Field Testing and Evaluation of Innovative Technologies for Maintenance Data Collection

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Automated electronic procedures for data capture and transmission appear to be superior compared with manual paper-based methods. Many highway agencies are now either using or exploring some of these innovative technologies for many of their data collection activities. For maintenance management, a variety of recording and data entry procedures involving pen and paper could be considerably improved using electronic equipment such as portable and pen-based computers, identification technologies including barcoding and voice recognition, and location systems such as global positioning system and geographic information system. In addition, data transmission can be accomplished much faster and in real time between distant locations using telecommunications systems such as mobile phones. The application of advanced data acquisition technologies for maintenance management in state highway departments is summarized.

Maintenance management has suffered from slow and tedious procedures for inspecting highway condition, scheduling maintenance work, reporting field maintenance accomplishments, updating changes in roadway and stock inventories, and in transferring and posting information from the field reports to the headquarters for processing. It takes a significant amount of time and effort to conduct field inspections, prepare biweekly and daily schedules, check and enter daily maintenance reports, and record changes in the agency's field and warehouse inventories. Indeed, in all these aspects of maintenance management, there is a need for "one-time, quick and easy" data collection, entry, and verification systems for directly entering information into maintenance management systems. In addition, location reference systems such as route-milepost and discursive methods are unable to identify exact locations of maintenance work and field inventory items.

Innovative technologies can be used by maintenance supervisors and field workers in lieu of their current data collection methods. Automating existing procedures can reduce or eliminate paperwork, create more accurate and reliable information, provide quick turnaround of data from field to office, and improve the overall productivity of the maintenance unit.

This paper presents the approaches and findings of a number of research projects undertaken by the Urban Institute on the application of field data collection equipment for maintenance management. One project was conducted for the National Cooperative Highway Research Program (NCHRP) and consisted of two-phase research and investigation on improvements in data acquisition technology for maintenance management systems (NCHRP 14-10). During the first phase, the research identified requirements and design considerations for applying new technologies to various maintenance data collection scenarios (*1*). With assistance from several equipment vendors, some of these technologies were field-tested and evaluated in three state transportation departments: those of Maryland, Connecticut, and Arizona (*2*). Analyses indicate the potential for these agencies and possibly others to reduce costs and improve the overall efficiency of maintenance data collection. Pen-based computers (including electronic clipboards and tablets), barcode scanners, voice recognition systems, global positioning system (GPS) receivers, regular and cellular telephones, and digitized maps were customized for applications involving work scheduling, work reporting, and the updating of roadway feature inventories by maintenance crew leaders and supervisors. In addition, these technologies were applied to sign inven-

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tory and sign maintenance management. After completing the NCHRP project, the Virginia Department of Transportation (VDOT) requested that the Urban Institute develop demonstration-level field data collection applications. Two portable electronic tablets with handwriting recognition capabilities were customized and field-tested for the evaluation of highway pavement maintenance by VDOT staff (*3*).

This paper first discusses the general characteristics of the maintenance activities for which the technologies were customized. Specific methods by which the activities are performed in the four field sites are briefly described, including the average lengths of time needed to record various types of data. Hypotheses concerning how innovative technologies can improve the existing methods are stated. The design and evaluation of the field tests are discussed. General findings drawn from the field tests are summarized in the conclusion.

Maintenance Data Collection Activities

Four different but interrelated maintenance data collection activities were the focus of the equipment field tests:

1. Work scheduling,
2. Work reporting,
3. Roadway feature inventory updating, and
4. Maintenance quality evaluation.

Applications of innovative technologies for the first three activities (referred to as a three-part process) were examined in Maryland, Connecticut, and Arizona as part of the NCHRP 14-10 (Phase 2) study. Maintenance quality evaluation was performed exclusively in Virginia.

Although the elements of the three-part process are common to most states, their implementation varies from state to state. The NCHRP project involved examination of the specifics by which the three-part process is conducted in Maryland, Connecticut, and Arizona. Detailed analyses, interviews, and focus group sessions with DOT staff were necessary to understand existing maintenance management practices and customize the design of the technologies to the host states. For maintenance quality evaluation, the research team worked closely with VDOT in identifying specific equipment design considerations. A description of the activities demonstrated and how the states normally carry them out follows. Hypotheses concerning how innovative technologies can improve these activities are briefly noted.

