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Implementation Plan for Automating Highway-Materials Testing

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This report documents the development of an implementation plan for automating highway-materials testing that is based on (1) identification of existing or developing technologies that may be used to automate current highway-materials testing methods and (2) evaluation and prioritization of selected technologies based on their potential for use in highway applications. Technologies and test equipment from other industries and other countries that have potential for use in highway-materials testing were identified and evaluated. The contents of this report are, therefore, of immediate interest to both highway and rail transit professionals responsible for operating materials laboratories and for inspecting materials and construction operations. The report is also of interest to those charged with pavement and structural design, energy and environmental concerns, management and budgeting goal, as well as to policy makers. Equipment manufactures and retailers will find information on potential markets for new equipment.

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Report 427

Implementation Plan for Automating Highway-Materials Testing

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Minneapolis, MN

Subject Areas

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Soils, Geology and Foundations
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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.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

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.

Note: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

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FOREWORD

By Staff
Transportation Research Board

This report documents the development of an implementation plan for automating highway-materials testing that is based on (1) identification of existing or developing technologies that may be used to automate current highway-materials testing methods and (2) evaluation and prioritization of selected technologies based on their potential for use in highway applications. Technologies and test equipment from other industries and other countries that have potential for use in highway-materials testing were identified and evaluated. The contents of this report are, therefore, of immediate interest to both highway and rail transit professionals responsible for operating materials laboratories and for inspecting materials and construction operations. The report is also of interest to those charged with pavement and structural design, energy and environmental concerns, management and budgeting goals, as well as to policy makers. Equipment manufacturers and retailers will find information on potential markets for new equipment.

Braun Intertec Corporation of Minneapolis, Minnesota, was awarded NCHRP Project 4-25, "Implementation Plan for Automating Highway-Materials Testing," to find new uses for existing or new technologies to automate highway-materials testing and to propose a plan to induce government and private laboratories to evaluate and implement these technologies. The research included not only technical feasibility studies of these technologies, but also financial feasibility studies because the automation of specific testing activities must have a market large enough to induce equipment manufacturers to produce and retail the new equipment at prices laboratories can justify. The research developed conceptual designs for 20 of the most suitable automating technologies to prove their applicability and to prioritize their execution. Once the feasibility of automating these technologies was affirmed, the research developed a plan to foster the implementation of the recommended, or any other, new automated highway-materials testing methodology into a working laboratory setting.

To successfully implement automation, several audiences must be convinced that new equipment will be beneficial. Manufacturers must be convinced there is a suitable market, laboratory decision makers must believe that there will be a satisfactory return on their investment, test data users must believe that the resulting data at least maintains the accuracy of the present testing procedures, and regulatory and standards-setting agencies must accept the new methodology. The proposed implementation plan addresses those audiences in ways tailored to their interests, emphasizing the issues most relevant to each audience. The plan incorporates three paths covering the varying states of readiness of the specific conceptual designs: (1) automating existing tests where the benefits are clearly visible, (2) automating tests requiring a demonstration project, and (3) replacing existing tests with tests using new technology. The report suggests that one venue for implementation is to task NCHRP with the execution of any selected implementation plan through additional AASHTO funding.

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This work was conducted through the National Cooperative Highway Research Program, which is administered by the Transportation Research Board of the National Research Council. The research agency was Braun Intertec Corporation, Minneapolis, Minnesota.

Fred Z. Sitkins, CMfgE, CMCS, Associate Professor, Department of Industrial and Manufacturing Engineering, Western Michigan University, and Russ Foster, President, Factory Systems Engineering, Inc., were significant contributors to the search for and application of technologies to materials testing. They also assisted in the financial evaluations of the feasibilities of the conceptual designs.

The author appreciates the review and guidance of Erland Lukanen, PE; Kevin MacDonald, PE, PEng; and Chunhua Han, PhD., PE; all Principal Engineers at Braun Intertec Corporation.

