapsed (and therefore relative distance) continues, and an easier way to record the roadway features and the location of work is devised.

It is also relevant to mention that DMIs have been used with one or more sensors, such as a profilometer, to provide a running log and location reference for maintenance feature inventory and pavement condition. The most obvious trend is toward automated collection of road surface conditions for pavement management systems. Another is the integration of elapsed distance with photo or video data collection systems.

The main problem is that DMIs measure a continuous series of points whose location must be established with respect to starting reference points such as intersections and mileposts. The initiation of the DMI must be fairly precise, otherwise the error will be reflected in the distance measurements. Another drawback is that many agencies are beginning to establish geographic information systems that identify location by latitude and longitude. If an agency plans to implement a geographic information system, distance measuring instruments are less attractive, in the long run, than the GPS.

#### Hand-held GPS

By the end of 1993, the NAVSTAR system of 21 global positioning system satellites orbiting at about 11,000 miles above the earth is scheduled to be fully operational. It will provide the satellite infrastructure to enable persons almost anywhere on the globe to locate their position 24 hours a day. The only exceptions are where tall buildings, canyons, steep mountains, heavy forest canopy, or other obstructions block the line of sight to the orbiting satellites.

The NAVSTAR satellites transmit at frequencies of 1227.6 and 1575.42 MHz within the L band. These transmissions are digitally encoded in two different ways—one for military and the other for civilian use. The military code is called the P-code, which stands for precise or Protected code. The civilian code is called C/A code, which means the standard Clear/Acquisition code (*20*).

At present, civilians are generally precluded from using the P-code which can potentially provide locational accuracy within 1 cm. However, the National Geodetic Service and at least one state transportation department have been using the precise code for satellite surveying and they are achieving locational accuracies of less than 1 cm.

There is a major debate concerning how much degradation in accuracy should be provided civilians in comparison to the military. There is a good chance, because of pressures from both the private and public sectors, that ultimately satellite transmissions for civilian GPS units will be more precise than they are today.

Recently, relatively inexpensive hand-held or highly portable GPS receivers could be purchased for $2,750 and, with assistance of satellites, latitude and longitude could be determined anywhere on the earth within an accuracy of about 40 ft (13 m). The hand-held unit includes a satellite receiver and a microprocessor, and employs exact time and differential signal processing to determine location. The information appears on a digital display. With degradation of the civilian code under "selective availability," locational accuracy is now roughly 330 ft (100 m) 95 percent of the time. However, some receivers, when used with a base station at a known datum that can obtain a fix on the same satellites, are able to attain accuracies of about 15 ft (5 m) or better with differential corrections. The base station may be up to 500 mi (800 km) away, although long base lines are typically more like 100 km.

If a GPS receiver can obtain a fix on three satellites, it can establish location in two dimensions. But if the GPS unit can obtain a fix on four or more satellites, it can determine location in three dimensions—latitude, longitude, and altitude. In the demonstration conducted for this project it was found that even with roughly half the satellites operational, it was unusual not to obtain a fix on three satellites, and often four or five were above the horizon.

The hand-held units now available have been manufactured mainly for marine navigation. However, they are highly suitable for maintenance field use. One is so small that it is about the size of a hand-held portable data entry device. Another is a bit larger, but is also easily held in a single hand and has a more rugged and weather resistant case.

A portable GPS receiver is easy to use by anyone who can read numbers. A unit that was demonstrated to field supervisors has no moving parts other than a knob for setting the equipment to the mode the user desires. First, it is put on a proper setting to obtain the satellite fix, which takes a minute or so. Then, a knob is turned to the appropriate setting to obtain the latitude and longitude, which appear on the display. This particular unit will provide information on location every second once a satellite fix has been achieved and maintained (Figure 17).

Once the latitude and longitude are determined, a person can write the information down, key it into another data input device, or with some GPS portable units upload it to a hand-held, data logger, laptop portable, or personal computer. The information can then be transferred upstream to the host central computer.

*Figure 17. Portable GPS receiver.* (Reproduced by permission of Trimble Navigation, Sunnyvale, California)

A single hand-held GPS receiver is an ideal locational device provided the required accuracies can be achieved—better than 50 ft (16.7 m) for most reporting purposes but less than 3 ft (1 m) where it is necessary to locate driveway inlets, traffic signals, or other roadway features. Highly accurate roadway feature updating would require this resolution. However, if civilian GPS units eventually achieve accuracies approaching that of military positioning, GPS would be the locational instrument of choice, provided the cost is judged sufficiently low. The cost per unit can be expected to decline significantly as it has over the past 5 years from over $20,000 to $2,750. Those familiar with manufacturing estimate a $500 unit will be available by 1993 once all the satellites become operational.

**Dead Reckoning Systems**

Brief mention of dead reckoning systems is warranted in connection with GPS. As noted previously, buildings and some types of terrain can block the line of sight to satellites and, therefore, interfere with obtaining locational readings. When the GPS unit is interrupted, it may be necessary to use complementary locational or navigational equipment to determine one's position.

A dead reckoning system uses inertial gyroscopic navigational equipment that provides nearly continuous distance readings from a reference point. A dead reckoning system can pick up where the GPS left off and provide accurate interim locational information until the GPS obtains a satellite fix again and provides another reference point. Dead reckoning locations can be recalibrated when a GPS or radionavigation fix is available for comparison.

Dead reckoning systems are not generally suitable for use by maintenance field supervisors, except for a system in a vehicle. At present, their current maintenance application is for establishing a roadway feature inventory data base in a heavily instrumented mobile van.

## FACSIMILE (FAX) MACHINES

A highly practical technology for communicating maintenance field reports is a facsimile machine. Fax machines are now widespread in business and home offices. So-called "portable offices" consisting of a personal computer, cellular telephone, and fax machine integrated into a single unit are now available on the market. A number of trucking companies use portable fax machines connected to cellular telephones to communicate bills of lading and other information to headquarters.

Another handy device that fits into a shirt pocket is a "fax-modem." It plugs directly into a portable or desk top computer and serves the same function as a fax board (card). Indeed, the miniaturization of this type of equipment is leading to fax-modems built directly into laptops. This technology will receive facsimile transmissions and will transmit a copy of anything that appears on the computer screen through the fax-modem and a phone link.

A maintenance field supervisor working in a rural or isolated area could clearly benefit from this type of technology both to receive daily work orders and to report work accomplishments and resource utilization.

## OPTICAL SCANNERS

This technology deserves mention because it is another way to input and electronically transmit information on a page. Optical scanners are now widely used in desk top publishing in order to transfer image or text on a page to a computer terminal. Noted earlier was the potential use of an optical scanner for inputting a map into an electronic clipboard that functions like a digitizing tablet. Once the map appears on the screen, a field supervisor can establish the location of maintenance work by tapping the appropriate spot on the map with the electronic pen (or mouse).

## DESCRIPTION OF TELECOMMUNICATION TECHNOLOGIES

### Ground-to-Ground Radio Links

Radio Links are traditionally used by highway departments, law enforcement agencies, and others for the purpose of voice communications with mobile units in the field. In addition, many police departments and railroads are also using these radio links to obtain data transfer to and from a mobile unit.

Radio signals propagate over longer distances at lower frequencies and over shorter distances at higher frequencies. The VHF and UHF frequency links tend to be essentially line of sight and require repeaters to cover large distances. However, the equipment tends to be small; only low power is required and coverage can be good using repeaters.

In the telephone industry a two-way simultaneous conversation was made possible by special equipment in both the motor vehicle and at the base station. This full duplex mode very closely resembles a land line telephone circuit. It uses two sets of radio channels (one each way).

Full duplex voice links are suitable for the transmission of facsimile and data. The older push to talk (simplex) technology does not provide for two-way communication which will allow either forms of data transmission to correct itself using normal two-way compare and correction. Pure simplex technology is, therefore, much less suitable as a telecommunications medium.

### Cellular Telephone

Cellular telephone works in much the same way as the full duplex radio technology. The principal difference is that cellular telephones are lower power than point-to-point VHF mobile units because they must connect only to base stations in cells that are closely spaced. The concept of a cell, then, is one of many small base stations with many channels. Each base station is spread out across the service area. As the mobile unit moves across the service area it is "handed off" from one base station to another by the cellular telephone switch located in the mobile telephone switching office. Cellular telephone communication is quite clear because the distance between the mobile unit and the base station is usually just a few miles, usually less than 5.

Currently, most of the large cities of the United States have at least two cellular telephone systems (one operated by the local telephone company and the other operated by a competitor) and most rural area systems are beginning to be built. The vast majority of the major highways of the United States are anticipated to have cellular telephone service by the mid-1990s. Therefore, the use of cellular telephone technology for transmission and reception of facsimile of data and voice to and from the highway department equipment is considered to be viable.

Cellular equipment is inexpensive to the consumer, often below $200.00 for a transportable unit that can be plugged into a cigarette lighter and be moved from vehicle to vehicle, provided that the purchaser signs up with a service provider for a sufficient period of time. In the cellular business revenue comes not from the selling of the equipment but from the providing of air time.

The disadvantage of cellular telephone communication is that the 50 to 60 cents per minute air time can result in a substantial bill if it is used for the dispatching of highway vehicles. Cellular equipment could certainly be combined with existing radio links for highway department use and would be used only where high quality facsimile or data transmission would be needed. Even if the average U.S. cellular telephone bill of $100.00 per month per unit were factored in, the cellular telephone would still be less expensive than the per unit cost of purchasing and amortizing over a 3-year period a normal, highway department, VHF simplex push-to-talk radio equipment.

Another advantage of the cellular telephone is the feature called "roaming." Roaming simply means that vehicles may move from area to area without the need to coordinate frequencies or worry about interfering with each other. This means that the equipment can be moved from one district to another or even across state lines on a project by project basis without the need for coordinating frequencies with other users in the areas, and one can be assured that communication is limited to the dialing and receiving parties. Because it is a dial-up service, there is no eavesdropping or idle talk.

Cellular telephones operate in the 800 to 900 MHz (UHF) frequency range almost strictly line of sight.

Most cellular telephones now come with a RJ-11 standard modular telephone jack so that fax machines, modems, and extra handsets can be plugged into them and used. This makes the use of cellular telephones quite feasible for field supervisors who wish to send and receive faxes and data from a laptop computer in a field vehicle. In addition, cellular telephones are available which automatically answer in the absence of the driver.

### Wideband Networks

Wideband networks refer to those wire line networks characterized by fiber optic cables and cable television. Wideband simply means that they provide an electronic highway over which television data, telephones, and any other sort of information can be transmitted.

Cable television reaches approximately 60 percent of U.S. homes and in many areas is being converted into a two-way interactive system. It is expected that data transmission from and to each home will be readily available in most areas of the United States using these in-place systems.

This two-way capacity to the home means that field grade supervisors would be able to download laptop or other communication devices through their local television system, for example, at a much higher rate than the telephone lines could absorb and be able to transmit and receive high quality digital pictures as well.

These wideband networks started out as microwave links across the country to carry telephones and television, expanded to use satellite links, and are now augmented by fiber and cable.

### Satellite Radio Links

Wideband networks that are terrestrially based are often connected in rings or loops, but in all cases are designed to serve many users over a wide area. On the other hand, satellite links are best suited to one point to multipoint or multipoint to one point communications. In highway maintenance one is generally looking at a point to multipoint situation with the multipoints being mobile vehicles or field offices and a single point being state or regional office.

Satellite links can be point to point. That is to say, a satellite ground station with a dish aimed at a satellite transmits its signal through that satellite to a single additional station. This is very expensive and quite inefficient for the transmission of all but very large amounts of data or television.

If a state or region has a hundred or more mobile units or remote field offices it is advisable to consider building a dedicated "hub" ground station at one central point, perhaps at a state or regional office. This type of network is not distance sensitive as is a terrestrial network. This point to multipoint approach will be cheaper than wire line connection and much more reliable.

As a point of interest, terrestrial networks are usually backed up by satellite links, but satellite links are never backed up by terrestrial networks because of their relative infallibility. For example, satellite links are not subject to a backhoe digging up a land line.

For more modest or smaller operations there are several shared hub facilities in the United States that will take terrestrial telephone lines and link them to remote mobile satellite terminals or fixed satellite terminals. This shared hub is operated by a communications company for the benefit of subscribers to its service. For example, a single satellite earth station in a remote area can be served this way without incurring the high cost of the point-to-point system.

These satellite networks use small dishes because the transmission power in the network is concentrated in the shared hub which has a large and powerful transmitter and dish combination and very sensitive receivers. Using this concentration of power and receiving ability allows the earth stations located at remote offices and the mobile units to be inexpensive and low power. For example, many large supermarket chain stock brokerage houses and automobile manufacturers have these private satellite networks. These are called VSAT (very small aperture terminal).

VSAT networks service a host of users either through dedicated hubs or shared hubs. There is currently widespread availability of small earth stations from several manufacturers, which can be plugged directly into telephones, PBXs, facsimile machines and computers, so that the satellite links are off-the-shelf, plug-compatible, communications and devices using existing technology. Mobile satellite terminals are widely available now and are being used for both voice and data transmission.

The most widespread use of mobile satellite terminals currently is the International Maritime Satellite Organization (Inmarsat) program which provides service to mobile users on land and on the sea. The new generation of L-band satellites will allow even hand-held satellite two-way voice data telex and facsimile transmissions.

Costs for the use of Inmarsat and other satellite facilities are considerably higher than cellular telephone of UHF-VHF-UHF terrestrial radio links. However, they are available everywhere and require no commissioning or start-up time. It is possible just to buy an Inmarsat terminal, subscribe to the service, and make a telephone call in the space of a day. Inmarsat terminals that are truly portable cost about $15,000 per unit as contrasted to several hundred dollars for a cellular telephone.

## RADIO FREQUENCY COMMUNICATION

Mobile radio, cellular equipment, and satellites are suitable for wide area communications to and from the field. However, radio frequency data communication (RF/DC) is intended mainly for short range communication, for example, within a warehouse, a maintenance yard, or a distribution complex. RF/DC transceivers built into hand-held and mobile terminals can send and receive data over narrowband industrial radio communication links in the VHF (about 450 MHz) and UHF (900 MHz) bands, although new "spread spectrum" systems, less subject to radio interference, exist in the 900 MHz, 2400 MHz and 5725 MHz bands.

RF/DC is a desirable communication technology when workers need to enter and retrieve data in virtually real time while moving freely about. RF/DC avoids the need of cables of other physical forms of data transfer such as removable memory and paper. An RF application often occurs when there is an extensive need to verify data and the only place the data reside is in the host computer. For example, in typical, inventory control systems, it is necessary to periodically determine whether the supplies on hand match the information in the data base.

The communication protocols most suitable for RF/DC vary with the number of data entry terminals and the intensity of use. When data entry rates are moderate (say less than 16), polling is frequently most advantageous. In polling, the base station makes sequential requests of each data entry terminal until all have been queried and then the requests start over again in the same sequence. If there are too many terminals, the response time becomes too long. Polling times can be reduced with an adaptive system that "puts to sleep" terminals that have not been on for a predesignated amount of time.

Contention techniques, in contrast to polling, allow transmission of data whenever the communication channel is free. Contention systems work well as long as there is not a peaking problem, when, for example, everyone returns from lunch and starts transmitting data at the same time.

Design of RF/DC systems requires care to ensure response rates are appropriate for the application, transmission rates are adequate, and suitable provisions for data retention are made should the host system crash(*4*).

CHAPTER FOUR

# FINDINGS—SYSTEM DESIGNS

A cardinal rule of effective date collection and use made possible by today's technology is to acquire data through those closest to the source of data, to keep the data nearest its applications, and to integrate data into operational and reporting processes. Highway and transportation agencies find field managers are the natural choice for collecting maintenance data because of their proximity to field operations. However, field managers often perceive the data acquisition procedures as onerous and not directly relevant to the work at hand. Data acquisition procedures that are much less laborious and directly serve the needs of the field manager can increase acceptance of the need for data collection. Indeed, if the data are sufficiently useful for day-to-day operations, field managers will actively support data collection. A data collection system for maintenance field supervisors consists of a data collection device, communications including a feedback loop, and a link to the host computer which provides data storage. This chapter presents a variety of system designs to show the range of practical options.