Work Scheduling

Highway maintenance work is usually scheduled to attain agency-specified level-of-service goals as well as address emergency or urgent repair needs. Scheduling helps management efficiently allocate its labor, equipment, and material resources, which are often limited. Management also seeks to ensure that all short-run work (daily, weekly, or biweekly) conforms to the state's annual work program and at the same time meets the local needs of the constituencies. Short-run scheduling considers various inputs, which differ among states and may include all priority listings based on maintenance needs surveys (including pavement evaluation), monthly schedule based on annual work program, leftover work from previous daily assignments, supervisor patrol survey forms, service requests, and emergency and urgent repair needs.

Biweekly schedules in Maryland are often subject to changes, making them informal and optional in most places. Scheduling supervisors have developed their own procedures for scheduling upcoming work. In the Westminster shop, Carroll County, where the field tests were conducted, it is common practice to assign activities to maintenance workers on a daily basis. The supervisors usually require 30 min to prepare the daily assignments on their forms. The supervisor relies on his expert judgment and familiarity with the scheduling process to identify which activities will be done and how they will be carried out.

Section superintendents and supervisors in Connecticut conduct biweekly scheduling meetings to determine the types and amounts of routine maintenance work needed and their locations. Like Maryland, the basis for the schedule is the annual maintenance work program for districts throughout the state. Litchfield garage, the site of the field tests, has 20 maintenance field workers including the supervisor. The procedure is informal and may involve preparing the schedule on the standard form, which takes about 45 min. Daily work assignments are made by the supervisor on a piece of paper.

In Arizona, the schedule is prepared by a supervisor and approved by the area superintendent. The supervisor fills out a standard weekly schedule form for the crew (a crew is also called an "org") and lists the activities in priority order. The scheduling practices of sign orgs in Tucson and Phoenix (those who participated in the field tests) are not significantly different from those in Maryland and Connecticut. Maintenance operations, however, are more ad hoc, since in most cases the crews respond to urgent needs such as repairing damaged signs.

Analysis of these practices and those of other states indicates that short-run scheduling can be aided by a laptop computer or electronic clipboard. Such equipment can combine data bases used for scheduling and allow incorporation of expert system functions. To be accepted by the schedulers, however, computer-aided scheduling should be simple, convenient, and practical. One perceived advantage of computer-aided scheduling is that the forms for daily work reports or crew cards (assumed here to be created by the computer as well) can be automatically filled with some or most information from the schedule, thereby eliminating the need to write the same information when preparing the daily work reports.

Work Reporting

Daily work reports provide maintenance headquarters with a basis for comparing planned work with actual work and assessing the adequacy of the maintenance budget. These reports also provide data for evaluating the productivity of maintenance jurisdictions; keeping track of labor, materials, and equipment use; and determining whether adjustments to quantity and performance standards are necessary. In many states, daily work reports are combined with time sheet preparation, payroll documentation, and accounting.

Maryland DOT uses crew day cards with preprinted data for daily work reporting. Each card issued by the central office is related to the maintenance budget for the county or area and represents a certain amount of resources for 1 day's work on a particular activity. Crew leaders usually fill out their crew day cards at the maintenance shop after completing the day's work, using field notes written in a notebook or on scratch paper in the field. Information on crew cards is turned over to a timekeeper who manually fills out the time sheets. Crew cards are then passed on to another clerk who fills out the maintenance activity summary worksheet. On the average a crew leader takes 5 min to fill out a card for an average crew of four persons. The clerks need about 5 min to transfer data from each crew card to the time sheet, 3 min to the maintenance summary, 2 min to the equipment inventory (18 min during winter), and 2 min to the budget balance (18 min during winter). This means a total data entry time of between 12 and 44 min for a single crew card.

A standard daily job assignment form or a crew leader's daily assignment sheet, or both, is used for daily work reporting in Connecticut. Each crew leader in the garage fills out a separate form. At the end of the day all the data are combined in the general supervisor's daily report for the entire garage. Information from this report is manually transferred every day onto a maintenance management system summary sheet, the biweekly time sheets, and the equipment rental report. These are sent to the district office for processing. In the Litchfield garage, the crew leaders spend an average of 5 to 20 min each filling out their work reports for an average crew size of three. It takes 3 to 4 hr every day for the clerk to transfer the information from the crew work reports to various forms in the garage.