Many people from state highway agencies provided information, responding to surveys at a time when they were particularly busy (construction season). Their tolerant help is also appreciated.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

Highway agencies are facing increasing pressure to reduce costs and improve efficiency in all facets of their operations. Automation of materials testing is an opportunity to do this. While advanced technology has led to significant improvements in materials testing in many industries, test automation has not kept pace in highway-materials testing. Effective automation of highway-materials testing has the potential to improve response time, labor utilization, and the quality and consistency of test results. Because test automation has not kept pace, there is a need to overcome barriers that prevent taking advantage of appropriate new methods. Identifying technologies that can be applied and developing an implementation plan for the automation of highway-materials testing are essential steps toward maximizing the potential returns on investments in automation of testing.

RESEARCH OBJECTIVE

The objective of NCHRP Project 4-25 was to develop an implementation plan for automating highway-materials testing on the basis of

- Identification of existing or developing technologies that may be used to automate current highway-materials testing methods or create new testing methods; and
- Evaluation and prioritization of selected technologies on the basis of their potential for use in highway applications.

Technologies and test equipment from other industries and other countries that have potential for use in highway-materials testing were identified and evaluated. Appropriate technologies were matched to highway-materials test procedures in equipment and procedures that are financially feasible and technically dependable.

Successful implementation will require an industrywide educational effort to show how to create and put into use new test equipment and methods from the identified technologies. Barriers to use of automation must be identified and overcome.

For automation to be successful, four audiences must be convinced that benefits will occur and that the risks will be minimal and tolerable. These four audiences are as follows:

- Materials-testing laboratory managers and supervisors;
- Test equipment manufacturers and sellers;
- Engineers and contractors who use the information; and
- Regulatory and standards-setting agencies, such as AASHTO, ASTM, FAA, FHWA, Corps of Engineers, Bureau of Land Management, and others.

SCOPE

The search for technologies and test equipment that could be adapted was worldwide through the Internet and international library databases. Further, the knowledge of engineers working in the field of automation was tapped through personal contacts and through relevant publications. Sales information from equipment manufacturers was also a valuable source of data.

Candidate tests for automation included tests of all materials used in highway facility construction.

The implementation plan includes a multimedia approach to the four audiences identified.

RESEARCH APPROACH

The study began with a comprehensive search of literature and other available information to identify automation technologies available for application to highway-materials tests. Traditional sources such as research publications and educational theses provided some information. Some technologies were identified through corporate sales publications. Personal contacts within associations of automation manufacturers also provided valuable information. Since automation has been in place for decades in other industries, much of the technology that such industries consider routine is new and valuable to highway-materials testing.

The study of feasible applications of technologies included not only the technical aspects but also a general market study to evaluate financial feasibility. Automation that is technically feasible also must have a market large enough to attract equipment manufacturers to produce and sell the new equipment at prices laboratories can justify.

Two surveys of state highway agency testing laboratories, commercial testing firms, research institutions, and associations identified the following:

- Types and yearly volume of tests, which are being conducted at this time;
- Time required to conduct the tests;
- Elapsed time from receipt of sample to transmission of results;
- Salary, overhead, and equipment costs for current testing;
- Projections of future volumes of tests;
- Perceived barriers to implementation of automation; and
- Priorities among suggested automated tests.

Matching the potential adaptation of technologies from other industries with appropriate highway-materials tests was an iterative process to identify technologies that could be adapted in a technically successful manner at a price that would (a) be a productive investment for laboratories and (b) provide enough market and potential profit for manufacturers. Conceptual designs for technologies, which provided excellent automated tests, but were too expensive to be sold in large enough numbers to justify a manufacturer's cost of development, were given a low priority for implementation.

Conceptual designs thus identified were then prioritized based on documented financial and technical considerations and on a second survey of the interests of state highway-testing laboratory managers.

The implementation plan considers the best thinking of technology transfer within the highway industry. It includes presentations at conferences and committee meetings, video presentations to reach senior managers, and dissemination via the Internet and CD-ROM media. The plan's message documents that automation is a valid way to conduct tests with better precision and reproducibility at lower cost and that there is a market large enough to warrant an investment by equipment manufacturers.

ORGANIZATION OF THIS REPORT

Chapter 2 presents a summary of the research findings, which include the results of the search for technologies, the results of two surveys of laboratory managers, and other related information.

Chapter 3 presents the processes used in conceptual design to identify new automated testing, in financial and marketability evaluations of the designs, and in prioritization for implementation of the new methods. There is also a discussion of the plan for implementation of automation in laboratories.