The alternative systems concern maintenance data collection activities of nearly all the states: (1) crew card data collection, (2) equipment and materials inventory management and control, (3) roadway inventory feature updating, (4) inputs to short run scheduling, (5) bridge inspection and maintenance, and (6) monitoring snow plow operations.

The first four types of data collection systems can help improve the efficiency of various maintenance activities undertaken by a highway agency: roadway surface repairs, shoulder repairs, roadside maintenance, bridge repairs, snow and ice control, and so forth. These data collection systems are intended to improve work reporting for maintenance activities, provide better management of the materials and equipment used for each type of maintenance work, help combine various inputs for scheduling work, and improve estimates of the annual work load required for the various activities as a result of having better and more current information concerning the roadway inventory and maintainable features. The fifth type of data collection has been included because bridge inspection and maintenance is an activity of all the states. Bridge inspection and preparing maintenance recommendations have traditionally involved filling out lengthy forms and often preparing handwritten reports including drawings and photographs. Because the character of bridge data collection differs from other maintenance data acquisition, it has been given separate treatment here. Somewhat analogous issues could have been addressed concerning manual and automated collection of pavement distress and condition survey data, but it is the subject of other NCHRP research and beyond the scope of this study. The sixth system design, for snow and ice control, has been included in this study because snow storms affect a large fraction of the states, and the technology examined in this study is highly suggestive of a way to monitor snow plows operating in remote locations under dangerous storm conditions.

As shown in Table 5, system designs generally satisfy the requirements set out in Chapter Two. The system designs for field data collection (crew card data, inputs to scheduling, and roadway feature inventory updating) are intended to meet virtually all the requirements for field devices, maintenance management, and integrated systems. The system design for bridge inspection and data collection is more tentative, because the ability of the recommended data collection device to satisfy all the field work requirements is more questionable. The system design for inventory management and control only has to satisfy requirements for data collection devices that are usable in maintenance depot and warehousing operations. The devices do not have to be as rugged or environmentally resistant as data collection equipment for field use. Many of the requirements set out in Chapter Two are not relevant to snow-plow operations, but the system design does provide the ability to locate within 330 ft (100 m) snow plows operating in remote locations and heavy storm conditions.

For each of the six basic maintenance collection activities, different system designs are presented involving different technologies. Where applicable, alternative system designs are provided to reflect a variety of field environments and agency operating procedures. For example, the system designs for crew card data collection recognize the desirability of portable or hand-held collection devices that will work outdoors, at all times of the day or night, and in a range of weather conditions. Another design recognizes that economic costs may preclude such an all-purpose data collection system. Instead, data collection equipment that works inside a vehicle may be more than satisfactory. Both of these systems assume that the field supervisor or crew leader shows up at a local staging area for maintenance assignments at the beginning of the day and returns to the staging area at the end of the day and furnishes information on the work done and resources used. Yet, another design assumes the field supervisor works in a rural or remote location, perhaps out of his or her home, necessitating a different kind of communication link or feedback loop.

Each system design emphasizes the potential substitutability of equipment. For instance laptops, electronic tablets and hand-

**Table 5. Ability of data acquisition systems to satisfy requirements.**

| Requirements of Integrated System | Crew Card Data | Inventory Mgmt & Control | Roadway Feature Updating | Inputs to Scheduling | Bridge Inspect. & Maint. | Snow Plow Operations |
|---|---|---|---|---|---|---|
| Meets requirements for field devices. (See Chapter 3) | x | n.a. | x | x | ? | n.a. |
| Prompting, verification & error checking | x | x | x | x | x | |
| Automatically performs calculations | x | x | x | x | x | |
| Modular/plug compatible | x | x | x | x | x | x |
| Commercially available modules | x | x | x | x | x | x |
| Two way data flow | x | x | x | x | x | |
| Turnaround time 1 day or less | x | x | x | x | x | |
| Retrieval of data from | | | | | | |
| - office | x | x | x | x | x | x |
| - home | x | x | x | x | x | |
| - public phone | x | x | x | x | x | |
| - vehicle or field | x | x | x | x | x | |
| **MMS Requirements** | | | | | | |
| Addresses one or more MMS functions directly or indirectly | | | | | | |
| - work planning | x | x | x | x | x | |
| - work authorization | x | | | x | x | |
| - work reporting | x | x | | | x | |
| - work evaluation | x | x | | | | x |
| Data & time stamping of data | x | x | x | x | x | x |
| Location <50 ft. | x | n.a | x | x | x | 330 ft |
| Data Transfer | | | | | | |
| - direct transfer at staging areas | x | x | x | x | x | |
| - remote transfer by phone | x | | x | x | | |
| - serves 1st level field manager | x | indirectly | x | x | x | |
| - serves higher level management | x | x | x | x | x | x |

held portable data entry terminals may all serve a nearly identical function in a particular application.

All designs involve commercially available equipment and, therefore, are technologically feasible. The economic feasibility and receptivity of the organization must be determined case-by-case.

The field devices generally consist of integrated equipment that combines a number of technologies or they consist of units that plug together. The emphasis is on integrated but modular systems. However, in some instances where a complementary but independent unit may substantially increase the accuracy or speed of data collection, it is part of the system.

Table 6 provides a summary of the various data collection systems.

## CREW CARD DATA COLLECTION

For crew card data collection, it has been concluded that maintenance field supervisors would be attracted to one of three primary options used in conjunction with a portable GPS unit which would permit automatic or manual entry of location data: (1) laptop computer, (2) hand-held computer with keypad and integrated bar-code reader, and (3) electronic tablet (clipboard).

The software governing the data input would require the user to enter the data in a particular order. Sequence prompts would appear on the display to guide the user. Software for the input device would check that the data are allowable and lie within proper range. Software could be programmed and compiled on another computer and then downloaded into the data collection device.

Figure 18 shows the design for a portable field system. Data would be transferred every evening into the local office computer for further processing. Any of the three data collection devices could be connected to a portable printer to obtain a printed copy of data entered.

The laptop is a practical option because Caltrans is already implementing a laptop computer system for crew card and other data entry. Examples of Caltrans' data entry fields for material and equipment use are shown in Figure 19.

The electronic tablet is another practical alternative for field data collection from inside a vehicle and in selected outdoor settings. At the demonstration, field managers entered crew card data into an electronic tablet, and had mixed, though generally favorable, reactions.

At the equipment demonstration, maintenance field supervisors responded most positively to using a pocket-sized bar-code reader to scan the bar-code menu in Figure 20, a crude version

**Table 6. Summary of data collection systems.**

| Types of Data Acquisition | Systems | Options: Device | Options: Location | Options: Data Transfer/Telecom | Data Retrieved: Types | Data Retrieved: Turnaround Time |
|---|---|---|---|---|---|---|
| 1. Crew card data | Portable Field Data Collection | Handheld computer w/ bar code scanner<br>Laptop<br>Electronic Tablet (Clipboard) | GPS<br>Bar coded map | Direct Link (RS232)<br>Docking Device<br>Removable Memory | Work Orders<br>Planned vs actual<br>Comparative Efficiency of Methods | At least daily |
| | In-vehicle Data Collection | Electronic Tablet<br>Laptop<br>Handheld computer<br>Voice Recognition | GPS<br>Distance measuring instrument | same as above | same as above | At least daily |
| | Remote Location Portable Field System | Electronic Tablet<br>Laptop<br>Handheld computer<br>Portable Facsimile | GPS | Dial up telephone<br>- cellular<br>- home phone<br>- public phone | same as above | Nearly real time |
| 2. Inventory Mgmt and Control | Physical Assets:<br>- Equipment<br>- Tools<br>- Vehicles<br>- Office Furniture | Handheld computer w/ bar code scanner | Same as data acquisition device | Direct Link (RS232)<br>Docking device<br>Removable Memory | quantity on hand<br>location of item<br>order status<br>unit costs<br>vehicles in shop | At least daily |
| | Comprehensive Inventory Mgmt and Control System | Handheld computer w/ bar code scanner (plus others as cost effective and appropriate)<br>--w/ radio link<br>--laptop<br>--electronic scales<br>--fixed terminals<br>--RF ID access to bulk supplies<br>--Bar coded/mag stripe user IDs for gas withdrawal | Same as data acquisition device | Direct Link<br>Docking Device<br>Removable Memory<br>Radio Link | Same as above | At least daily<br>Real time if radio link |
| 3. Roadway Feature Inventory Updating | Portable Field System | Electronic Tablet<br>Laptop<br>Voice Recognition<br>Handheld computer | GPS | Direct Link<br>Docking Device<br>Removable Memory | Recent inventory data, location of inventory item<br>Distance to next similar element | At least daily |
| | In-vehicle field system | Electronic Tablet<br>Laptop<br>Voice Recognition<br>Handheld Computer | GPS or Distance Measuring Instrument | Same as above | Same as above | At least daily |
| | Remote System | Same as above | GPS | Dial up telephone<br>- cellular<br>- home phone<br>- public phone | Same as above | Nearly real time |
| 4. Inputs to Short Run Scheduling | Needs identification aid | Voice activated recorder | n.a. | Transcribe to paper form | n.a. | n.a. |
| | Identification & Scheduling | Electronic Tablet<br>Notebook size computer<br>Laptop | GPS<br>Distance Measuring Instrument | Direct Link (RS232)<br>Cellular phone<br>Home phone | Planned vs actual work<br>Citizen complaints<br>Condition and distress data<br>Performance standards<br>Resource availability | At least daily |
| 5. Bridge Inspection - maintenance | Field data collection | Electronic tablet w/ digital still camera | GPS | Direct Link (RS232)<br>Cellular phone<br>Home phone | Inventory data<br>Condition data<br>Prior work orders<br>Photos<br>Diagrams | At least daily |
| 6. Monitoring Snow Removal Equipment | Snow plow/blower status | Vehicle and environmental sensors | GPS<br>LORAN | Low Data Rate Satellite | At monitoring station<br>--location<br>--vehicle operating (yes/no)<br>--air temperature<br>--snow density | Nearly real time |

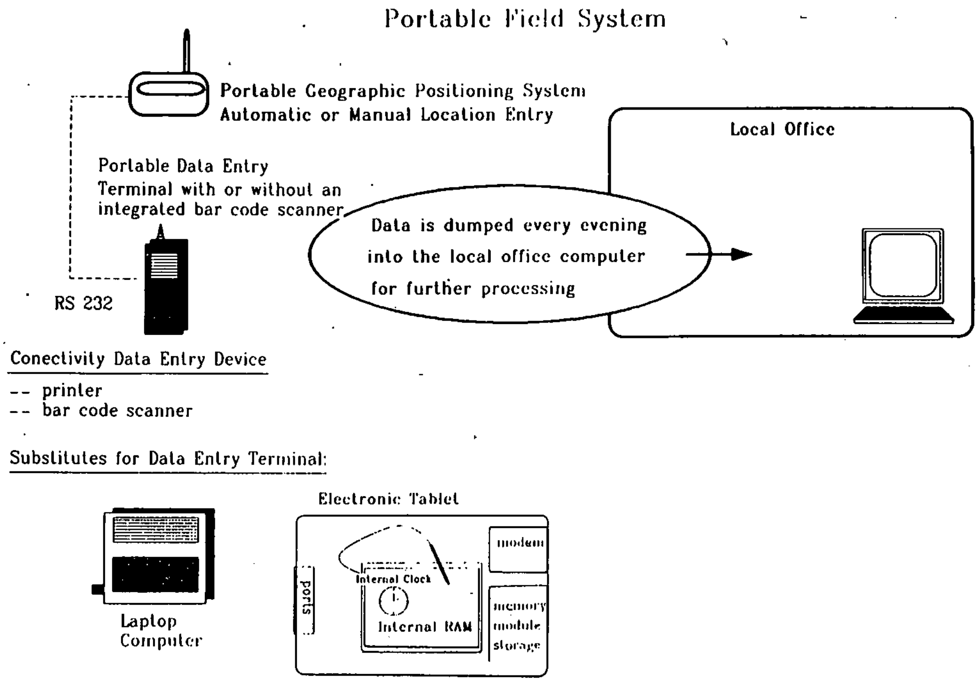
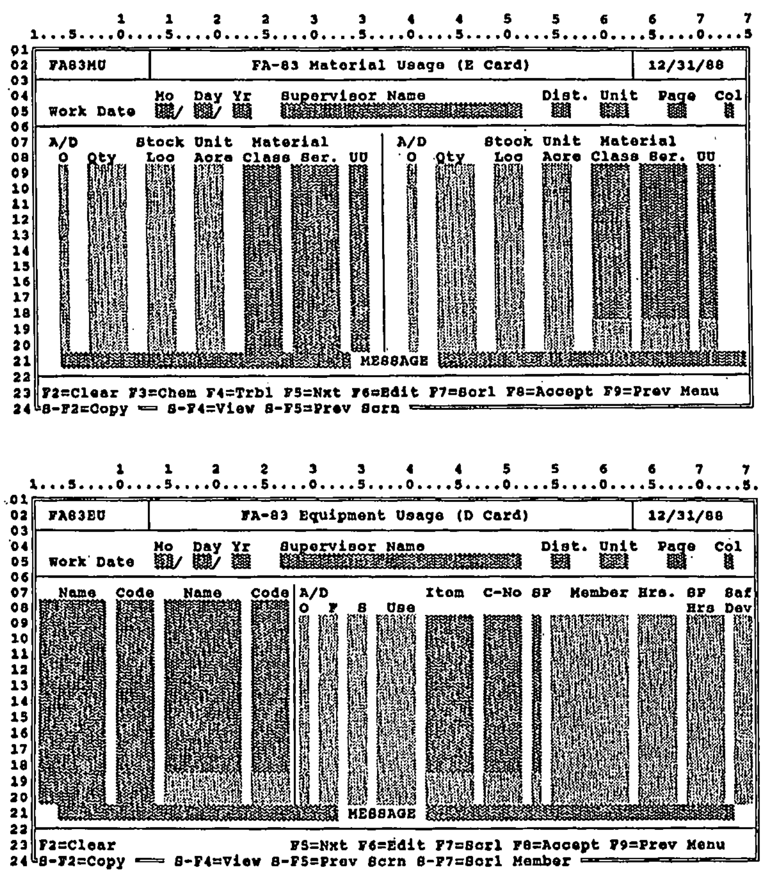



*Figure 18. Portable field system for crew card data.*




Legend:

= User Entered Information

= System Supplied Information/Default

*Figure 19. Caltrans' data entry fields for material and equipment use.*

of a crew card. Ideally the bar-code reader should be an integral part of a portable data entry terminal with keypad, display, a microprocessor, internal memory, internal clock, ports, and visual and audible cues of a successful scan.

In principal, a road maintenance agency could print crew cards for each maintenance activity similar to that in Figure 20. These bar code menus could be printed on demand when a work order is issued or they could be furnished to each maintenance field supervisor in a notebook, which is updated periodically. Some laser printers can print most types of bar codes accompanied by text or figures in any format on a sheet of paper.

Upon completion of any maintenance activity, the field supervisor can scan bar codes representing start and end time, the type of work performed, the names of the workers, and the equipment and materials used. If the names or types of equipment are not preprinted, the field supervisor can use a keypad to enter the number representing the data entry item (or name if the keypad includes letters). Alternatively, the field supervisor can scan the code number representing the data entry item. The menu includes bar codes for the numbers 0 through 9. In addition, the person can scan in the location from a bar code on a milepost, or from bar codes printed on a map similar to a AAA trip ticket. Location information also can be obtained from a hand-held GPS device and will be readily available as long as obstructions do not block line-of-sight to satellites.