A lead worker or senior crew member in Arizona fills out the standard crew work report form. Like other states, the Arizona crew work report has entry fields for describing their day's activity, labor, equipment use, materials, and accomplishments. Each completed report is given to a data entry staff or clerk, who checks it before entering the data into a PC-based maintenance management system, PeCos, which most org computers have. Arizona DOT has a network communications system that allows an org to upload work reports, planning files, and materials inventory to the area terminals. Orgs that are away from the area office submit their work reports by courier. It takes crew leaders between 6 and 20 min to fill out their daily work reports. A clerk collects the reports and keys in the information to PeCos. For each daily work report, the average time to transfer the data into the computer is 2 to 5 min, depending on how much error the crew leader makes.

A review of the states' daily work reporting procedures indicates that electronic data capture can help decentralize the activity to the level most appropriate for maintenance management—the field. However, new procedures would have to be easy to use and reflect actual practices. Equipment that provides feedback and useful information for field workers also has the potential to improve staff performance. Finally, automatically created time sheets, equipment and material inventory reports, and other summary reports can increase the efficiency of field and office maintenance management.

Roadway Feature Inventory Updating

Regular updating of maintenance features inventory allows an accurate accounting of the quantity and status of all maintainable elements throughout the state. This inventory is often the major input for annual work programs and budgets. Allocation of maintenance resources among districts or lower-level organizational units also depends on the quantity of maintainable items in each jurisdiction. Generally for the three demonstration states, the task of updating roadway feature inventory is not the responsibility of general supervisors and crew leaders.

Maryland DOT maintains a roadway feature inventory on logs. The inventory is updated using the back portion of the maintenance improvement crew day card. Crew leaders and general supervisors are required to fill out this card in place of the regular crew day cards when the activities performed involve safety improvements, maintenance improvements, or new installations. The maintenance management system, which prints the crew day cards and resides in the central office, has a feature inventory program that updates the master inventory file and carries out the procedures for planning the statewide annual work program. In the Westminster shop, crew leaders rarely use the back of the improvement card because they seldom do work that involves addition to or deletion from the inventory. Shop requests for updated inventory of their maintainable elements from the central office takes a lot of time to process.

In Connecticut, roadway inventory data are used to compute and define work programs. The district planning section is responsible for maintaining an up-to-date roadway inventory record. Inventory data are updated before creation of the annual work program. Adjustments are made if there are additions to or subtractions from the highway inventory as a result of new construction, betterment work, or changes in pavement surface. The nature of maintenance activities and the manner in which quantity standards are defined determine which roadway features are included in the inventory. In the Litchfield garage, the supervisor does not have an updated record of the roadway inventory for his jurisdiction. There is currently no reliable feature inventory in place for maintenance management nor a means to update it.

The org supervisors in Arizona are responsible for maintaining an accurate feature inventory of roadways. A periodic condition assessment is conducted with the help of the area superintendent. Maintenance features include roadway and roadside elements, shoulders, drainage installations, landscape, and signs and striping. Field inventory forms are used by field personnel. An inventory of all maintenance features for each district is compiled, showing quantity and location of existing features. Arizona DOT maintains a link feature file on a mainframe computer. This file contains the inventory values on which the maintenance management system depends. Information contained within this file is also used, either directly or indirectly, in establishing the annual work program and budget. In addition to the link feature inventory file, Arizona maintains a sign record system that stores the sign inventory (field tests in Arizona focused on sign management). The sign orgs fill out the sign record forms as various actions are taken on each sign. However, sign managers have problems getting updates of the sign inventory because the clerks have no time to transfer the information from the forms into the mainframe computer.

It appears that roadway feature inventory updating is most effectively performed by crew leaders and supervisors. Accuracy, ease of use, and perceived value of information are the most influential factors for acceptance of field data collection devices for inventory updating. The integration of inventory updating with daily work reporting may result in cost savings.