The overall conclusions from this study and recommendations for further actions are included in Chapter 4.

Appendixes A through D include the financial and marketability analyses of the individual conceptual designs and the information on which prioritizations were based. Appendix D is the detailed implementation plan, which addresses each of the conceptual designs, names specific audiences and ways to reach them, and cites ways to overcome anticipated barriers.

CHAPTER 2

FINDINGS

INTRODUCTION

The key findings of this study are summarized in this chapter. These findings include the following:

- Summary of the issues that facilitate automation,
- Discussion of the barriers that impede automation,
- Technologies identified in the literature search and considered in the conceptual designs,
- Results of the survey on current and future testing,
- Current and future labor statistics,
- Automated equipment already available,
- Precision and reproducibility of current tests, and
- Survey results of conceptual design prioritization.

FACILITATING AUTOMATION

Studies of automation in industry have shown that there is a logical, relatively common progression of steps toward full automation. Automation of testing processes in manufacturing companies was addressed at an ASTM conference in 1993. Several good ideas were available from those papers to guide this research and identify issues to be addressed during feasibility evaluations and in communications to encourage implementation.

Automation has to fit into the strategic goals of the highway agency to receive management support (*1*). Communications should emphasize how automation will fit such goals. Goals that automation can help meet include more services at lower costs, better working conditions for staff, and quicker service to contractors and motorists.

Successful automation requires the coordination of testing, specimen preparation, process control, laboratory data management, maintenance of equipment, employees, and safety (*2*). Thus, when developing automation for a laboratory, it will be necessary to consider the laboratory as a total production system rather than just a collection of independent machines.

Depending on the laboratory size and the number of tests conducted over a given time period, automation may be financially feasible only in stages. Even in large laboratories, it will not likely be feasible to automate all tests. One suggested phasing of automation stages starts with computer data acquisition for limited numbers of tests, followed by computer-controlled test machines, an interface to a host computer, an automated specimen identification system, and, finally, an automated specimen-loading system (*3*). This is also the general pattern observed in the survey results when state laboratories were asked about their existing and planned automation.

The number of repetitive tests to be performed is the primary criterion for evaluating the feasibility of an automated system. Other criteria for this decision include transport of samples, specimen preparation, incorporation into an existing data communication system, availability of skilled personnel, required time to have results available, precision and bias of test procedures, maintenance support (availability of the system), and safety and environmental requirements (*2*). It is the researchers' experience that primary criteria should be a combination of the number of repetitive tests and the number of labor hours required for each test. This gives a better indication of the potential savings from automation. The opportunity to reduce the number of tests that have to be re-run because of operator error can also provide considerable savings. It is widely recognized that automation will reduce testing costs where there are enough tests that the initial cost of automating is offset by the savings in labor and operating costs.

Automation should improve precision and bias by reducing human errors in conducting tests and by automatically maintaining and calibrating the equipment. Benefits include a reduction in the number of tests needed to evaluate a material and a reduced risk of materials failure in service arising from poor testing. These benefits increase with the complexity of the test process and the personal judgment required.

Labor projections suggest that the size of the labor force will decline in the near future. A benefit that will become important is the reduced need for staff as the labor pool shrinks and technician-level staff are harder to attract and retain. This is discussed in a later section of this chapter, titled "Future Labor Force."

BARRIERS TO AUTOMATION

The primary barrier is, of course, demonstrating that automation will be financially successful for laboratories and for equipment manufacturers. Laboratories should have a volume of tests that is large enough to justify purchasing equipment. There also must be a large enough market for a specific piece of automated equipment so that equipment manufacturers will be willing to invest in the time and costs of development, marketing, and sales.

Related barriers are that financial success is not always considered in the automation decision and financial success is measured differently from laboratory to laboratory. Many states have different funding sources for equipment than for labor, so an investment in equipment that will save labor may not get the same consideration. Funding for equipment is scarce and not always available even if a strong justification exists. Further, many states do not consider the real costs of labor when they do a financial analysis of the cost savings of reducing labor. Often the indirect costs of unproductive time, supervision, training, office space and utilities, and other costs are not included in the analysis. The implementation plan must give managers the tools to document and sell the advantages of automation at budget time.