Figure 21 presents an in-vehicle data collection system if the portable field system is judged not desirable. This system includes a distance measuring instrument to obtain location information. The distance measuring instrument is coupled to an electronic clipboard, laptop computer, voice recognition system, or portable data entry terminal. An advantage of the in-vehicle system is that the data collection device does not have to be rain-

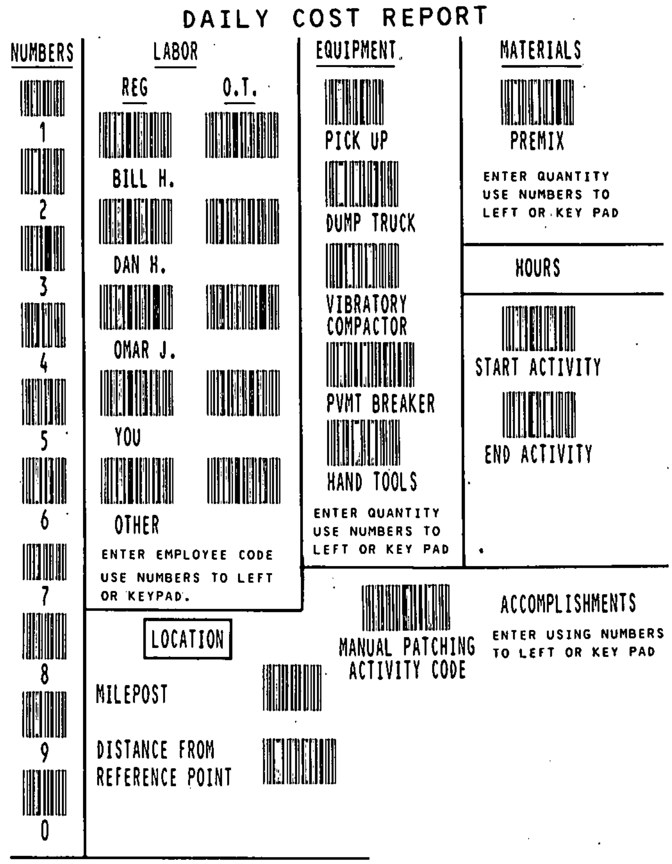



*Figure 20. Bar code menu for crew card data entry.*

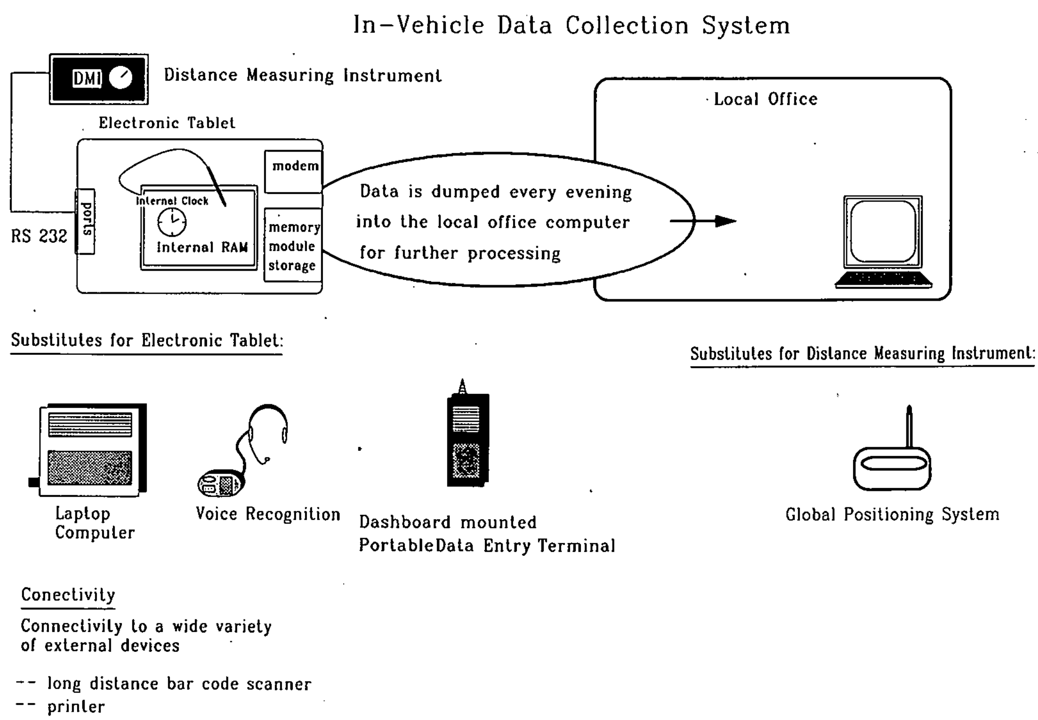



*Figure 21. In-vehicle data collection for crew card data.*

proof, although it still must withstand condensation and extreme temperature variations in this vehicle. Another advantage is that the distance measuring instrument operates in obstructed conditions whereas GPS does not. To prevent equipment damage, the data collection device may have to be easily removed from the vehicle.

Figure 22 shows the communication loop to enable the maintenance field supervisor and the district office to enter and retrieve information from the maintenance management system. Feedback of other information useful to the field manager flows from the headquarters organization to the district or local office and the field. Most data will flow between the field supervisor and the mainframe computer in the central office so that the field supervisor will be the primary beneficiary of information stored in the headquarter's computer. However, the district may have locally stored data it wishes to provide local field supervisors. Communication links in the system are by modem via a telephone or a dedicated circuit.

Where managers report each day to a staging area for their work orders, they will be able to retrieve information they desire from the maintenance management system by requesting a printout. They can also download data into their data collection device for later retrieval in the field, assuming the device has a suitable display. For example, data on planned versus actual accomplishments can be transferred to a portable data entry terminal for subsequent viewing at the work site.

In this system, the type of feedback and other information the field manager may extract from the maintenance management system includes: (1) comparative efficiency of methods, (2) work orders/schedule, (3) planned versus actual (accomplishments, labor, materials, and equipment), (4) other performance indicators helpful to the supervisor, (5) budget balances, (6) urgent/emergency work, (7) equipment and material availability (quantity, location, equipment in shop for repairs, and order status), (8) unit costs for local bid estimates, (9) maps showing location of work sites, (10) photographs of maintenance problems.

The kind of data collection device the field manager uses will place limits on the type of information that can potentially be retrieved in the field. A laptop and electronic clipboard offer the most flexibility because they can display data, text, and digital images of maps and photographs. However, an electronic tablet is better for annotating data entries and drawing by hand. The small display of a portable data entry terminal precludes lengthy text, and simple bar-code scanners will provide no way to retrieve data unless integrated into or combined with other equipment.

If the field supervisor works in a remote or isolated location, a system with a different type of communication link will be appropriate, such as shown in Figure 23. Data can be communicated directly by modem via dial-up cellular telephone, home phone, or public telephone.

States and localities that wish to more carefully evaluate implementing a crew card data collection system need to develop some first-hand experience with the technologies of interest. They also need to develop a detailed computer systems analysis that describes how various crew card data collection systems will interface with the maintenance management systems and/or the emerging geographical information system.

Exposing field supervisors to a technology and later training them mainly require putting the equipment in their hands and letting them enter and retrieve data. There should be a full review of the strengths and weaknesses of any data collection device from the standpoint of field supervisors, higher levels of management, and personnel from the data processing shop.

Further recommendations concerning implementation are included in the discussion in Chapter Five.

## INVENTORY MANAGEMENT AND CONTROL

State and local road maintenance organizations have yet to capitalize on automated inventory management and control systems similar to those used in a large number of industrial, wholesale, and retail enterprises.

Bar code data collection systems potentially offer significant

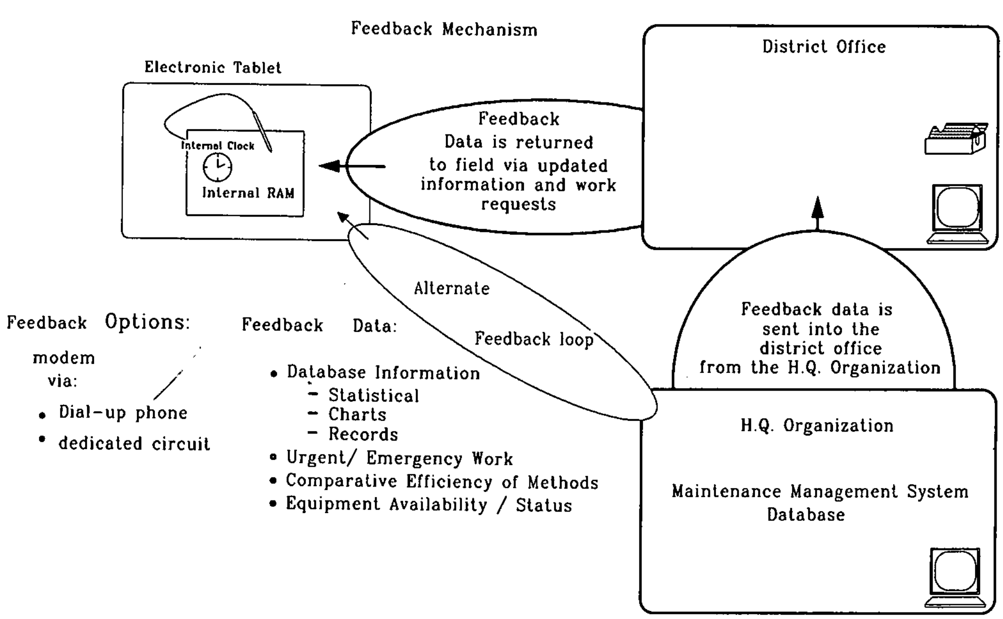



*Figure 22. Crew card data feedback loop.*

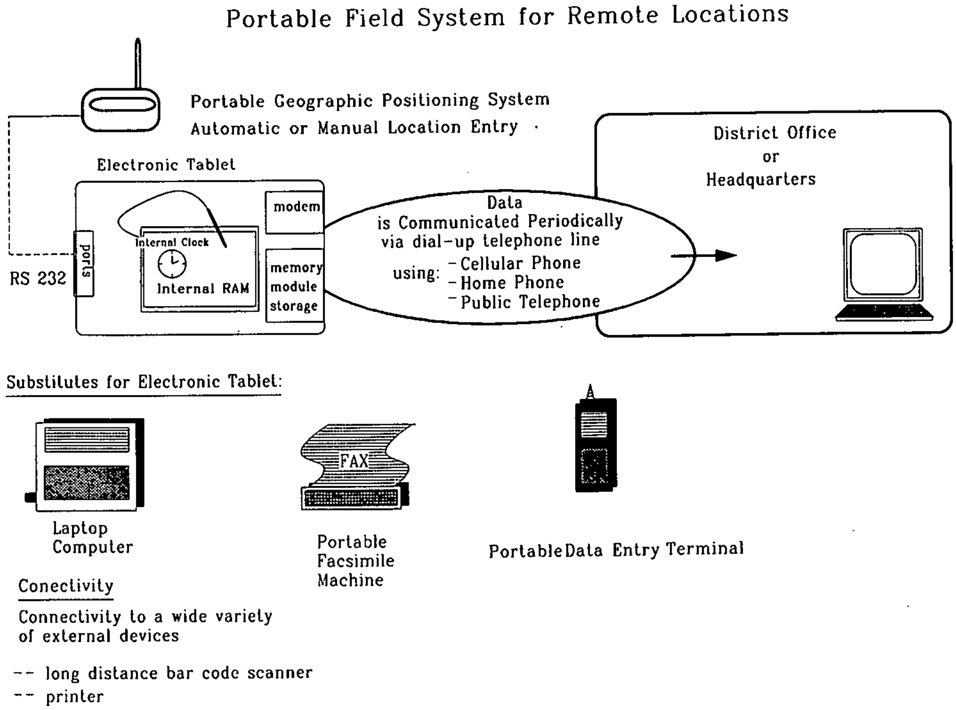



*Figure 23. Portable field system for remote locations—crew card data.*

savings in the time and cost it requires to take periodic inventories of physical assets such as maintenance vehicles, equipment, tools and even office furniture. To the extent cost savings can be achieved, and labeling is practical, all such equipment should be labeled with a unique bar-coded number. A person can then use a portable data entry terminal with a bar-code scanner to quickly take inventory and rapidly upload data to the host computer. Scanning bar codes on each piece of inventory would replace the need to check off lists of inventory items and then key the data into a terminal. If an agency were to implement only one data acquisition system based on this study, one of the strongest candidates should be a physical asset inventory system that uses bar code labels and portable data entry terminals with scanners.

A bar code inventory system that also encompasses materials and supplies is more complicated. But it may also yield considerable time and labor savings for many organizations. In private industry, the rule of thumb is that the payback time of an automated inventory management system is one year. Even if the payback period in a highway or transportation department is 2 or 3 years, the investment is still worth it.

A comprehensive system may involve not just bar codes but other types of data acquisition. The types of data acquisition devices and the configuration will depend on the number, nature, and location of maintenance shops; the layout and types of storage facilities (sheds, warehouses, parking lots, stock yards); and the types and quantity of vehicles, equipment, tools, supplies and materials. The main problem is serving the broad range of maintenance activities performed by an agency. The diversity of equipment and material used in highway maintenance is extremely varied and includes: pipe, signs, premix, sealant, lumber, metal plates, tools, trucks, bladers, paving equipment, crash attenuators, work zone safety barriers, herbicides, paint protection systems, nails, nut and bolts, and other miscellaneous small parts.

A system that can inventory all or most of these things will complement the field supervisor's daily responsibility to report the equipment and materials used for each job. It will facilitate accounting and budgeting, and it will also enhance maintenance management through more accurate and timely cost and inventory data including material and equipment availability. Furthermore, an automated stock ordering system can be an integral part of the inventory system, and so can an equipment management system such as that used by the U.S. Army (*21*).

While bar code data collection will be applicable to most physical assets, materials, and supplies, other data collection technologies may be a desirable complement or better choice in some instances. Figure 24 is a schematic of a comprehensive inventory management and control system potentially involving many different types of data collection devices and procedures. Maintenance personnel can use various data collection devices to furnish information to a host central computer. The data collection equipment can be distributed in a cost-effective way both within and among each maintenance yard/facility, be it at the district or subdistrict level. In addition to bar coding, the data collection devices of a comprehensive system may include: (1) electronic tablets (clipboards), (2) laptops, (3) fixed-in-place data entry terminals, (4) data entry terminals mounted on lift trucks, (5) terminals with radio links to controllers connected to a host computer (the radio links will permit real time communication with the material and equipment inventory data base), (6) voice recognition system, (7) electronic scales for weighing small parts or odd lots, (8) vehicle scales for weighing bulk materials, (9) employee identification cards with bar codes or magnetically encoded stripes for access to fuel pumps (the identification card can also be a smart card), (10) electronic fuel gauges on gas pump, (11) radio frequency identification tags for automatic vehicle identification and maintenance yard access control.

In some settings an electronic tablet or laptop computer may

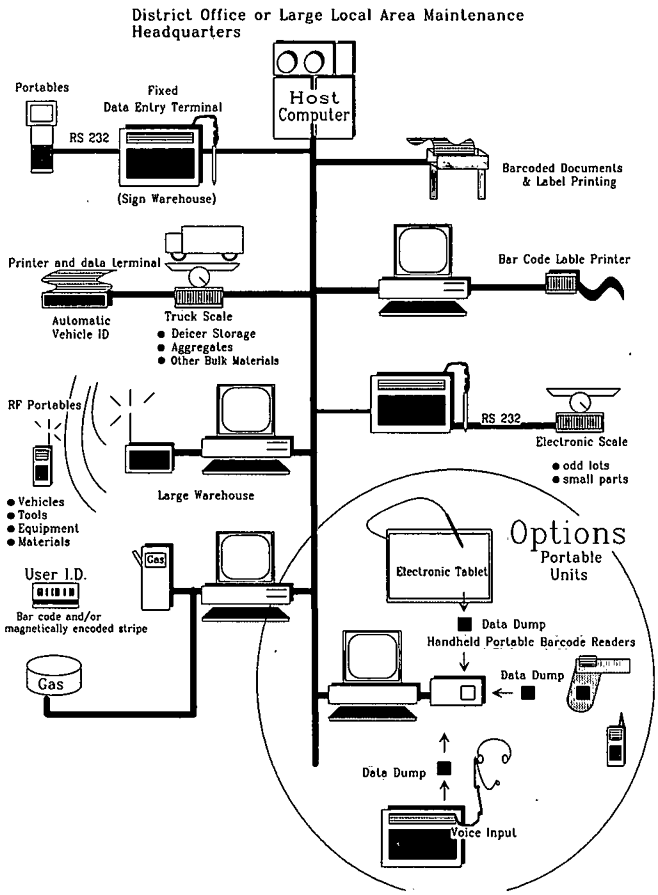



*Figure 24. Materials and equipment inventory.*

serve the inventory data collection and management function better than a smaller hand held data entry terminal. Data entry terminals fixed in place with bar code readers attached are common in many inventory management operations, as are data entry terminals on truck lifts. If there is a need for rapid data entry and retrieval from the host computer, for example to make emergency or urgent repairs or to quickly process large amounts of materials, selected use of portable data entry terminals with radio links may be warranted. Voice recognition systems may be advantageous where "hands free" data entry is required. For example, a manufacturer that relies on just-in-time inventory management may employ voice recognition as part of their material acceptance procedures to make sure deliveries match original orders. A person can simultaneously help unload freight from a truck and enter data concerning the shipment if a voice recognition system is used. Electronic scales for weighing and keeping track of odd lots and small parts can be part of the inventory and management control system if the objectives of accounting and record keeping dictate such detailed accountability and control. There may be occasional instances where installation of a vehicle scale to measure use of deicers, abrasives, aggregates, and other bulk materials is cost-effective. Automatic vehicle identification using RF/ID technology may be warranted to control access to a maintenance yard and to estimate bulk material usage. If an RF/ID tag were placed on the vehicle, the unique vehicle number encoded in the tag could trigger a gate to open. If there were a terminal mounted by the gate, the maintenance worker could enter the amount of material picked up and the fraction of a truck load it represented. Then the quantity removed could be automatically estimated based on vehicle characteristics (stored in the data base). To control access to gasoline pumps, identification cards with bar codes and/or magnetically coded stripes are commonly used. Electronic fuel gauges on gasoline storage tanks could be used to match fuel deliveries to fuel withdrawals.