Sign Inventory and Maintenance Management

Signs and traffic control devices are valuable to highway agencies. Large inventories of signs and materials used to fabricate signs are usually kept in stock, in addition to those already in the field. The central sign and striping warehouse in Phoenix, for example, maintains an inventory worth over $10 million in 1992 (excluding interstate signs). In addition, districts and yards all over the state have their own inventories.

The tasks involved in managing and maintaining field and warehouse sign inventory can be enormous, as is the case in Arizona. Automating many of these recording and data updating tasks would substantially reduce the level of effort. Moreover, these valuable assets can be effectively managed if the warehouse inventory is tied to the roadway inventory. Sign inventory is probably best performed by crew leaders who are responsible for these features. Automated location and attribute-point data collection for signs, especially if carried out in conjunction with a map, is valuable for sign inventory and maintenance management.

Maintenance Quality Evaluation (Virginia DOT)

One mission of VDOT's maintenance division, headquartered in Richmond, Virginia, is to ensure that the state highways are adequately maintained, meaning that their conditions are within acceptable limits. This is the main goal of the department's maintenance quality evaluation (MQE) program, which involves field inspection of sample highway sites and sections to determine whether the conditions of the sites pass or fail statewide standards. The site selection is based on a statistical process that randomly generates a list of highway segments, each 161 m (0.1 mi) in length, for every district throughout the state. The highway segments are classified by district, county, route number, section number, and other location identifiers.

In 1993, only three persons in VDOT conducted the site inspections. These inspectors identify the locations of sample sites on a map before going out in the field. The inspector rates each site on the basis of visual assessment of various characteristics of five major elements of the highway: traveled way, shoulders, drainage, traffic control/safety, and roadside. The inspector also enters the data from the survey forms into a Lotus 1-2-3 spreadsheet application on a computer in Richmond. On the average, it takes 30 min to enter the information for 60 sample sites.

Virginia has 9 districts and 100 counties. The computer generates 1,000 sample sites on the average for each district. Also for each district, about 3 months are needed to complete the evaluation, including surveys, computer processing, and report generation.

The existing procedures for recording and uploading site condition data can be significantly improved using field data collection equipment. Inspection surveys recorded in the field device can be uploaded to a computer for processing, thereby eliminating the paperwork and time required by each inspector to enter survey data into the computer. The calculations of both individual and aggregate site ratings can also be performed by the field device, allowing quantitative evaluation of the sites to be carried out in the field and immediately presented to the district or residency.

FIELD TESTS AND EVALUATION

Very detailed software design and customization of equipment for each testing site were performed prior to actual field tests. Data specifications and functions that conform to actual practice were built into each piece of equipment. Field tests and evaluations lasting between 1 and 2 weeks were conducted in the field sites on various dates. The following describes the technologies used and the software applications that were developed for various activities.

Computer-Aided Work Scheduling

Scheduling is the first stage of the three-part data collection process described earlier. For the field demonstrations in three NCHRP host states, a biweekly or weekly scheduling procedure was developed on an electronic clipboard with glass screen. The scheduling procedure was customized for the three states using their standard short-run scheduling forms. An innovative method was developed that permits the scheduler to create a weekly or biweekly schedule from candidate projects in six categories of potential work: (*a*) annual work program, (*b*) service requests, (*c*) patrol reports, (*d*) leftover work, (*e*) emergency needs, and (*f*) recommendations of a pavement management system (PMS). Information from these lists can either be downloaded into the electronic clipboard or built up daily. A master list is built by selecting activities from the various categories to allocate activities to various workdays. Each activity is identified by the location of work, crew size, and number of days. The scheduling system generates and fills out portions of work orders in the form of crew day cards. The crew leader fills out the remaining portions of these crew day cards, including actual labor, equipment, materials, and accomplishments, when the job is done.

The time and effort required to fill out a schedule using pen and paper are approximately the same as those using electronic clipboard. The main advantage of computer-aided scheduling is in letting a person build a schedule from a more complete list of candidate activities. Very few if any states have the means to combine recommendations from their PMS with other candidate projects. Automated generation of work reports with some preloaded information reduces data entry time for crew leaders.