Concerns about the cost of maintenance and the down time of automated equipment are another barrier. This barrier is overcome when competition among manufacturers creates reliable equipment and maintenance through warranties, service contracts, or other planned maintenance.

Manufacturers must be convinced they can make a profit developing new equipment. In their competitive world, they must allocate research and development funds to areas that have the greatest potential for return.

A significant barrier may be laboratory management attitudes. Laboratories that have been generally set in their ways may be reluctant to change their way of doing things (*1*). Many states responded to the survey indicating that managers and staff are not familiar or comfortable with computers and automated equipment. Some have had negative experiences with automated equipment that was not robust in operation. A lack of knowledge of the capabilities of automation is another barrier to acceptance of the concept of automation.

Additionally, the time required to develop new test methods, go through ruggedness testing, and get the new process reviewed and adopted by agencies such as AASHTO and ASTM may affect the cost of developing new test methods.

One technical barrier is the need for operator judgment in some test methods. Judgment may be more difficult to incorporate into a design and to mathematically model for computerized analysis. However, recent advances in computer software using "neural network" and "fuzzy logic" design have resulted in software that can be "taught" to make decisions patterned after the human decisions made in controlled situations.

Another technical barrier is the need for special preparation of test samples, particularly natural soil samples. It does not appear practical to develop automated methods to prepare natural soil samples for tests on "undisturbed" samples.

A barrier for manufacturers is that the market for future equipment may have to be national and international to justify an investment to develop the equipment. Not all manufacturers have the sales and distribution systems to participate in national and international markets. Possibly the Internet as a sales tool will address that barrier.

Finally, not all test equipment manufacturers recognize the size of the highway-materials laboratory market. The implementation plan will address this issue.

AUTOMATED EQUIPMENT AVAILABLE

There are several pieces of equipment commercially available that automate at least parts of test procedures. Computer-controlled testing of soil samples for consolidation, direct shear, and triaxial methods is available from a number of manufacturers. Automated sample splitting and screening equipment is available. At least one automated compression machine for concrete cylinders is available. Recent studies have proven the suitability of nuclear asphalt content gauges (*4–6*). Companies are producing the gauges, and states are beginning to use them.

An automated, robotic workcell for mortar testing has been developed by the Texas State Technical College for the Texas Department of Transportation (DOT). It is estimated that the new process will save $31,000 per year when implemented statewide in Texas. (*7,8*).

Some recently developed highway-materials test equipment has at least basic levels of automation. A good example is the bituminous testing equipment developed by the Strategic Highway Research Program (SHRP).

Some state laboratories have or are developing automated equipment for certain test methods. To find out how many laboratories have some automation, the initial survey asked about automation of data handling and test methods. From the responses, it appears that about 40 percent of the states do not have any automation of data handling and 60 percent have automated data handling in parts of the laboratories. One responding state has a Laboratory Information Management System (LIMS) that automates data handling almost totally. Bituminous testing developed by SHRP is mentioned most frequently as a test that has automatic data handling.

Automation of test methods is most prevalent in the geotechnical area of the state laboratories. Test methods such as direct shear, consolidation, and triaxial testing were mentioned by a number of laboratories.

Automation being planned in state laboratories responding to the survey is largely for data acquisition and handling. Some states are planning to purchase automated test equipment for the geotechnical area.

A variety of new test methods are being evaluated by various states. New test methods are being investigated for particle size analysis of aggregates and soils in Alabama and Minnesota. Alabama had a research project to evaluate two laser-based methods and two X-ray methods of particle size determination. Alabama has selected an X-ray-based method. Minnesota is evaluating a laser-based method. Alabama is evaluating the use of a helium-filled pycnometer that greatly reduces test time for specific gravity of fine-grained soils. Minnesota has an automated sample splitter for aggregate tests. Washington has bar code labeling of field samples and an information management system to track sampling and results.