In addition to data collection devices, bar-code printers will be necessary to provide labels. Some printers will create labels on demand, whereas others may generate numbered labels in sequential order.

To avoid an excessively costly inventory system, an agency will want to identify which types of items it considers most important to inventory and control through more automated procedures. The remainder can be handled by other methods.

From the standpoint of the individuals collecting inventory information, the data acquisition system would be as shown in Figure 25. The warehouse person or stockkeeper would use a hand-held computer with integrated bar-code scanner, or a substitute data acquisition device, to enter inventory data. Data would be uploaded at the end of every day into a local office computer for further processing unless a portable terminal with a radio link were to provide real time data entry (Figure 26).

Those maintaining inventory and maintenance field supervisors will be able to extract the following kinds of information: (1) quantity on hand of each inventory item, (2) location of each inventory item, (3) order status, (4) unit bid prices, (5) defective supplies, parts, and equipment, (6) vehicles in repair shop.

Turnkey inventory data base systems housed on personal computers are readily available. If an agency desires a customized system, considerable software programming will be required. In either case careful, step-by-step implementation appropriate to the actual working environment is necessary. Generally, a more detailed system design will be required that fully specifies input procedures, outputs, data flows, hardware and software, and addresses organizational and other institutional issues. Although states will probably not find a statewide inventory management system with radio links cost effective, such a system does represent the upper range of complexity. Presented below are some of the communication issues involved in installing a statewide data collection system that not only uses bar codes, but also uses UHF or VHF radio frequency links to provide real time transactions between stockkeepers and the host computer system:

1. System capacity is determined by the number of users, the amount of usage per user, peak loading and acceptable blockage at peak time.

2. System saturation can occur if the actual system loading reaches only about 40 to 45 percent of the communication link.

3. In typical systems with RF radio links, stockkeepers will become impatient if they must wait much more than 1 or 2 sec.

4. Response time will be degraded if there is slowdown in any of the following: the time for a radio to get ready to receive or send data (hardware overhead); time spent to detect errors in handshaking operations (overhead protocols), the time for the host to process a remote terminal request (host response delay), and the time required for a host to process a remote terminal request (data transmission rate)(*22*).

5. The system base stations and controllers should be of such number, size, and capability that they balance response time and cost. Selection of the proper controller and other hardware

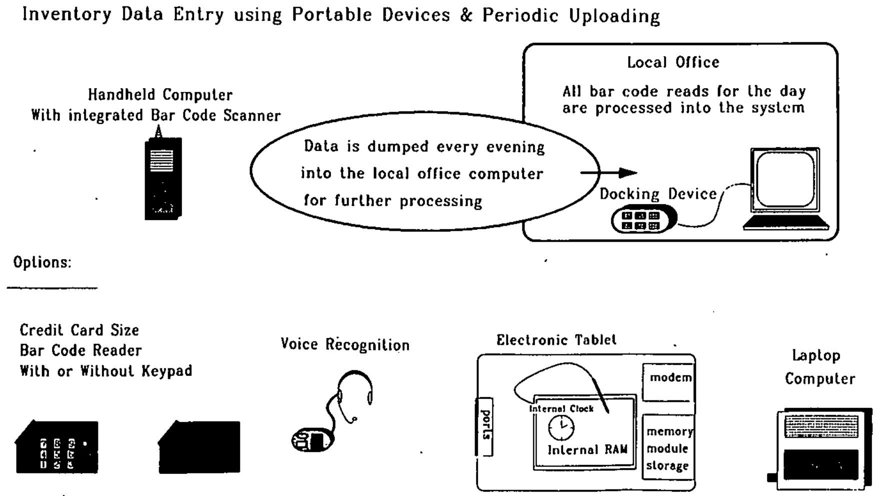



*Figure 25. Inventory data entry using portable devices and periodic uploading.*

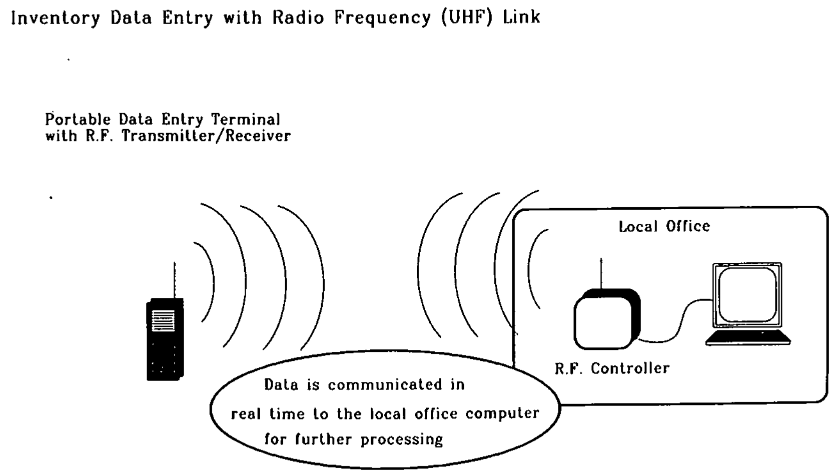



*Figure 26. Inventory data entry with radio frequency (UHF) link.*

requires technical sophistication and a thorough knowledge of hardware options. For example, a radio frequency controller recently introduced to the marketplace uses technology similar to cellular telephones in order to handle multiplant, multisite operations.

## ROADWAY FEATURE INVENTORY UPDATING

Recently, the Engineer of the Fairfax Residency in Virginia remarked, "Several years ago we spent about 20,000 man-hours in my residency undertaking a thorough inventory of our road and roadway assets. We issue about 5,000 permits affecting change on and along our roadways each year. Within 18 months our inventory was obsolete." Given scarce human resources and the pressing demands of daily maintenance work, keeping a roadway feature inventory current is an imposing challenge.

Demand will accelerate for statewide inventory data about the roadway, the physical structures along it, and the cultural and environmental features affecting road use. Given the likely future integration of maintenance management systems with pavement and bridge management systems, the demand for reliable inventories and accurate, timely updates will increase dramatically.

The rapid introduction of geographic information systems—those systems that can translate computer files into decision maps—will create an additional pressing need for inventory updates referenced to longitude and latitude. As with current maintenance management systems, collection of field data and maintaining current data are the bottlenecks of geographic information systems. Currently, 38 states are engaged in the "GPS/GIS Multi-State Project." This project will lead to more rapid development of roadway feature inventories and speed the implementation of geographic information systems. The high level of state DOT participation, the rapid increases in technological capability, and quickly falling costs promise to make geographical information systems a widespread tool for use at local, district, and headquarter offices.

Roadway feature inventory data are one of the key factors that drives a typical maintenance management system in addition to needs, budgets, average production rates for each activity, and performance standards. Responsibility for updating inventory information is decentralized to varying degrees. In California, for example, the District Maintenance Systems Coordinator is responsible for changes that occur because of contract work. In Maryland, a similar person has the responsibility, and the field supervisors furnish the information.

Figure 27 shows Caltrans' maintenance inventory transactions which used to be written down by hand and then keyed into a terminal. Examples of inventory features are: pavement surface; pavement base; pavement subbase; shoulders; traffic lanes; turning lanes; curb and gutter and sidewalk; posted speed limit signs; curve and winding road signs; intersecting routes; limits of state, county, city and town jurisdictions; signals and flashers; entrances to businesses and schools; overhead signs; railroad separations; mowable swatches, ditches, drainage structures, and guardrail.

The roadway feature inventory is intended to identify each occurrence of these elements. For purposes of maintenance management it is necessary to know the measurement units of maintainable elements and their location. Figure 28 is an example of a typical inventory sheet.

The system design proposed for updating roadway feature inventory data presupposes the existence of an inventory data base. The options presented accommodate two possibilities. The first is the current prevalent type of inventory data base. Inventories consist of linear representations of elapsed distance between maintainable features, and their location is established using a distance measuring instrument. The second possibility is that the inventory rests on a geographic information system (GIS) platform where inventory features are referenced to latitude and longitude. A mobile van that uses GPS, a dead reckoning system (inertial guidance system) and distance measuring instruments, collects the data necessary to draw digitized maps of the road network with latitude and longitude provided for each inventory item.

A maintenance field supervisor can update the inventory features using the same data collection systems proposed here for in-vehicle crew card data collection (see Figure 21) or more complex equipment described in Appendix A. If the base inventory relies on a linear measure of distance, the system will enable a field supervisor to update inventory data using a distance measuring instrument in conjunction with an electronic tablet, portable hand-held computer, or a laptop computer.

One can substitute a portable GPS receiver for the distance measuring instrument, which will enable the field supervisor to establish the latitude and longitude of any field location. By being able to carry the GPS receiver around outdoors, the field supervisor will have better access to maintainable features, which should result in much more accurately located inventory elements. Field supervisors working outside their vehicles can use the system for outdoor collection of crew card data (Figure 18) to update roadway feature inventories and to transfer data daily at a crew staging area. Similarly, the crew card data collection for remote locations (Figure 23) can serve as a roadway feature inventory updating system in isolated areas.

The feedback required for these systems would include the ability to extract the most recent inventory information, the location of a maintainable item, and the distance to the next maintainable item of a similar type.

Information from the inventory management system could be coupled to "a shortest path algorithm" in order to tell maintenance field supervisors the shortest or fastest route among vari-

MAINTENANCE INVENTORY TRANSACTIONS

Fred Super
Signature

DISTRICT 01 FOREMAN 733 DATE MO 07 DAY 25 YR 8

EXAMPLES

| | DELETE | ITEM CODE | COUNTY | ROUTE | PREF | FROM POST MILE | SUFF | TO POST MILE | CITY CODE | QUANTITY | + OR - | TRANSFER TO FOREMAN | (NOT KEYPUNCHED) QUANTITY AFTER CHANGE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A. | | M510 | 10 | 001 | | 46.0 | | 47.0 | | 5.00 | + | | 38.00 |
| B. | | M510 | 10 | 001 | | 51.0 | | 52.0 | | 2.00 | − | | 41.00 |
| C. | | C610 | 10 | 020 | | 17.3 | | 18.0 | | 1.00 | + | | 1.00 |
| D. | X | M610 | 10 | 020 | | 19.0 | | | | | | | 0 |
| E. | X | | 10 | 001 | | 51.0 | | 56.0 | | | | | 0 |
| F. | X | D310 | 10 | 001 | | 46.0 | | 50.0 | | | | | 0 |
| G | | | 10 | 222 | | 18.0 | | 27.0 | | | | 747 | |
| H. | | D111 | 10 | 141 | | 1.0 | | 10.0 | | | | 747 | |
| I | | D111 | 10 | 141 | | 12.0 | | 13.0 | | | | 747 | |
| J | | M113 | 14 | 232 | | | | | | | | 747 | |

*Figure 27. Maintenance inventory transactions.*

Maryland Department of Transportation

# STATE HIGHWAY ADMINISTRATION MAINTENANCE FEATURE INVENTORY FORM

PAGE 1 OF 1 INVENTORY BY Roy Young, C. Hammond, E. Thompson

COUNTY NAME Mont LENGTH OF SECTION 10.42 MI.

TERMINI FROM MD355 @ Henderson Cor TO Ho/Mont Co/Li

ROAD NAME:

| CARD NUMBER (1) | EDP (2) | COUNTY (3–4) | ROUTE (5–12) | SYSTEM CODE (13) | DISTRICT (14) | AREA (15) | INVENTORY DATE (16–21) MONTH DAY YEAR |
|---|---|---|---|---|---|---|---|
| | | 15 | MD00027 | S | 3 | 2 | 08 09 86 |

MILEAGE 0 .2 .4 .6 .8 1 .2 .4 .6 .8 2 … 10 .2 .4 .6 .8

LT

| | |
|---|---|
| FENCE | |
| MOWING LIMITS | 10 — 5 |
| DITCH | U — P — U — P |
| SHOULDER | CB — LB — HB CB HB CB HB CB HB — CB — HB — CB — HB — CB HB CB HB HB — CB — HB |
| SURFACE | 2HB — 3H — 2X — 3H — 2X |

DIVIDED HIGHWAYS ONLY

| | |
|---|---|
| INSIDE SHOULDER | |
| MEDIAN MOWING LIMITS | Md 108 |
| MEDIAN DITCH | |
| MEDIAN FENCE | |
| MEDIAN MOWING LIMITS | |
| INSIDE SHOULDER | HB |
| SURFACE | 1HB |

RT

| | |
|---|---|
| SHOULDER | LB — HB LB U — LB — CB LB — HB CB HB — CB — HB CB HB — HB — CB — HB — CB — HB — CB — HB |
| DITCH | U — P — U — P — U — P |
| MOWING LIMITS | 10' — 5' |
| FENCE | |

MILEAGE 0 .2 .4 .6 .8 .0 … .2 .4 .6 .8

| ROADSIDE PARKS (22) | STEEL BEAM GUARDRAIL (FEET) (23–27) | OTHER GUARDRAIL (FEET) (28–32) | (33–34) | OVERHEAD SIGNS (35–36) | OTHER SIGNS (37–40) | MINOR DRAINAGE STRUCTURES (LESS THAN 20 FT.) (41–43) | FENCE (MILES) (44–46) | MOWING (ACRES) MEDIAN (47–49) | MOWING (ACRES) ROADSIDE (50–52) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 10488 | 00000 | 00 | 00 | 0162 | 161 | 000 | 000 | 017 |

REMARKS G. Rail @ Co Li given to Mont. Co.

| DITCHES (MILES) PAVED (53–55) | DITCHES (MILES) UNPAVED (56–58) | SHOULDER (MILES) UNPAVED (59–61) | SHOULDER (MILES) LOW BIT. (62–64) | SHOULDER (MILES) HIGH BIT. (65–67) | SHOULDER (MILES) CURBED (68–70) | MEDIAN (MILES) (71–73) | RAMP (MILES) (74–76) |
|---|---|---|---|---|---|---|---|
| 021 | 093 | 001 | 107 | 162 | 040 | 000 | 000 |

CODES:

| SYSTEM | SURFACES |
|---|---|
| I= INTERSTATE | U= UNPAVED |
| P= PRIMARY | LB= LOW BIT. |
| S= SECONDARY | HB= HIGH BIT. |
| R= INTERCHANGES SPURS, RAMP ETC.. | X= BIT. OVER P.C.C. |
| M= MUNICIPAL ROUTES | C= P.C.C. |
| C= COUNTY ROUTES | **SHOULDERS** |
| **DITCHES** | LB= LOW BIT. |
| P= PAVED | HB= HIGH BIT. |
| U= UNPAVED | U= UNPAVED |
| | CB= CURBED |

NUMBER OF LANES / MILEAGE BY SURFACE TYPE

| NUMBER OF LANES | UNPAVED | LOW BIT. | HIGH BIT. | BIT./P.C.C. | P.C.C. |
|---|---|---|---|---|---|
| 22 | 23–25 | 26–28 | 29–31 | 32–34 | 35–37 |
| 38 | | 39–41 | 42–44 | 45–47 | 48–50 |
| 51 | | 52–54 | 55–57 | 58–60 | 61–63 |
| 64 | | 65–67 | 68–70 | 71–73 | 74–76 |

SUMMARIZED BY [signature] 9-11-86

*Figure 28. Example of detailed inventory.*

ous maintenance elements at different locations. Generally, maintenance personnel know the way around their area very well, but occasionally they will not know which is the shortest or quickest route, dependent in part on traffic conditions.