Daily Work Reporting Using Electronic Clipboards, Barcode Scanner, and Voice Recognition

Two types of pen-based systems, one with glass screen and the other with paper overlay, were programmed for daily work reporting of maintenance activities (see Figure 1). A digitized image of the crew day card shows up on the screen as work reporting is initiated. The user can tap different portions of the screen to access different portions of the crew card for project description, labor, equipment, materials, and accomplishments. The user can provide information simply by selecting from a pick list, writing in block characters or numbers, or hunting and pecking from a typewriter or calculator keyboard displayed on the screen. The equipment displays the lists of personnel, equipment, and materials for each activity as defined by performance standards. These performance standards can also be viewed on the screen.

FIGURE 1 Pen-based electronic tablets can replace paper as the means to collect field maintenance data (photograph taken in Connecticut).

The other clipboard requires a paper form to be placed over the digitizing tablet. The user simply writes in block letters in the appropriate fields on the form. The tablet is programmed to accept data entry for all the blocks on the form, showing each entry on the screen. The equipment was also programmed for validating and checking user inputs. The record can be saved in memory and the paper copy kept for records.

Both pen-based tablets accept graphics input but only the glass-screen device could display it on the screen, although a recent version of the other clipboard can display graphics. Both also allow the user to work on any sections

FIGURE 2 Maintenance workers were impressed with the capability of voice recognition system for data collection (photograph taken in Maryland).

of the crew card in any order or save a partially completed report and fill out the rest of the data later.

To use barcoding technology, a preprinted menu with barcode labels pertaining to the sections and elements of the daily work report was created. A barcode scanner, which has an alphanumeric keypad, was programmed for recording crew card data. This data terminal prompted the crew leader with various inputs for the daily work report. The crew leader could either scan a label from the menu or use the keypad to record data on the terminal. The equipment also has a data validation function and an editing feature that allowed the user not only to review the crew work report but also to modify data inputs.

Finally, two crew leaders in Maryland tried and evaluated a voice recognition system, which consists of a belt-mounted battery pack connected to a headset with microphone and earphone (see Figure 2). Using a software development tool kit, the data entry task was developed on the equipment using a vocabulary list applicable to the particular maintenance work. Before the system can be used, it has to be trained to recognize the operator's voice. The system asks a series of questions pertaining to different elements of the report and repeats what the operator says. The system also compares the operator's responses with a list of acceptable responses. The user can control the type of information he or she wants to enter by specifying the appropriate section of the work report. In addition, the system can be commanded to change volume if noise interferes with reception. Every time the system is initiated by an operator it goes through a short training period during which it filters the noise in the background. Different operators can use the system by simply specifying the operator's name or identification. However, the interaction between the user and the system is limited by the system's vocabulary. The training time is also a function of the size of the vocabulary.

All equipment described and tested in the field operated reliably. The software that drives the applications worked well, except that the software for the electronic tablet with glass screen was quite elaborate, resulting in slow processing speeds (a recent upgrade of this equipment would overcome this problem). Surprisingly, most field workers were not bothered by the slow equipment response. Generally speaking, software development tools for programming the different pieces of equipment provide high reliability and convenience. Crew leaders were mostly very receptive to the equipment. However, there was no general preference for one piece of equipment over another. Some disliked all pieces of equipment and prefer to continue using pen and paper.

Crew leaders recommended greater flexibility in data entry to make notes concerning traffic control procedures, variations from normal procedures, problems, and special conditions. The equipment varied in its capability to record this type of information. Some crew leaders expressed concern about keeping the equipment secure from theft, damage, weather, and other conditions in the field.

Time savings, cost savings, and productivity enhancements resulting from the use of the equipment differ among states. In Maryland, for example, the adoption of field data collection devices and the automation of time sheets and maintenance summary reporting can reduce the total time for a shop clerk to post data into the computer from 12 to 44 min to around 6 to 15 min per crew card. This does not include the potential time savings that will be generated in the district as a result of more efficient data transfer from the shop.

If crew leaders in Connecticut were to use the field acquisition devices, the time it would take to complete their work reports would be reduced to about 3 to 10 min. With the computer-automated reporting system in place, the upload time from the devices to the computer (in the Litchfield garage, for instance, with four crew leaders each using electronic equipment) would be less than 20 min (a maximum of 5 min per crew leader).