TECHNOLOGIES IDENTIFIED FOR CONSIDERATION

The comprehensive search of literature and other available information identified many technologies being used in other industries, which can be applied to highway-materials testing. Technologies such as bar code labeling, machine vision, laser measurements, and robotic movement of materials are common in many industries. Industrial testing of powders provided a number of technologies for tests of particle size, specific gravity, and particle surface area. Several technologies for measuring moisture content are being used in agriculture and food processing industries. Medical-imaging techniques are among the newest technologies being adapted to construction materials. Laboratory automation with robotics is particularly advanced in chemical, medical, and biological laboratories, where sample sizes are small and relatively consistent compared with highway materials.

Sample Identification and Labeling

There are a number of technologies in use that could automate sampling and labeling. The most common is bar code labeling and reading. When combined with a computer-based sample documentation system, remote data entry and label printing equipment, and bar code readers, this technology is used in such diverse applications as material control in manufacturing, retail stock control, and express package delivery tracking.

Magnetic chips offer another method of creating a label for future automated reading. A chip is attached to or implanted in a sample. An advantage of the chip is that it can be read from a variety of positions so it is less limiting than the typical bar code equipment. Also, information about the sample can be stored in the chip.

Field equipment for wireless transmission of sample documentation into a computer system is used in many applications. A familiar example is the pen-based computer used by express package delivery people to record and track packages.

Laboratory Information Management Systems (LIMS)

There are many commercially available systems for computerized tracking and processing of laboratory information (*9*). Most of these systems are intended for use in analytical chemistry laboratories but can be adapted to a highway-materials laboratory. Such adaptations are easiest if there are no computerized systems in place.

A limited number of state highway laboratories have or are developing their own LIMS systems. There is a federally funded project to develop Site Manager, a computerized system for total control of construction projects from conceptual design through construction. A module to include construction testing requirements, sample tracking, and test results acceptance is planned.

Drying

Technologies for drying soils and aggregates include the traditional hot plates or open burners, ovens and ovens enhanced with circulation systems, and moisture removal systems. Microwave ovens are in use in materials laboratories but are limited by the potential for changing the nature of the materials, sometimes violently. Centrifuges may have a place in some applications.

Weighing

Mechanical and electrical balances are the common methods in use. A robotic arm can be designed to weigh what is being carried to eliminate a stand-alone balance.

Particle Sizing

Mechanical and hand-operated sieves and hydrometers are the accepted test methods. Geologists have had various semi-automated systems available since the early 1960s and an automated method available since 1985 (*10*). This Automated Particle Size Analysis System integrates a settling tube and an electroresistance multichannel particle-size analyzer with a computer to determine particle sizes through coarse and fine fractions and prepares reports of various types.

The FHWA and others are studying a piece of equipment that uses a form of machine vision (video) to determine aggregate sizing. The VDG-40 was developed and tested by the LCPC, the French central laboratory for material and structural testing for bridges and highways (see Figure 1). This equipment is potentially capable of determining particle sizes in a range of 1 mm to 50 mm. (A similar piece of equipment is available from Micromeritics; and other sources may exist.)

The Alabama DOT commissioned a research study of particle size analysis, which concentrated on a range of 300 to 0.1 micrometers (fine sand to colloidal clay). The study used four commercially available methods of automated test equipment. The study found that X-ray absorption