Equipment that displays digital maps showing a vehicle's location with respect to highway features (intersections, routes) is already optional equipment on some new automobiles. If one enters the origin and destination, this equipment will determine the shortest path and display the route on the screen. Similar equipment used for marine navigation was demonstrated to maintenance field supervisors.

## INPUTS TO SHORT RUN SCHEDULING

Many maintenance field managers, especially second level managers and superintendents, have responsibility for weekly or bi-weekly scheduling of maintenance work, labor, and equipment. They must ensure immediate problems and deficiencies are addressed along with routine, periodic, and corrective maintenance that has been planned over the year, as well as maintenance deficiencies citizens report. Annual work load requirements are typically derived from condition and distress surveys for pavements and bridges and from quantity standards (annual production rates) for each activity tracked by the maintenance management system.

Maintenance managers periodically receive target levels of accomplishment for various types of work, and it is their responsibility not only to schedule enough work to meet the planning targets but also to address any pressing maintenance needs that have recently emerged, including urgent or emergency repairs.

As maintenance field supervisors and superintendents travel about their maintenance area, they develop a sense of what specific work is required to meet their targets. They also identify new maintenance needs, such as potholes, pavement blowups, blocked drainage, or damaged signs and guardrail.

Consequently, field managers have a need to record the maintenance deficiencies as they travel about. They must ensure these maintenance needs are integrated into the schedule for addressing other deficiencies. They may also wish to report the needs to the next highest manager or enter them into the maintenance management system data base.

A simple approach to help field managers collect information during their daily activities is to supply them with a voice-activated tape recorder. They can then make verbal notes of maintenance problems while patrolling or traveling to and from work sites. Normally, they would note deficiencies or needs on a paper form. Many maintenance deficiencies get neglected, however, because field managers and superintendents lack a convenient way to record them while driving. If they had a tape recorder, to refresh their memory at the end of the day, they could prepare more accurate and complete needs reports. This recorded information could then be combined with other inputs required for scheduling.

Figure 29 depicts a more automated data acquisition system for daily maintenance needs identification which may aid in short run scheduling. A notebook computer, laptop, or electronic tablet would be furnished to field managers with scheduling responsibilities. Deficiencies identified in the field would be recorded in the data collection device and transferred from within the vehicle by cellular telephone to a host computer. If the field manager returns directly home at the end of the day, data can be transferred from the device by modem over the home telephone. If the manager returns to the local office at the end of the day, the data can be directly transferred to a computer via an RS232 cable. The field manager can also electronically initiate a work order or print a crew day card. Enhanced collection of locational information can be achieved using GPS, a distance measuring instrument or some other method.

When it is necessary to develop a weekly or bi-weekly schedule, the field manager can retrieve planned work targets based on annual work programs, the problems noted in the field, citizen

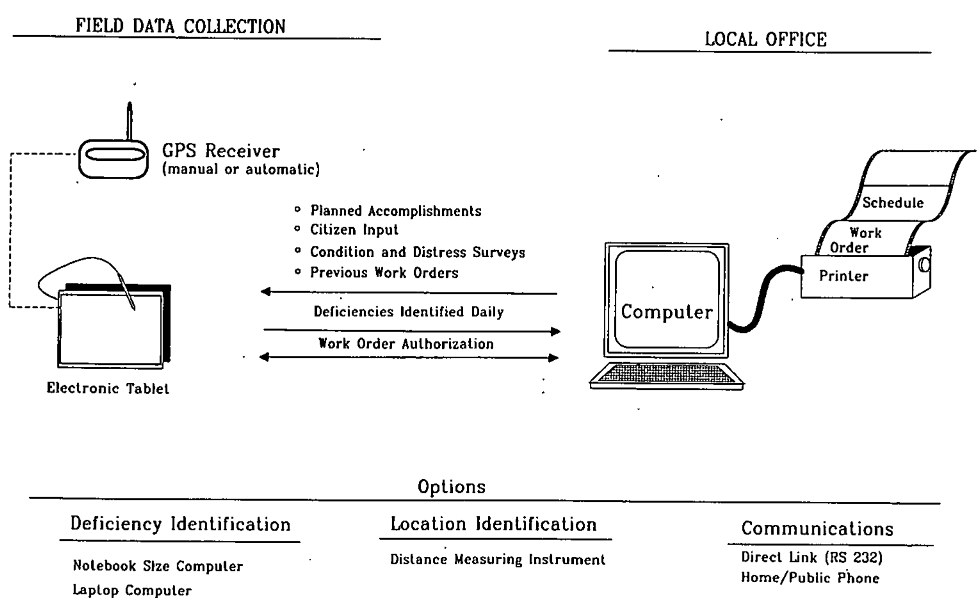



*Figure 29. Inputs to short-run scheduling.*

complaints, condition and distress data, performance standards, and available labor, equipment and material. The field manager would then use this information to schedule the work and identify the resources required.

This combination of information will also be useful to top maintenance managers responsible for programming and budgeting.

## BRIDGE INSPECTION AND MAINTENANCE

The horror of bridge collapse—the New York Thruway or the San Francisco Bay Bridge—dramatizes the nation's infrastructure problems. The Federal Highway Administration estimates that the backlog and accruing needs to roughly maintain the current condition of the nation's 585,000 bridges from the period from 1987 through 2005 is $92 billion in 1987 dollars (*23*). These needs reflect expenditures on replacement and rehabilitation. They do not account for the potential cost savings of routine, preventive, and corrective maintenance, and repairs.

A conscientious program of bridge inspection and maintenance at all levels of government is essential to minimizing bridge costs. Under the National Bridge Inspection Standards, generally each bridge must be inspected at least every 2 years. Bridges with fracture critical members, scouring, or other special problems require more frequent inspection. States can examine a safe bridge less often, but they must justify to the Federal Highway Administration less frequent inspection.

Bridge inspectors use a variety of forms (standardized in each state) to collect inspection information, including the data to support the condition and appraisal evaluations states must submit to FHWA. Inspectors may supplement the form with narratives, sketches, and photographs. Figure 30 shows part of a typical form.

Pennsylvania developed a hybrid bridge inspection and maintenance needs report shown in Figure 31. This form represents a creative synthesis of the bridge inspection and maintenance functions.

Some types of data collection technology already discussed in this report (laptops and electronic tablets) can potentially improve the speed, accuracy, quality, and documentation of bridge inspection and maintenance needs.

Some agencies have already tried using laptop computers to collect bridge inspection information. One can develop menu-driven software to display the standard bridge inspection forms on the screen. The bridge inspector keys in data, which can be checked by the computer for errors.

The main disadvantage of laptops for bridge inspection is that they are relatively bulky compared to paper and pencil, and inhibit an inspector's movement on and about the structure, especially if it is necessary to climb a ladder or walk or crawl onto a beam.

Another alternative is the electronic tablet (clipboard) whose data entry screen functions like a digitizing tablet. Preprogrammed inspection/maintenance forms such as those described above will appear on the tablet's screen. As explained earlier, with one type of electronic tablet, a person can enter elements on the form in a variety of ways. For example, the inspector can print the entry in block letters just as one may with a regular pencil and paper. A person can also just tap the proper checkoff box next to a set of multiple choices.

BRIDGE INSPECTION REPORT

Bridge No._____ Bridge Type_____ Inspector_____
Name_____ Crossing Over/Under_____ Date___
Year Built___ District_____ County_____ Photographs_
Field Book No._____

CONDITION RATING — REMARKS

58 DECK
1. Wearing Surface
2. Deck - Structural Condition
3. Curbs
4. Median
5. Sidewalks
6. Parapet
7. Railing
8. Paint
9. Drains
10. Lighting Standards
11. Utilities
12. Joint Leakage
13. Expansion Joints or Devices
14. Record Elevations
Gutterline @ ℄ Brgs
@ ℄ Spans

Inspectors Condition Rating

59 SUPERSTRUCTURE
1. Bearing Devices
2. Stringers
3. Girder or Beams
4. Floor Beams
5. Trusses - General
- Portals
- Bracing
6. Paint
7. Machinery (Movable Spans)
8. Rivets or Bolts
9. Welds - Cracks
10. Rust
11. Timber Decay
12. Concrete Cracking
13. Collision Damage
14. Deflection under load
15. Alignment of Members
16. Vibrations under load

Inspectors Condition Rating

*Figure 30. Example bridge inspection form (first page of a typical bridge inspection form).*

With an electronic tablet, a bridge inspector can make handwritten notes and sketches of problem areas found on bridges. Bridge inspectors can write their signatures directly onto the screen. Data can be stored internally and then transferred to other storage media, including, if needed, an optical disk.

Electronic tablets do not wholely eliminate the difficulty of carrying a piece of equipment around a bridge in the outdoors, although manufacturers have designed some for rugged field use.

A bridge inspector may wish to use a digitizing still camera to complement information being recorded on the inspection forms. The camera will work under normal lighting and mild weather conditions. The digital pictures can be stored along with other inspection and maintenance data.

Figure 32 shows a proposed systems design for collecting bridge inspection and related maintenance information. The bridge inspector can upload the information at the end of the day into a computer. The inspector can also transmit the information electronically via modem and cellular or regular telephone.

In principal, with an electronic tablet that has a built-in computer, all types of bridge inspection data can be retrieved by the inspector or maintenance field supervisor with a modem and cellular telephone. Thus, data flows to the field manager would include work orders, emergency and urgent repair needs, condition ratings and appraisals, and results of detailed or special inspections including sketches and photographs.

# BRIDGE MANAGEMENT SYSTEM
## BRIDGE INSPECTION REPORT: MTCE. & MAJOR IMPROVE. NEEDS

D-4[illegible]F (12-[illegible])
PAGE 3

| INSPECTION REPORT FOR: | | STRUCTURE IDENTIFICATION NUMBER |
|---|---|---|
| ENTIRE BRIDGE | ⊔ | A01 ⊔⊔ ⊔⊔⊔⊔ ⊔⊔⊔⊔ ⊔⊔⊔⊔ |
| MAIN SPANS ONLY | ⊔ | |
| APPROACH SPANS ONLY | ⊔ | |

| | | H01 ITEM NO. | H03 LOCATION | UNIT | H05 EST. QUANTITY | H08 PR |
|---|---|---|---|---|---|---|
| APPROACH ROADWAY | PAVEMENT (PATCH/RAISE) | RDPAVMT | N F | S.Y. | | |
| | PAVEMENT RELIEF JT (REP/REPL) | RDRLFJT | N F | S.Y. | | |
| | SHOULDERS (REPAIR/RECONSTR) | RDSHLDR | N F | S.Y. | | |
| | DRAINAGE-OFF BRIDGE (IMPROVE) | RDDRAIN | N F | E.A. | | |
| | GUIDE RAIL-(CONNECT TO BRIDGE) | RDGDEPL | N F | E.A. | | |
| | LOAD LIMIT SIGNS (REPLACE) | RDLDSGN | N F | E.A. | | |
| | CLEARANCE SIGNS (REPLACE) | RDCLSGN | N F | E.A. | | |
| | CUT BRUSH TO CLEAR SIGNS | RDBRUSH | N F | E.A. | | |
| | APPROACH SLAB (REPLACE) | A7442011 | N F | S.Y. | | |
| CLEAN/FLUSH | DECK | A743101 | | E.B. | | |
| | SCUPPER/DOWNSPOUTING | B743101 | 123450 | E.B. | | |
| | BEARING/BEARING SEAT | C743102 | 123450 | E.B. | | |
| | STEEL-HORIZONTAL SURFACES | D743102 | 123450 | E.B. | | |
| DECK | BITUL DECK W. SURF (REP/REPL) | BITWRGS | 123450 | S.Y. | | |
| | TIMBER DECK (REP/REPL) | B744301 | 123450 | S.Y | | |
| | OPEN STEEL GRID (REP/REPL) | C744302 | 123450 | S.Y. | | |
| | CONCRETE DECK (REPAIR) | D744303 | 123450 | S.Y. | | |
| | CONCRETE SIDEWALK (REPAIR) | E744303 | 123450 | S.Y. | | |
| | CONCRETE CURB/PARAPET (REPAIR) | F744303 | 123450 | S.Y. | | |
| DECK JOINTS | RESEAL | A743301 | N1230F | L.F. | | |
| | REPAIR/RESEAL | A744101 | N1230F | L.F. | | |
| | COMPRESSION SEAL (REP/REHAB) | B744102 | N1230F | L.F. | | |
| | MODULAR DAM (REP/REHAB) | C744102 | N1230F | L.F. | | |
| | STEEL DAMS (REP/REHAB) | D744102 | N1230F | L.F. | | |
| | OTHER TYPES (REP/REHAB) | E744102 | N1230F | L.F. | | |
| RAILING | BRIDGE/PARAPET (REP/REPL) | PLCBRPR | N1230F | L.F. | | |
| | STRUCT MOUNT (REP/REPL) | PLCSTRM | N1230F | L.F. | | |
| | PEDESTRIAN (REP/REPL) | PLCPEDN | N1230F | L.F. | | |
| | MEDIAN BARRIER (REP/REPL) | PLCMEDB | 123450 | L.F | | |
| DK DRAIN | SCUPPER GRATE (REPLACE) | DRNGRAT | 123450 | E.A. | | |
| | DRAIN/SCUPPER (INSTALL) | B744401 | 123450 | E.A. | | |
| | DOWNSPOUTING (REP/REPL) | C744402 | N1230F | E.A. | | |
| | | | | | | |
| BEARINGS | LUBRICATE | A743501 | N1230F | E.A. | | |
| | STEEL (REP/REHAB) | A744501 | N1230F | E.A. | | |
| | STEEL (REPLACE) | B744501 | N1230F | E.A. | | |
| | EXPANSION (RESET) | C744502 | N1230F | E.A. | | |
| | PEDESTAL/SEAT (RECONSTRUCT) | D744503 | N1230F | E.A. | | |
| TIMBER | STRINGER (REP/REPL) | A744801 | 123450 | E.A. | | |
| | OTHER MEMBERS (REP/REPL) | B744801 | 123450 | E.A. | | |
| STEEL | STRINGER (REP/REPL) | A744802 | 123450 | E.A. | | |
| | FLOORBEAM (REP/REPL) | B744802 | 123450 | E.A. | | |
| | GIRDER (REPAIR) | C744802 | 123450 | E.A. | | |
| | DIAPH/LAT. BRACING (REP/REPL) | D744802 | 123450 | E.A. | | |
| RC/PS | STRINGER (REP/REPL) | A744803 | 123450 | E.A. | | |
| | DIAPHRAGM (REP/REPL) | B744803 | 123450 | E.A. | | |
| | OTHER MEMBERS (REP/REPL) | C744803 | 123450 | E.A. | | |
| TRUSS | MEMBER (STRENGTHEN/REP/REPL) | A744701 | 123450 | E.A. | | |
| | PORTAL (MODIFY) | B744701 | 123450 | E.A. | | |
| | MEMBER (TIGHTEN/FLAMESHORTEN) | C744702 | 123450 | E.A. | | |

| | | H01 ITEM NO. | H03 LOCATION | UNIT | H05 EST. QUANTITY | H08 PR |
|---|---|---|---|---|---|---|
| PAINTING | SUPERSTRUCTURE-SPOT | A743201 | 123450 | E.B. | | |
| | SUBSTRUCTURE-SPOT | B743201 | N1230F | E.B. | | |
| | SUPERSTRUCTURE-FULL | C743201 | 123450 | E.B. | | |
| | SUBSTRUCTURE-FULL | D743201 | N1230F | E.B. | | |
| ABUTMENT – WING – PIER, ETC. | BACKWALL (REP/REPL) | A744801 | N F | C.Y. | | |
| | | | | | | |
| | ABUTMENTS (REPAIR) | B744802 | N F | C.Y. | | |
| | WING (REP/REPL) | C744802 | NLRFLR | C.Y. | | |
| | PIERS (REPAIR) | D744802 | 123450 | C.Y. | | |
| | | | | | | |
| | FOOTING (UNDERPIN) | E744803 | N1230F | C.Y. | | |
| | | | | | | |
| | MASONRY (REPOINT) | F744804 | N1230F | C.Y | | |
| | | | | | | |
| | ABUT SLOPEWALL (REP/REPL) | A745101 | N F | S.Y. | | |
| | ABUT SLOPEWALL (CONSTRUCT NEW) | B745102 | N F | S.Y | | |
| | | | | | | |
| | PILE REPAIR | A745801 | N1230F | E.A. | | |
| EROSION CONTROL | STREAMBED PAVING (REP/CONSTR) | A745301 | UPUNDN | C.Y | | |
| | ROCK PROTECTION | B745301 | UPUNDN | C.Y. | | |
| | SCOUR HOLE (BACKFILL) | C745301 | UPUNDN | C.Y. | | |
| | STREAM DEFLECTOR (REP/CONSTR) | D745302 | UPUNDN | C.Y | | |
| | VEGETATION/DEBRIS (REMOVE) | ECREMVG | UPUNDN | C.Y | | |
| | DEPOSITION (REMOVE) | ECREMOP | UPUNDN | C.Y. | | |
| CULVERT | HEADWALL/WINGS (REP/REPL) | A745201 | IN OUT | S.Y. | | |
| | APRON/CUTOFF WALL (REP/REPL) | B745202 | IN OUT | S.Y. | | |
| | BARREL (REPAIR) | C745203 | – | S.Y | | |