In terms of automating the processing and consolidation of maintenance data, Arizona DOT is the most evolved among the three host states. The incremental benefits from adoption and full-blown implementation of advanced data acquisition technologies would be minimal for an organization like Arizona DOT, which at the time of the field tests had already automated most of its in-office data handling procedures. However, the incremental cost associated with making the best use of the field devices is also minimal for Arizona DOT, since computer systems are already in place. Daily work reporting using the field devices can be reduced by half the time (about 3 to 10 min) per daily work report. The data stored in the devices can be uploaded electronically into PeCos in less than 2 min per device.

Locating Maintenance Work Using GPS

Aside from the standard data items recorded on the daily work reports, geographic coordinates of work locations were added to the data fields on the field data entry devices. Crew leaders used an unaided GPS receiver to determine their location in latitude and longitude. Accuracy of the location measurements is an important issue for the use of GPS in the field. All the data collection devices tested were programmed to receive data describing geographic coordinates. Whereas the GPS can and should be interfaced with the electronic devices for automatic transfer of coordinates, for this demonstration the crew leaders were asked to read the coordinates from the GPS receiver and write or key in the coordinates on the equipment.

All three states have a route-milepost system established to identify highway locations. However, only Arizona uses this system for identifying the location of maintenance work and highway assets. The Maryland and Connecticut DOTs use the route number and a discursive location description (e.g., road intersections) to identify the location of maintenance work. The use of GPS for daily work reporting and roadway feature inventory updating makes the most sense for organizations that have or are committed to implementing a geographic information system (GIS) for representing their roadway inventories. None of the three states had such a system in place, but all three states were taking steps in that direction. Some supervisors and crew leaders realize the usefulness of the technology in establishing roadway inventories that can be recalled on a computer in the form of a map. Many of them also believe that the GPS can give them a more accurate description of location than their current procedures, which are only exact in terms of identifying route number. Even elapsed distance measurements, which are accurate to within 16 m (approximately 50 ft), lack the required accuracy for identifying specific roadway inventory features, especially in urban areas. The GPS unit used in the demonstration was unaided and had an accuracy of about 100 m (approximately 300 ft) because of selected availability. Accuracies of between 2 and 5 m were obtained with differential GPS during field tests in Arizona.

Roadway Feature Inventory Updating Using Field Data Entry Devices

The roadway feature inventory updating procedure was programmed on the two types of electronic clipboard. Inventory updating on the electronic clipboard with glass screen was demonstrated in all three states and was demonstrated on the one with paper overlay in Maryland and Arizona. The data recording application was generic and included only a number of representative inventory elements such as guardrail, signs, and roadside parks. The user could record the changes (i.e., additions and subtractions) to these inventory elements using either clipboard. In addition, the electronic clipboard with glass screen was programmed to display a digitized map of the locality and to permit the user to mark a specific location of a maintainable feature by placing an icon there. A mock-up of data entry facility for capturing geographic coordinates from a GPS receiver was also provided under the assumption that the receiver would be directly attached to the device with an RS-232 cable, or possibly integrated into the device. The mock-up required the user to touch a button on the display screen to obtain the coordinates from the GPS receiver.

An electronic version of the roadway feature inventory updating form used in Maryland was developed on the paper-overlay clipboard. This application was part of the crew card data collection application on the same equipment used by a crew leader in Maryland to record maintenance improvements information. In Connecticut, roadway feature inventory updating was demonstrated only on the electric clipboard with glass screen. The Arizona sign org staff used both electronic clipboards to enter sign record data on a form separate from the daily work reports. A barcode wand was connected to the clipboard with the paper overlay and used to scan barcode labels affixed to installed signs to associate a unique number to sign attributes, which include type and geographic coordinates (see Figure 3).

The hand-held data terminal with barcode scanner was also demonstrated for updating roadway sign inventory in Arizona. This was the principal piece of equipment investigated in a "cradle-to-grave" sign inventory and management demonstration.