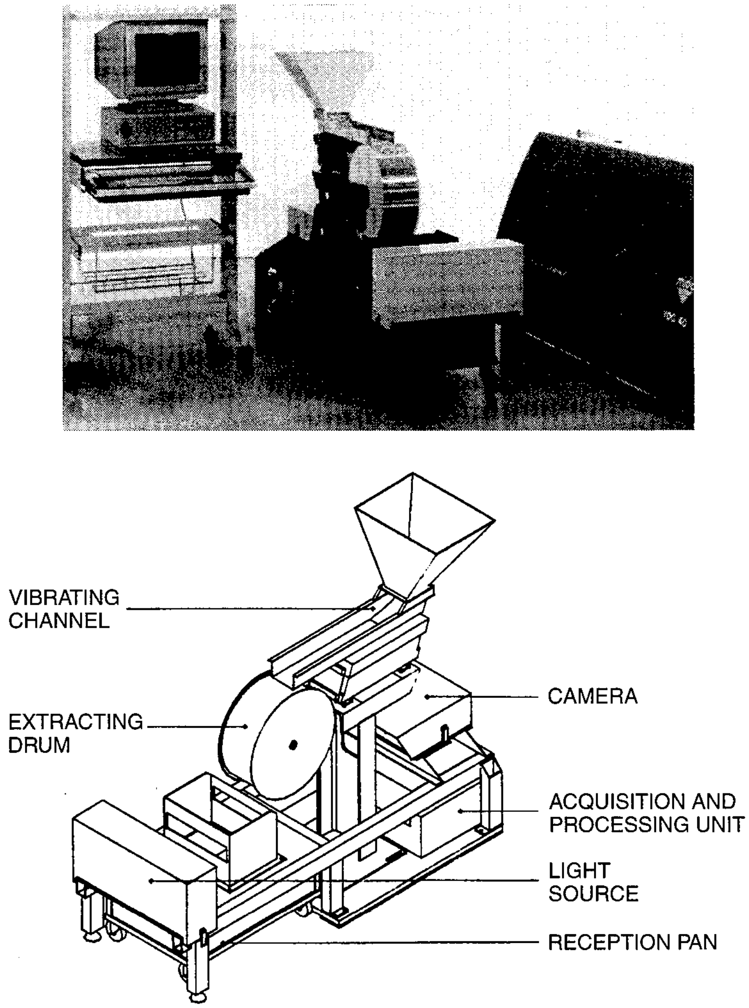

Figure 1. VDG-40 Machine Vision System for determining particle size (Source: Emaco [Canada] Ltd.).

instruments agreed much more closely with the hydrometer test results than did laser-based methods (*11*). These methods have high potential to replace traditional sieving and hydrometer methods.

The aerosol industry has instruments for particle sizing of aerosols, but it appears there would be limited application to highway materials (*12*).

Machine vision systems are one of the most rapidly advancing technologies. There is great potential for systems to replace sieves.

In-Line Vibratory Feeding

In-line vibratory feeding is an industrial technology that could be used for a number of tests where the sample has to be split, sieved, or otherwise manipulated. This feeding technology can be coupled with vibratory or ultrasonic-mixing techniques.

Robotics

Robotics are in general use throughout manufacturing, warehousing, and other industries to move objects from one position to another or to accomplish activities that require moving past an object (welding or cutting). This general category includes a variety of technologies that are used to accomplish the objectives of the specific machines. Many companies exist to design and manufacture robotic processes. Some specialize in laboratory or product testing (*13*). A robot being used in a biological laboratory is shown in Figure 2.

Neural Networks and Fuzzy Logic Techniques

Artificial neural networks and fuzzy logic techniques for computer analysis of nonmathematical decisions are growing in use in many applications. Basically, neural networks allow the computer to teach itself how to make decisions based on its internal analysis of initial decisions by the user. Fuzzy

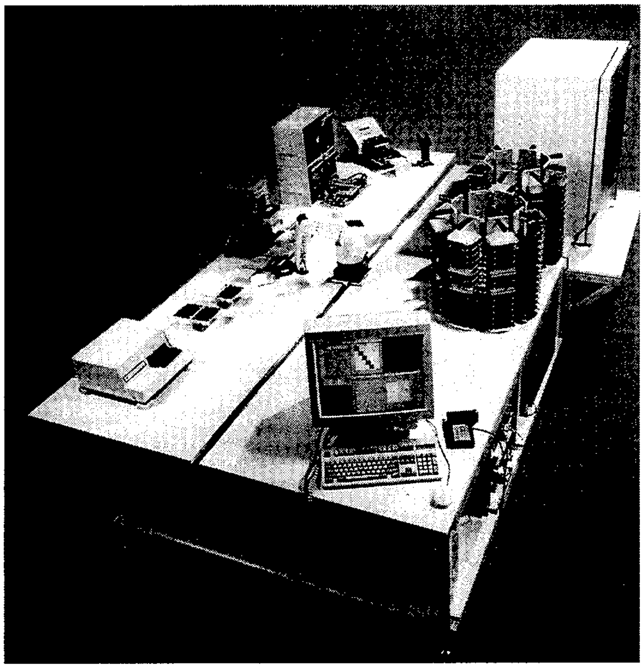

Figure 2. Robot in biological laboratory (Source: CRS Robotics).

logic is a form of logic in which variables can have degrees of truth or falsehood. These technologies may be an answer to operator judgments that are a part of many test procedures.