FOR COMPLETION BY REVIEW ENGINEER

APPLY PROTECTIVE COATING

| | | | | | |
|---|---|---|---|---|---|
| DECK/PARAPETS/SIDEWALK | A743401 | DPS | S.Y. | | |
| SUBSTRUCTURE | B743401 | N1230F | S.Y. | | |

CONSTRUCT TEMPORARY

| | | | | | |
|---|---|---|---|---|---|
| SUPPORT BENT | A745401 | N1230F | E.A. | | |
| PIPES | B745401 | LT & RT | E.B. | | |
| BRIDGE | C745401 | LT & RT | E.B. | | |

**LEGEND**

N = NEAR
F = FAR
1 2 3 ETC = SPAN OR PIER NUMBER
O = OTHER
NLR = NEAR LEFT OR RIGHT
FLR = FAR LEFT OR RIGHT

UP = UPSTREAM
UN = UNDER
DN = DOWNSTREAM
IN = INLET
OUT = OUTLET
E.B. = EACH BRIDGE (SITE)
XXX = BMS DATA ITEM ID.

PR = PRIORITY CODE

0 - CRITICAL SAFETY DEFICIENCY, PROMPT ACTION REQUIRED (INFORM BRIDGE ENGINEER)
1 - EMERGENCY, WITHIN 6 MONTHS
2 - EMERGENCY, WITHIN 12 MONTHS
3 - PRIORITY, WITHIN 2 YEARS
4 - ROUTINE STUCTURAL, CAN BE DELAYED UNTIL FUNDS ARE AVAILABLE
5 - ROUTINE NON-STRUCTURAL, CAN BE DELAYED UNTIL PROGRAMMED

**MAJOR IMPROVEMENT NEEDS**

F01 YEAR NEEDED ⊔⊔⊔⊔ F02 TYPE WORK ⊔⊔⊔

F04 IMPROV LGTH ⊔⊔⊔⊔⊔⊔

*Figure 31. Penn DOT's inspection and maintenance needs report.*

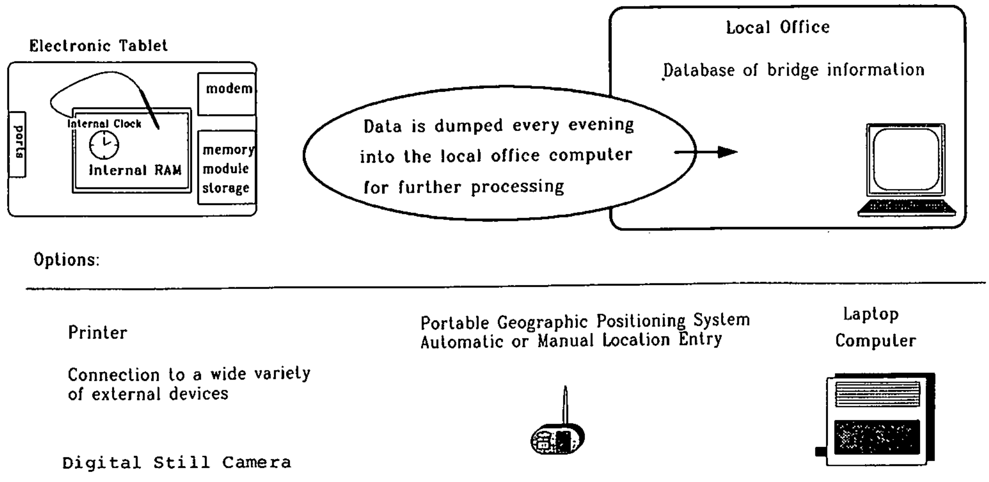



*Figure 32. Bridge inspection.*

To obtain this type of feedback, the bridge inspector or maintenance field supervisor can make a request of the data base, by making a selection from a preprogrammed menu. Assuming there were a cellular telephone link, after a few minutes the information would be transmitted and stored within the electronic tablet for retrieval and viewing on the screen (Figure 32).

The practicality of this bridge data collection system can be quickly determined through field tests. One effective way to evaluate the clipboard is to compare it to pencil and paper data acquisition, and a similarly programmed laptop and voice recognition system. A shakedown of the clipboard and rival approaches to data collection will determine if, indeed, the clipboard is as effective in field conditions as one believes it may be.

## HEAVY SNOW REMOVAL EQUIPMENT MONITORING

Snow removal in cities and areas with light snowfall usually involves a plow fitted to the front of a heavy piece of equipment such as a dump truck. In areas of heavy snowfall a snow blower capable of removing drifts sometimes in excess of 15 ft deep accompanies the snow plow.

In areas of heavy snowfall it is necessary to stay ahead of the "power curve" and remove the snow nearly as fast or faster than it is falling, otherwise accumulations will exceed the local highway department's ability to remove it in a reasonable length of time and reopen roads. Interstate and other major freeways must be kept open. Snow-blowing equipment usually keeps roads open in rocky mountains and other high snowfall areas.

The job of snow removal in many rural and remote areas is a solitary one. It is a job that requires the heavy equipment operator to work long hours sometimes in hazardous blizzard conditions. Drivers often become fatigued and prone to accidents. Snow plows and snow blowers sometimes hit parked vehicles under deep snow or leave the roadway and become immobilized in a ditch or ravine.

It is desirable to implement a monitoring system which will, without any assistance from the driver, transmit the location of rural snow plows and snow blowers to a monitoring facility. It will also be desirable for the monitoring facility to know whether or not the plow is moving, the engine is running, and some other basic information about the condition of the equipment. In the event of an equipment failure or the vehicle leaving the road, a passive monitoring system will alert the monitoring facility as to the nature of the difficulty so that other equipment can be dispatched to take over, and if necessary rescue a trapped or injured driver.

Many highly rural or remote areas are out of reach of the high frequency radio network maintained by most highway departments. Even where radio communications are adequate, in the event of an equipment accident, the radio can be disabled or the driver may be seriously injured and unable to use it. On the other hand, a passive reporting system will not need assistance from the driver.

The data acquisition and telecommunications technology examined in this study suggests a practical solution to this problem. The solution is consonant with the trend toward real-time monitoring of snow and ice control operations throughout the country.

In this study, the research team looked at ways to provide a passive monitoring system for snow removal work. Several navigational systems were considered including Loran C, Omega, and satellite GPS. Several government agencies have successfully tested a system to passively identify and locate carriers of hazardous material on the nation's highways. These systems have used both GPS and Loran C as the source of the longitude and latitude data and both have transmitted those data via satellite to remote points.

Of major importance is the accuracy of the location of the disabled vehicle. A number of satellite locational systems can provide acceptable accuracy. Loran C is accurate to within a 100-m circle under most conditions and is generally available over most of the continental United States. Omega, a military system, is in widespread use but is no more accurate on land than Loran C. GPS is at least as accurate and is becoming widely available.

Therefore, there is commercially available equipment which is capable of passively recording and reporting the location of snow plow or other vehicle without attention from the driver.

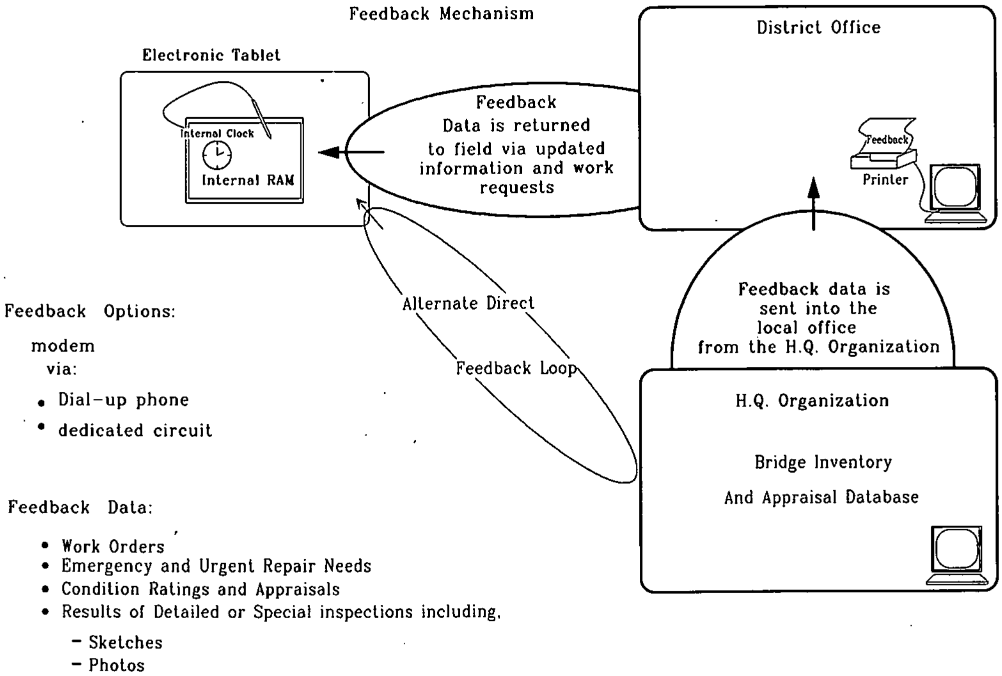



*Figure 33. Bridge inspection feedback loop.*

The telecommunications links used to transmit the position and status information to a distant location were also addressed in the study. Cellular telephone technology, conventional VHF and UHF radio links ("push to talk"), other conventional radio technology, as well as the more recent developments in satellite communications, were considered.

The widespread availability of L-band satellite capacity for mobile satellite services at an inexpensive price has made satellite monitoring of snow removal equipment a practical solution for the nation's highway departments. This longitude and latitude information is periodically transmitted via a low data rate satellite terminal on top of the cab of a snow plow or truck (Figure 33). This is a very small unobtrusive and virtually indestructible antenna. It is not a dish nor is it a protruding whip that could be easily damaged physically. Moreover, the antenna is omnidirectional so that trucks or snow plows which become tipped on their side will still be able to send their information to the receiving satellite.

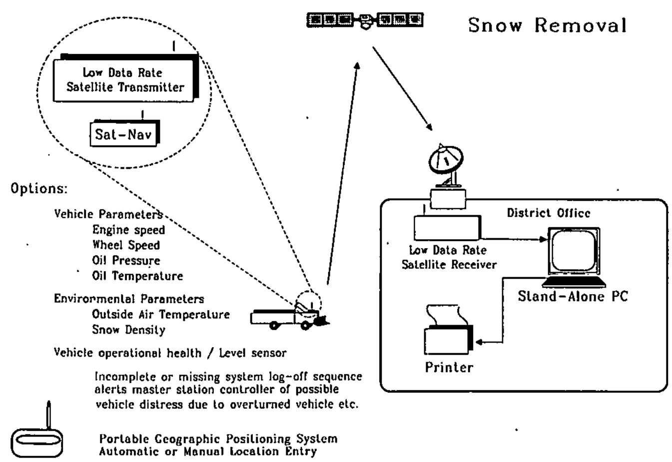



*Figure 34. Snow removal.*

Information on the status of snow removal equipment would be transmitted at a low data rate and then pass through the satellite down to the monitoring facility (Figure 34). The monitoring facility could be a single one within a state or shared by several states. If a particular highway district's snow plow has a problem, the system could be easily programmed to dial up and alert that highway district to the problem and the location of the plow. Several kinds of data could be sent from this snow plow, depending on the requirements of the highway department: location, outside temperature, cab temperature, axle speed, engine speed, and temperature. It would also be possible to put a small communications terminal, such as a laptop computer, on the seat next to the driver in order to send and receive messages via the satellite. The time delay between sending and receiving the message will be no greater than transmitting data via a wire line or any other telecommunications technology. This system would consist of plug compatible commercially available components.

Four thousand dollars is the approximate cost to place monitoring devices, a transmitter, and a satellite antenna on a large snow plow. Cost will decline in the future. There will be additional costs for software development, hardware at the monitoring facility, and data transmission. Transmission would occur during snow removal operations and at periodic intervals, perhaps every 30 min. Transmission costs will be less than $0.05 per hookup plus $0.002 per character. The total number of characters normally will be few. Implementation will require a more detailed engineering and systems analysis.

CHAPTER FIVE

# INTERPRETATION, APPRAISAL, AND APPLICATIONS

## INTEGRATED MAINTENANCE DECISION SUPPORT TOOLS

Maintenance management is undergoing a rapid evolution emphasizing integrated decision-making. Maintenance management systems that were developed in the early 1960s are aimed at effectively managing the labor, equipment, and material resources allocated to maintenance. However, a variety of new decision support tools have since emerged that add new dimensions to maintenance decision-making. Pavement management systems are concerned with determination of highway capital and maintenance requirements and the optimal allocation of funds between these competing programs. Bridge management systems address similar issues for structures. Geographical information systems are being implemented in many states and provide a platform for all these decision support systems.

Indeed, there is a strong trend toward integrating these different management tools, which is the objective of a related NCHRP project (14-9(4)) to develop an idealized maintenance management information system (MMIS). This idealized MMIS, if fully realized and implemented, would become a new generation maintenance management system that would supplant the currently prevalent type.

The technologies that are the subject of this research can help speed the evolution of maintenance management systems toward an idealized and integrated system. For instance, if a cartographic map base, including maintainable roadway inventory features, is available to support GIS, various data acquisition technologies used in conjunction with GPS technology can provide more site-specific, accurate, and timely field data to crew leaders and other maintenance managers. Such data will also greatly enhance all other maintenance management functions whether it is needs estimation, budgeting, work planning, scheduling, reporting, or performance evaluation.

Some maintenance managers, accustomed to traditional ways of working, will resist changes, but most workers will welcome them. Expectations of what maintenance personnel can accomplish are continually increasing, including their technological prowess. Although maintenance field managers do not wish their activities to be intensely monitored, they will adopt a new way of working if it clearly benefits them. Data acquisition technologies that can significantly reduce or eliminate laborious paper work, and provide a variety of useful, timely information (emergency conditions, equipment availability, and location), will be well received by field managers. The rewards to upper management will be more accurate information that will improve maintenance decision-making generally.

Most of the technologies described here were initially developed for purposes of indoor or outdoor data collection. While not all commercially available equipment can withstand the wide variety of environmental conditions faced by maintenance workers throughout the United States, much rugged equipment is available. Moreover, by carefully specifying requirements for a particular setting, maintenance agencies may find that equipment with some limitations is adequate for the data collection task.