Much of the feature inventory updating process can be automated using the electronic clipboards. The procedure will also enable the crew leaders and general supervisors who are in daily contact with these highway features to update the inventory in conjunction with preparing their daily work reports. Inaccurate procedures for reporting location are part of the reason why inventory updating is not effectively carried out by these individuals. Digitized maps (i.e., GIS) and GPS equipment were received with great enthusiasm by crew leaders and supervisors who evaluated the technologies. In general they believe that these technologies can significantly increase locational accuracies.

Maintenance Quality Evaluation Using Pen-Based Systems

The Urban Institute customized and field-tested a data collection program that allowed VDOT inspectors to record maintenance quality evaluation data on two portable pen-based systems: a notebook computer that converts to

FIGURE 3 Barcoding and pen-based systems are ideal for sign maintenance and inventory management (photograph taken in Arizona).

a pen-based electronic tablet and an exclusive pen-based system. This equipment was field-tested for one week and evaluated by VDOT staff to determine its desirability for field use.

Field testing and evaluation of pen-based systems for VDOT's maintenance condition surveys allowed the Urban Institute and VDOT to examine the pros and cons of using the equipment, and other similar devices, in the field. The greatest source of benefits was the ability to perform all the calculations and generate the reports on site. The same capabilities could have also been demonstrated if the Lotus 1-2-3 spreadsheet application were loaded onto a laptop computer or a notebook computer and used in the field. In fact, key-based data entry was possible with the convertible computer. However, VDOT inspectors prefer a portable pen-based system to carry with them during their site inspections.

VDOT operators needed very little training to use the equipment. The handwriting recognition function of the equipment was reliable, although there was very little writing involved in the process. The keyboard pop-up utility gives the operators the option to choose character/numeric keys with the touch of the pen instead of writing the characters in. The touch-button utility of the equipment was very convenient, reducing the amount of writing involved and simplifying the data entry procedure. The prototype data collection program also allows the operator to review previously saved records.

Cost-Benefit Analysis

To assess the attractiveness of the data collection technologies, a cost-benefit analysis was performed for each maintenance unit in the three states that participated in the NCHRP projects. Two sources of benefits were investigated: time savings in recording, verifying, and checking field data, and time savings involved in automatically posting the data from the field device to the computer and creating the summary reports. These time savings were determined from interviews with field and office personnel in each state, which enabled us to compare current manual data entry procedures with automated methods. The number of years to recover (or break even with) the setup was computed. Statewide extrapolation of results showed that the break-even period for adopting the technologies is from 1 to 3 years (voice recognition was excluded from the analysis because equipment was too expensive to be cost-effective, although the cost is expected to decrease significantly in the future). These break-even periods, however, are sensitive to assumptions about costs and benefits and the discount rate.

The analyses also indicated that the improvements in productivity associated with automating the manual procedures significantly offset the cost of implementing them. Likewise, incremental benefits from field data collection devices are smaller for maintenance units that have already installed personal computers and automated most of their postprocessing methods. Savings were found to be greatest for maintenance units that record much information in the field and transfer the same information by hand to a form in the office. For detailed discussions of the cost-benefit analyses of the field data collection devices, the reader is referred to *NCHRP Report 361* (*2*).

Conclusions

The substantial savings in time and resources that result from automating current procedures for recording, error-checking, transmitting, and processing maintenance data suggest that new technologies are desirable for these purposes. The magnitude of savings relative to costs depends on the nature of the data acquisition process; the number of times that the initial data are processed for posting onto various forms and subsequently entered into the management information systems; the susceptibility to error of the current procedures; the adaptability of the agency and staff to the new technologies; the improvements in managing agency field and office operations, labor, and physical assets; and the amount of resources (personnel, computer and communications facilities, other physical infrastructure, and funds) needed to implement the changes.

Field tests and evaluation of new technologies in Maryland, Connecticut, Arizona, and Virginia provided an opportunity to assess how these factors influence the relative benefits and costs of adopting advanced data capture equipment and methods. It was not possible to control all the factors during the field tests as one might in an ideal situation. Technologies also continue to change, as we found out with much of the equipment used in the field tests. Current costs, sizes, processing speeds, storage capacities, and other functional features differ extensively from those in the past 2 years. The trend, however, is toward better and less expensive products. Highway maintenance agencies should definitely take advantage of what the new technologies have to offer.

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