"Expert" Systems

This computer software technique guides an interactive computer analysis of data. It uses an extensive series of "what if" questions and answers that are programmed using knowledge and analytical rules defined by experts in the field. Many companies exist to help write knowledge-based expert systems and could tailor a test system to an individual laboratory. Some of the software programs in the new SHRP bituminous mix design procedures are forms of "expert systems."

Test Cell

A promising technique is the use of a "test cell" that conducts similar tests requiring similar steps. A general vision of such a test cell follows.

Several tests require sorting, washing, drying, compacting, weighing, agitation, mixing, cleaning, and moving a test specimen from one activity to another. A test cell is established to perform multiple tests simultaneously. Each step is controlled by a unique specimen and process control system that maintains time, temperature, weight, and so on. Process variables are charted, and a fuzzy logic system determines the results and records them. A material handling, storage, disposal, or retrieval system is employed to eliminate human interaction. The laboratory is configured in such a manner that ovens, particle size apparatus, centrifuges, scales, and computers can be used by more than one test cell.

The test cell example would be expected to have an equipment cost of $250,000 to $350,000. Up to 10 different types of tests could be run in this facility for about $35,000 of equipment cost per type of test. Individual tests independently automated are estimated to average around $50,000 each.

Nondestructive Scanning Techniques

There are several nondestructive scanning techniques, which could lead to improved methods of evaluating construction materials. These include the use of thermal (specific heat), di-electric, ultrasound, acoustic emission, impact-echo, ultrasonic and X-ray computed tomography, and magnetic resonance imaging (MRI) testing. A Real Time Ultrasonic Imaging System is being used in the aircraft industry in situations similar to bridge inspections (*14*). MRI is beginning to be used in some industrial and agricultural engineering applications of nondestructive testing (*15,16*). A detector employing quadrupole resonance technology, a variant of magnetic resonance, has been developed to detect drugs and explosives. The portability of this device would be a useful attribute in the construction industry (*17*). The grain testing industry has had advances in rapid testing technologies using near infrared, machine vision and imaging, optical and color acoustics, odor detection advances and microwave (*18*).

MRI is being used at the University of New Brunswick to study the behavior of concrete. University physicists are also studying the mechanism of freeze-thaw resistance of concrete (*19,20*), which may lead to better design, testing and control of concrete during mixing and placement.

Traditional Technologies

Many additional traditional industrial technologies were considered for possible application to highway-materials testing but were not used. The following list identifies some of these technologies.

- Water jet machining for sample preparation or cutting (*21–23*);
- Smart card, radio frequency, and machine vision identification tools (*24,25*);
- Motion control technology (*26,27*);
- Material handling and sorting apparatus (*28*);
- Rapid-prototype tooling (*29–31*);
- Diamond and cubic boron nitride cutting tools; and
- Production scheduling that controls the unexpected and provides for finite capacity scheduling.

Nontraditional and Emerging Technologies

Likewise, there were a number of nontraditional and emerging industrial technologies that were considered, but feasible applications were not found for them. These may have some application in the future.

- Capillary optics X-ray device similar to fiber optics (*32*);
- Wireless magnetic tracker used to capture motion in real time (*33*); and
- Higher resolution clinometer for angular data (*34*).

FUTURE LABOR FORCE

In addition to evaluating the existing labor cost of salaries and overhead, it is necessary to make a prediction about the costs of labor in the future. The current cost of labor has been determined from the returned surveys. Projecting labor costs for financial evaluation must consider typical salary increases. It must also consider labor force changes that can be anticipated in the next few years. The Bureau of Labor Statistics, U.S. Department of Labor, has projected that the future supply of workers will have a net increase of 12 percent over a period from 1994 to 2005. This is less than the projected 17 percent growth in jobs. Further, the age group of 16 to 24 years is projected to grow only 11 percent, and the age group of 25 to 34 years will decline by 7 percent (*35*). These are the age groups most likely to be employed in testing laboratories.