Any data acquisition system that an agency implements should have an open architecture to ensure easy upgrading. Modular systems composed of plug compatible units have this characteristic. As improvements in technology occur, better and, perhaps, lower cost equipment can replace older equipment.

Continuing advances in telecommunications will have a beneficial effect on the types and quantities of data that can be transmitted easily. Already electronic mail (E-mail) is available not only for recording voice messages, but also for storing data files and facsimile copies that can subsequently be transmitted over any communication link capable of carrying digital information (telephone, satellite, cable). Also, integrated digital services networks (ISDN) will be widespread by the middle of the 1990s. ISDN promises easy data transmission of text, voice, and imagery. Advances in voice technology and digital image processing that are now occurring will create significant demand for digital communication networks, which, during the 1990s, will become nearly universally accessible to businesses and homes.

States that elect to automate a large part of the inventory control and management systems may wish to set up an electronic data interchange (EDI) with their key suppliers. EDI, which is employed by large numbers of manufacturers in the United States, eliminates much paperwork associated with purchasing, shipping, and receiving supplies, and can provide up-to-date information on shipment status. With EDI, material orders are placed electronically. Shipment data are on line at both the supplier and receiver end, so that it is easy to confirm that correct deliveries are being made. EDI helps make just-in-time inventory management systems feasible, and can significantly lower warehousing costs.

The challenge for highway and transportation agencies will be to fully evaluate the cost saving opportunities for various data acquisition technologies and procedures. The opportunities are constantly expanding as innovation takes place in both the public and private sector. This research has developed initial system designs that are suggestive of how an agency should proceed. Agencies should resist letting the lack of familiarity with these technologies serve as a barrier to considering, evaluating, or field testing them.

## IMPLEMENTATION ISSUES

An agency contemplating installing an advanced technology system for acquiring maintenance data should proceed both informally and formally. In either case, effective implementation may require identifying a champion for technological innovation within the maintenance division. That person will need to provide the enthusiasm and energy to overcome traditional operating procedures.

The champion will provide an important educational function and should be given the time to become immersed in the various options, gain working familiarity with the technologies, and share his or her new knowledge with both field supervisors and higher level maintenance managers. Vendors will usually be happy to loan equipment to a prospective client.

Simultaneously, it will be necessary to establish a steering committee or task force. An able and respected manager should lead it and that person should ideally be the champion. It is essential that top management, starting at the level of the Chief Administrative Officer, be fully informed of the project and fully support it. Without the support of the highest levels of management the internal communication required to install a new data collection system may break down. Implementation will require considerable interaction among numerous organizational units within the agency including maintenance, bridge, pavement management, and the data processing units. Implementation must be cognizant of trends toward integration of maintenance, bridge, pavement, accounting, and geographical information systems.

An early determination will be whether implementation will be an in-house effort, a consultant-assisted effort, a vendor effort, or a combination of all three. An agency would benefit from having an independent party familiar with the broad range of options work with the steering committee and prospective vendors.

This study has identified the pros and cons of different technologies and preliminary systems designs. The findings help narrow the choices. However, each implementation will have different requirements, and the agency will have to reassess the options—be it laptops, bar coding, radio frequency tags, electronic tablets, as well as the hardware, software, communications, and system configuration.

Simple demonstrations should occur during the early implementation stages. A technology may appear alluring. But, unless it has been field tested in a realistic setting with the communication and feedback links in place, it is presumptuous to assume it is a workable solution.

It is critically important to fully take into account standard operating procedures, the work culture, and the environment that will affect the practicality and acceptance of the system. The users should be heavily involved in the design of the system. They should be encouraged to identify bugs and suggest solutions. The more the users participate in the design, the greater will be their acceptance.

Among the challenging tasks for the agency is the requirement to articulate the data collection needs. The needs must be clearly established both from the standpoint of the field supervisors and the various decision support systems such as the maintenance management system. The agency must reaffirm the value of inputs and outputs (feedback), which this study has determined to be essential in a specific data collection activity, for example, crew card data acquisition. Inevitably an agency will identify a somewhat modified set of data inputs and outputs.

Other indicators of data needs are the value of tracked items, the volume of data required, and the number, location, and layout of maintenance facilities throughout the state or locality.

Once these preliminaries are completed, the agency must embark on a detailed systems definition. It would include detailed process flow charts that would specify data entry points, equipment connections, interfaces with the data processing system, such as local area networks or mainframe, and a variety of other factors.

The agency should avoid the mistake of underestimating the extent of data processing and software programming required to integrate an advanced data collection system. Portable computers, bar codes, and radio frequency tags are simply means of entering data. These technologies are no substitute for a sound data base management and decision support system.

Some type of benefit-cost analysis should be an integral part of the design phase to assure the agency will receive an ample payback for implementing a system. A benefit-cost analysis that includes comparisons of various technologies will assure that the best ones are selected. As pointed out earlier, an agency may wish to use more than one type of data collection technology, depending on the application and where the technology will be used. A benefit-cost analysis may address such factors as the characteristics of the data collection devices such as those discussed in Chapter Two (size, weight, operating and storage, temperature, adhesion of labels or tags, environmental resistance, ruggedness, error checking capabilities, battery life); costs (hardware, software, transmission, labor costs and economies scale); and reliability.

In addition to these, the agency should address vendor capabilities including warranty, response time, system integration capability, and system maintenance capability. Also, training requirements will have to be identified.

Before final authorization to commence a full implementation, the agency should develop a system prototype. Reputable vendors will not commence the full implementation of a technology and system unless the agency has tried it first and ruled out significant bugs in the approach. If a data collection device and feedback system proved to be promising, the agency might try the system in a number of different settings to ensure that its behavior was robust, before embarking on a full systems development effort.

CHAPTER SIX

# CONCLUSIONS AND SUGGESTED RESEARCH

## CONCLUSIONS

Data collection that supports maintenance field operations and maintenance management can become more efficient through judicious use of improved technology and telecommunications. Rapid, accurate data entry that is site-specific rather than oriented to maintenance areas and management units is practical, especially with the advent of GPS receivers. If geographical information systems are going to serve as a platform for maintenance management systems, the capability to collect maintenance data referenced to latitude and longitude is necessary.

Numerous procedures and telecommunications can be designed to enable field managers to extract useful information from the maintenance management system so as to more effectively carry out their daily responsibilities. Maintenance field managers need to know the location and nature of urgent and emergency work, the cost-effectiveness of different maintenance approaches, and the current availability of labor, equipment, and material. Higher level managers need to be able to extract such information as planned versus actual accomplishments and budget balances for different activities. Field managers may also wish to know this information.

Laptops, portable data entry terminals, bar coding, distance measuring instruments, and GPS receivers have already been demonstrated to be effective tools for acquiring data in many private and public sector field applications. Rugged equipment, some built to military field specifications, is available.

Electronic tablets (clipboards), which offer the ability to enter data by handwriting and drawing as well as keyless data entry (tapping data entry fields on a screen), have been recently introduced into the marketplace and are now being used in many indoor and outdoor applications. This type of equipment deserves special evaluation by highway agencies because of its unique capabilities.

Voice recognition systems are too costly and too bulky today to warrant widespread use. However, in the next 5 to 10 years, dramatic improvements and cost reductions in voice recognition technology can be expected. Miniaturization or embedding voice systems in vest jackets is likely to solve the problem of bulky, unfriendly equipment. Maintenance organizations should be alert to cost-effective opportunities to apply voice recognition systems over the next decade.

Implementation of any data collection system requires careful testing and evaluation in the actual operating environment. Demonstrations in a variety of specific settings should precede full-scale implementation. A particular data acquisition system should be compared to other approaches including the existing procedures. It is equally important that data acquisition technologies and data transmission methods satisfy the requirements of specific applications.

Conclusions pertaining to different types of data collection activities are as follows.

*Crew card data collection* should be aimed at serving the needs of those who have reporting responsibility. Data that can serve the needs of first and second level field managers should be the target of any data collection activity.

Crew card data collection procedures that record accomplishments, the location within 50 ft, duration of work, as well as labor, equipment, and materials are feasible with currently available, plug-compatible technology.

*Inventory management and control* can be significantly improved using the technologies assessed in this study. The choice and configuration of technologies will depend on the application. Because of the relative ease of implementation and the high likelihood of cost savings, it is recommended that agencies give strong consideration to a bar code inventory system for physical assets such as vehicles and equipment.

*Roadway feature inventory updating* methods will change as GPS is used to build cartographic map bases for GIS. Maintenance field managers are likely to have a significant responsibility for updating roadway feature inventories and will employ GPS receivers to do so. Agencies that are continuing to use relative elapsed distance to locate inventory features can use distance measuring instruments to update the maintainable elements of roadway feature inventories.

*Inputs to short run scheduling* must be gathered, combined, and processed in an effective way. Otherwise, near-term work priorities will be distorted. Data acquisition equipment, such as electronic tablets, laptops, and hand-held computers—well suited for gathering information regarding maintenance deficiencies spotted in day-to-day operations—may also be an ideal instrument for processing citizen complaints, pavement condition and distress data, and annual work loads based on maintenance management system information.

*Bridge inspection and maintenance* may be improved, significantly, using an electronic tablet that allows the inspector to fill out standard inspection forms, make written comments and sketches, and sign off. The electronic tablet also may permit the bridge inspector working in the field to electronically receive photographs of bridge problems.

*Monitoring of snow-plow operations* in remote locations using satellite positioning and communications can help locate maintenance workers in distress and return disabled equipment to work.

## RECOMMENDATIONS FOR FUTURE RESEARCH

As a direct followup to this study it is recommended that states, individually or collectively, conduct a variety of demonstration projects to further evaluate the practicality and desirability of using different technologies and procedures for field data collection and retrieval. The demonstrations should cover each of the data collection activities addressed in this study: crew card data collection, inventory management and control, roadway feature inventory updating, inputs to short run scheduling, bridge inspection and maintenance, and monitoring of snow plow operations in remote locations. The demonstrations should collectively involve field tests of all relevant technologies and telecommunications.

Other potential research includes the feasibility of establishing an electronic data interchange (EDI) between material suppliers and highway and transportation agencies; the desirability of requiring that all key suppliers to state highway and transportation agencies place bar codes on all deliveries, just as the automobile industry and the U.S. General Services Administration do; the future role of integrated digital services networks (ISDN) in transportation infrastructure management and data processing; implications of changing GPS receiver accuracies and the resultant impact on the implementation of GIS and maintenance data acquisition procedures; and a study of the potential uses of these technologies in other transportation applications.

# APPENDIX A

# ESTABLISHING ROADWAY FEATURE INVENTORY USING GPS

Demands will continue to accelerate for statewide inventory data and status (attribute) information about the roadway, the physical structures along the roadway, and the cultural and environmental features affecting road use. Demand for accurate, timely geographically located roadway feature data is increasing at all levels of DOTs. Collection of field data and maintaining current data are the bottlenecks of virtually all geographical information systems—those systems that can translate automated files into decision maps. These needs will impel the development and use of sophisticated spatial data collection and processing systems such as being pursued under the AASHTO 38 State GPS/GIS project (*24*). That pooled funded study, which expands on earlier demonstrations performed by Rockwell International (*25*) is exploring the use of mobile GPS to establish highway inventories at highway speeds. It is also seeking to interface video logging of roadway features with GPS data collection.

This appendix describes a prototype system for collecting roadway feature inventory data including maintainable items. The system is similar to that being developed under the AASHTO 38 State GPS/GIS project. This appendix also includes several options for updating feature inventory data besides those described in the main body of the text.

## PROTOTYPE SYSTEM

Rockwell International developed the generic components of a vehicle-based, partially automated, geo-referenced feature and attribute collection strategy: (1) sensors for locational and feature (and attribute assessment) data acquisition; (2) converters, the hardware and software means to correlate position and feature data; (3) recorders to record locational and feature data in the field; (4) output formats that enable post-field processing into useful information (Figure 35). The lower part of Figure 35 shows how a personal computer, using both standard and proprietary software, converts field data into graphics, maps, and roadway files.

The Prototype System (Figure 36), based on that being developed under the 38 State GPS/GIS study, makes several important changes to the earlier demonstration system:

1. Sensor components are simplified significantly by the ability to compute accurate over-the-ground (therefore "elapsed") distances directly from the GPS data, thereby relegating the role of DMI management to augmentation rather than an integral part of data collection. Distance measurement instrument sensors, crew management of DMI settings, and data conversion are simplified.

The Prototype System substitutes a high performance stereo CCD camera system for the eye-to-hand manual entry to a laptop PC used in the earlier demonstration system.

2. The earlier demonstration system converted multiple data streams through a single "black box"; the conversion strategy of the Prototype System, under development in the AASHTO 38 State study, relies on recording all data streams, retaining their separate identities and using post-field processing for data conversion and data stream correlation.

3. Recording in the earlier demonstration used standard, separate portable computers to record sensor data, enter feature data, and prepare extensive field notes. The Prototype System by-passes most manual entry operations for data collection but no doubt will retain field note capabilities. The CCD cameras require very large on-board storage capacity—probably optical disks. Maintenance managers may be equipped with compatible components to augment the Prototype System with point feature data, and the all important, often judgmental, assignment of attribute qualities to such features.

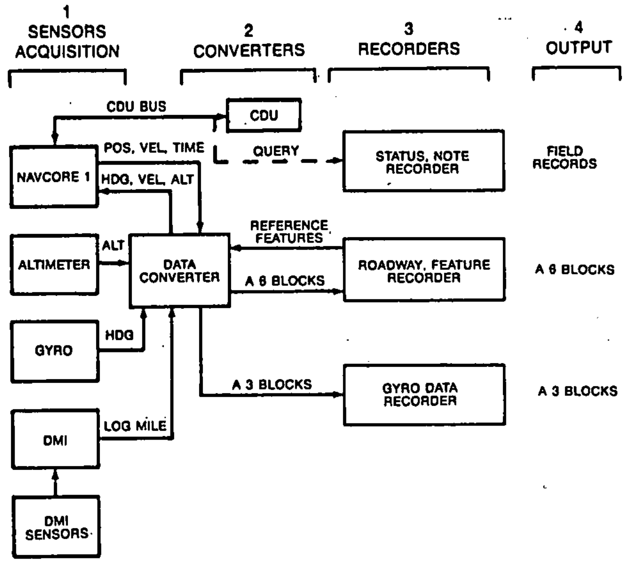
4. Outputs from the earlier demonstration project included digital road alignment, selective reference features (bridges, intersections, entrances, etc.), and the correlation of field road alignment data with a host of DOT historical feature data bases based on elapsed distance. Outputs from the Prototype System consist of more accurate road alignment and feature location, elapsed distance computed from a GPS, a digital visual record of roadway features, and perhaps roadway geometrics from other sensor data.

Options and other key considerations for various components of the prototype system are as follows:

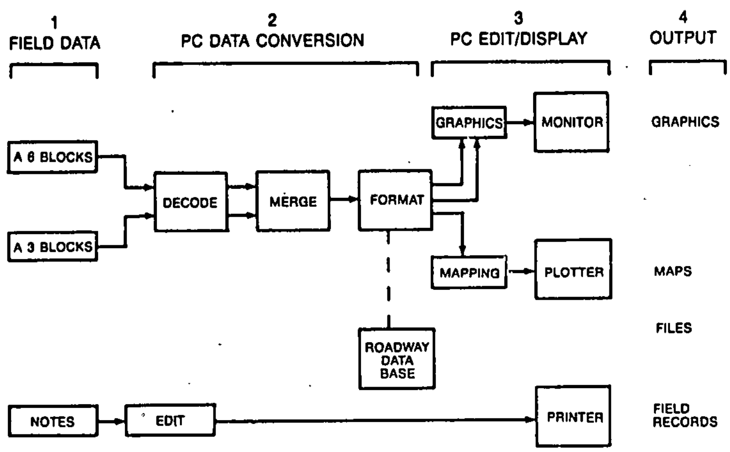
- A host of manufacturers will produce higher performance, lower cost GPS receivers as the GPS satellite constellation moves closer to full operational status over the next few years.
- Inertial guidance components to track collection vehicles through periods of GPS satellite blockage (e.g., tunnels, heavy forest canopy, extreme terrain) are expensive and will remain so. Maintenance units could be equipped with GPS/feature recording devices for selective or "point" data collection rather than continuous, very high quality automated alignment feature collection.
- Cost considerations also restrict the number of vehicles that can be equipped with stereo CCD cameras or other automated sensing systems linked to geo-positioning technology.
- Inexpensive digital recording technology and software to tie manual entries to DMI-GPS location outputs has been demonstrated. As part of a larger DOT commitment to geo-located data bases, maintenance units should be equipped with such equipment.

## PERFORMANCE SPECIFICATIONS

*Locational Accuracy.* Development of suitable roadway feature inventories requires absolute geo-position of road alignment and roadway features within 10 m acquired at highway speeds. This performance standard requires differential (one GPS unit recording over known datum, one mobile) GPS data collection. Multichannel receivers capable of achieving this accuracy are expected to come down in price to ± $10,000.




GPS Field Equipment and Data Flow.




GPS Data Conversion to GIS.

*Figure 35. Demonstration system and components.* (Courtesy of Rockwell International)

*Data Rates.* Data rates for the Prototype System are expected to require high performance, "hardwired," data acquisition and transfer to optical disk storage. Given that each digital stereo pair of video imagery may require 2 megabytes of data, the Prototype System specifications call for 360 megabytes of optical storage on board. Experience with GPS and selective feature entry with the earlier demonstration system allowed for the use of on-board storage of high density floppy disks and data rates under 2 megabytes per day for road alignment and feature collection.

*Vehicular Collection.* The Prototype System assumes the collection of road alignment and feature data at "highway speeds," with the locational constraint of GPS equipment being its location update once every second. The Prototype also calls for a highly customized "mobile work station" vehicle and crew support systems (Figure 37).

*Augmenting Prototype System Baseline Data.* If, as we think most probable, maintenance units are tasked with augmenting baseline road alignment and feature data bases, most of these tasks can be accomplished by equipment used to update roadway feature inventory data as discussed in the main text. Exceptions might be densely developed urban areas, very rugged terrain, etc., where inertial aiding will be necessary.

In addition to the updating procedures described in the main body of the report, two additional options can be used for augmenting and updating inventory features and referred to here as maintenance option 1 and maintenance option 2 (Figure 38). Maintenance option 1 assumes the use of portable GPS and feature recording equipment that requires a pause at the location of data acquisition. It can be transported by any maintenance vehicle, although a DMI-equipped one would be preferable. Maintenance option 1, which allows portable dwell time over features thus achieving necessary accuracies, can use less advanced equipment and a portable computer. Total equipment cost of maintenance option 1, in 1992, may be under $20,000 for a multi-county maintenance area. Maintenance option 2 incorporates GPS and feature entry into a maintenance work vehicle, but without the expensive provisions for all terrain, all obstacle

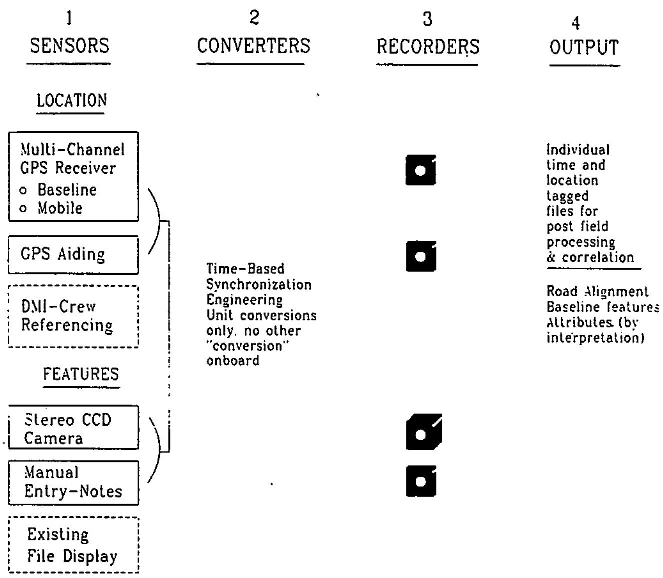



*Figure 36. Prototype system for establishing base roadway feature inventory.*

position tracking and without an automated vision system. Based on the earlier demonstration system experience and the first generation commercial offerings, a maintenance vehicle could be equipped for option 2 for ± $40,000. Such a vehicle could serve several maintenance units and areas.

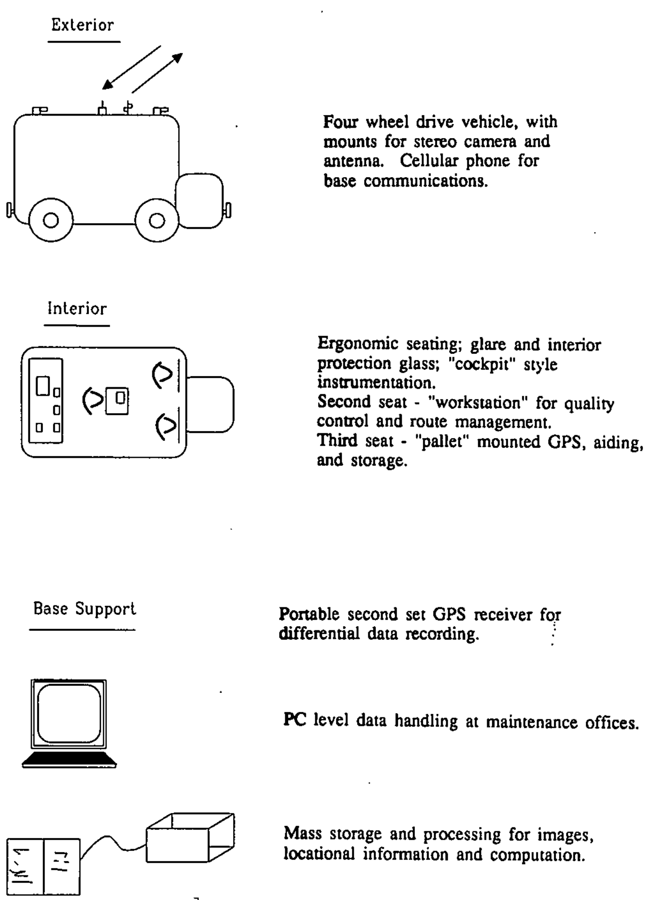



*Figure 37. Pictorial of mobile work station and base support.*

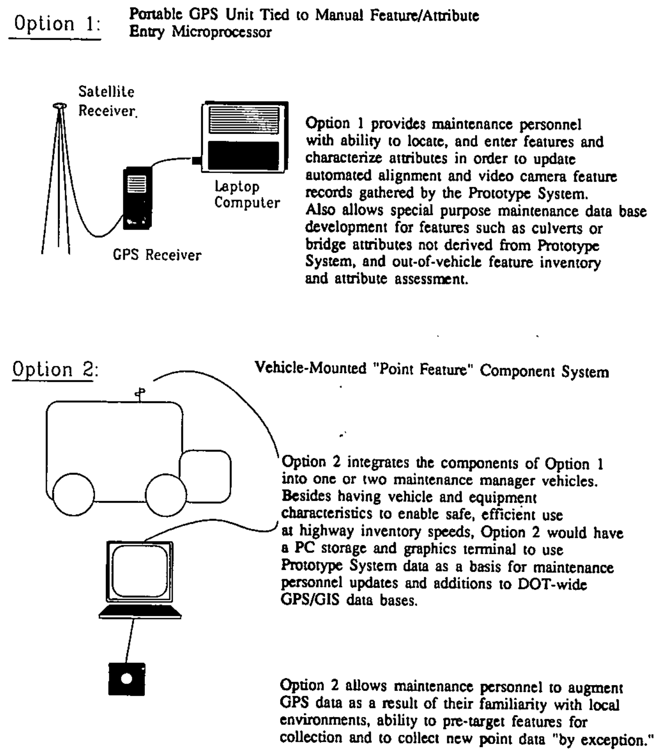



*Figure 38. Component options for maintenance managers.*

The strength of current spatial data handling technology is at the component level. Locational data entry, storage, and processing components are commercially available. Their characteristics appear to be firmly part of a trend toward higher capability at lower cost. The primary weakness of current technology is its lack of integration as a smoothly operating system, which results in less than ideal reliability, simplicity, and flexibility of use.

## ROLE OF MAINTENANCE PERSONNEL

Maintenance level inputs to the GPS/GIS systems will vary by state and region, but preliminary investigation reveals a digital version of road alignment and the baseline feature inventory collection will be developed by the Prototype System, or some similar procedure. Baseline features will include intersections, bridges, facilities, and pavement type. The feature baseline will be located and described by GPS and video cameras.

Maintenance units will be called upon to validate and interpret many classes of maintainable items, plus provide supplementary information. Inputs to GPS/GIS systems directly by maintenance units fall into several categories. The first is labeling or assigning attributes to the roadway feature elements that appear on the video, but which are not fully identified in the original data collection activity. The second is the collection of feature and attribute data for assets, cultural and environmental conditions not available at all from prototype technology, which can include "hidden" assets such as roadway geometrics, smaller culverts, sign nomenclature, right-of-way boundaries, and hazardous waste sites. The third set of inputs, some of which are no doubt included above, are those features and attributes that directly affect and contribute to maintenance management, but which may not be included in statewide data bases. These data may include permit support data, mowing segments, entrances, trash collection nodes, and a host of other information that are "inputs" to the maintenance management system.

The outputs of the Prototype System are the roadway network digital map bases (which also include political boundaries, water courses, railroads and place names and numbers) and DOT-determined feature inventory baselines. These baseline outputs can and should be down loaded to maintenance units once completed to act as the common geographical and feature "templates" for maintenance unit updates, assignment of attributes, and the collection of maintenance management data bases.

The fundamental output of GPS/GIS map templates as well as feature and attribute data bases is the ability to display selected "layers" of these data in graphic decision map form. PC equipment and software enables decision mapping to reach the maintenance manager's desk. The critical maintenance role in developing the DOT baseline and special purpose data bases should ensure the leverage necessary to place GPS/GIS output capability at the maintenance levels.

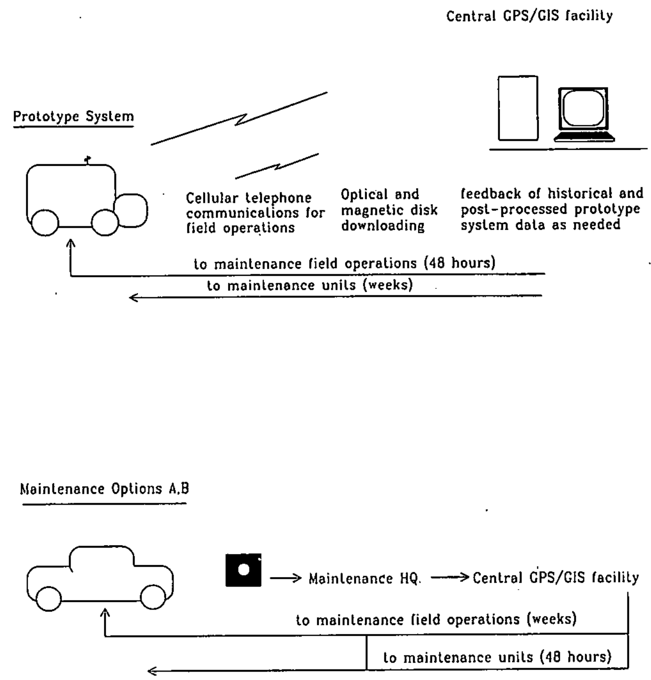



*Figure 39. Data flow and feedback.*

### Data Flow and Feedback

Figure 39 describes the data flow and feedback to the maintenance manager or maintenance management unit from the Prototype System and the maintenance option 2. Field experience and the design characteristics of the prototype and maintenance options indicate strongly that telecommunications transmission of the roadway alignment, feature and attribute data is highly unlikely. Manual downloading of optical and standard data recording media to post-field processing will be the operating standard. In the case of the Prototype, the CCD image data rates overpower telephone or even microwave transmission. For both Prototype and the 2 maintenance options, there simply is not any expressed demand for "on-line" data transfer.

### Training

Training maintenance units involve learning how to use GPS receivers in this field application, and it takes about half a day. Training needed to learn to operate a portable GPS and feature and attribute recorder (maintenance option 1) is a "classroom" day, plus several days of field applications. Operation of maintenance option 2 is more complex. Maintenance personnel should be involved from the outset in setting up and deploying equipment for maintenance option 2. Maintenance personnel need to understand the mechanical and electronic interfaces, requisite procedures for quality control, and how to remove and replace equipment when repair is necessary. Training must involve both drivers and operators. The smooth functioning of both is key to efficient feature collection and accurate results. Based on the research team's experience, a week to ten days of intense field experience is needed to operate a vehicle-mounted system. Months of working together as a team may be needed to optimize the collection process, which suggests that maintenance units assign a stable team to the feature and attribute updating task, with a trained backup team.

Training for the Prototype System is beyond the scope of this study, but involves a major investment of training and careful selection of the team or teams assigned to this exacting discipline.

# APPENDIX B

## WORKSHEETS FOR TECHNOLOGY ASSESSMENTS

During the second phase of this project, the technology assessment, scores for different attributes of various data collection devices, as well as a composite score, were developed. Figure 40 shows a typical attribute score sheet. Although this type of technology assessment is highly subjective, the exercise, nonetheless, was found to be useful.

Figure 41 was used to visualize how two different technologies compared along different dimensions of performance. By plotting the scores given to the attributes for Technology A and connecting all the points, and doing the same thing for Technology B, it is easy to see if Technology A or B is superior along most or all dimensions. If "0" is the highest score and "9" is the lowest, a technology with all 0's would hit "the bullseye." The technology with characteristics closest to the bullseye is the better technology, although normally Technology A would be superior to B in some respects and inferior in others.

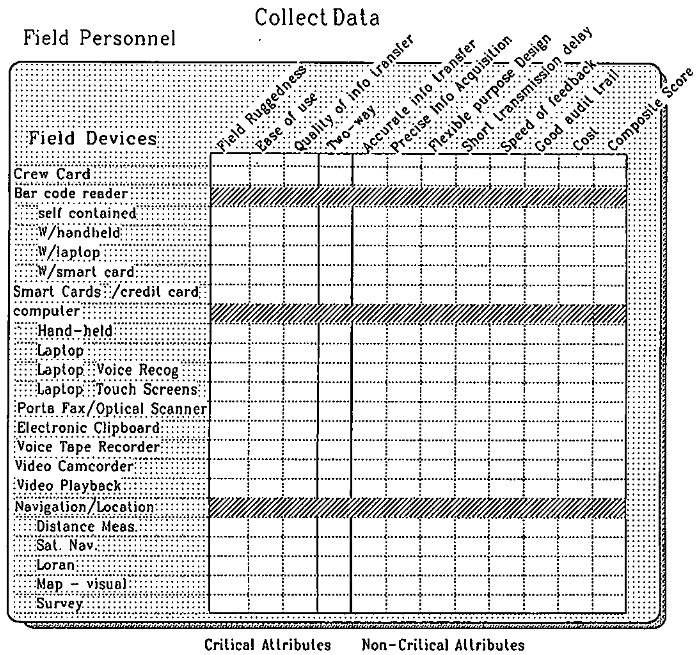



*Figure 40. Technology assessment scoresheet.*

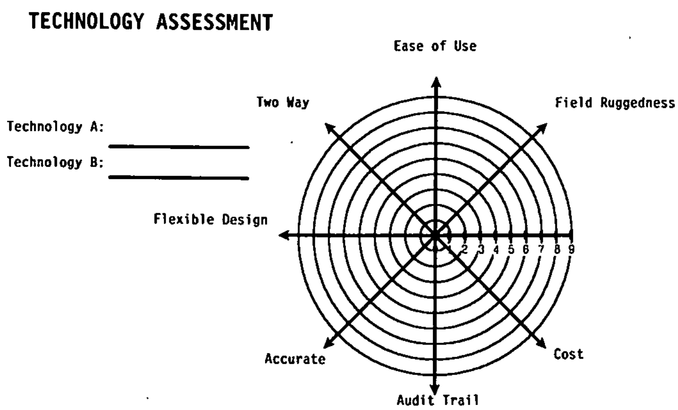



*Figure 41. Comparisons technologies.*

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