Thus, it seems that the labor force will be smaller relative to the number of jobs available. This will likely make it more difficult to hire and retain people and lead to higher salaries, making it more attractive to replace people with machines.

SUMMARY OF SURVEY RESULTS ON CURRENT TESTING

Early in the research, a survey was used to evaluate what tests were being run in a large enough volume to justify automation. The survey was sent to the state transportation agency central testing laboratories, a number of private materials testing laboratories, other governmental agencies and research laboratory facilities, and equipment manufacturers. A total of 29 state surveys, three private testing laboratories, and one manufacturer survey was returned. An additional seven states were surveyed by phone to learn of existing and planned automation and interests in automation.

The survey asked about the following issues:

- Volumes of tests per year, whether the test would be done more often, the same or less in the future;
- Labor hours required to do each of the tests;
- Elapsed time from receipt of sample to transmittal of test results;
- Salary costs of staff;
- Equipment costs;
- Existing laboratory automation;
- Planned automation; and
- Barriers to automation.

The information was placed in a database for statistical determination of average, median, and mode values.

As each test was analyzed, a decision was made whether to use average, median, or mode values based on the scatter and total range of the values. For newer tests, such as SHRP bituminous tests, the data from states doing higher volumes were considered more representative of future labor costs and the potential for savings. Some tests, such as moisture content determinations, are an integral part of many other tests. These uses were added to the reported uses of the individual tests when considering feasibility of automation.

State Transportation Agency Testing Laboratories

The results of the survey are contained in a database, which is not published with this report. Selected data are included in tables associated with the use of the data. Appendix A, "Reported Annual Volume of Tests from States" (not published herein) shows the data for yearly volumes from the states responding for all the tests requested and for those tests that states added to the survey.

Private Materials Testing Laboratories

Data for private materials testing laboratories were projected from the surveys returned. Projections were based on the market experience of the author and data on the number of firms and their total sales volume or staff size from Dun and Bradstreet data (*36*). A second estimate was based on information about member and nonmember firms of the American Council of Independent Testing Laboratories, a trade association of private materials-testing laboratories. A third estimate projected the number and size of firms based on the size of the 150 largest metropolitan areas and the known number of firms in a limited number of metropolitan areas of known sizes.

Other Governmental Agencies or Research Laboratories

Because no surveys were returned from other governmental agencies or research laboratories, their current test volumes and future needs were estimated based on the author's knowledge of the mission of the agencies or laboratories. This unsupported information was considered adequate for this study because the relatively small number of laboratories with enough tests to possibly warrant automation had a very limited effect on the analysis.

Aggregate, Bituminous and Concrete Producers, Suppliers, and Contractors

Some tests are conducted in volumes sufficient to warrant automation in laboratories operated by the producers, sup-

TABLE 1 Prioritizations of conceptual designs by states

States'[1] Priority	Conceptual Design to Automate or Replace Existing Test Methods	Prioritizations by Individual States (1 is highest, 20 is lowest)		
		Highest Rank	Lowest Rank	Average Rank
1	*New Test Methods* for AASHTO T 27-93, Sieve Analysis of Fine and Coarse Aggregates (ASTM C 136-84a) and AASHTO T 11-91, Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing (ASTM C 117-90*)	1	18	8.15
2	Superpave™ Binder Tests	1	20	8.25
3	ASTM D 5821-95 Fractured Particles in Coarse Aggregate, ASTM D 4791-95 Flat or Elongated Particles in Coarse Aggregate and AASHTO TP 33 Fine Aggregate Particle Shape	1	20	8.35
4	TP4 Superpave™ Gyratory Compaction of Bituminous	1	19	8.55
5	AASHTO T 248-95, Reducing Field Samples of Aggregate to Testing Size (ASTM C 702-93)	1	20	9.05
6	*Existing Methods* for AASHTO T 27-93, Sieve Analysis of Fine and Coarse Aggregates (ASTM C 136-84a) and AASHTO T 11-91, Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing (ASTM C 117-90*)	1	18	9.15
7	*New Test Methods* of AASHTO T 88-93, Particle Size Analysis of Soils	3	19	9.35
8	*New Test Methods* of AASHTO T 84-94, Specific Gravity and Absorption of Fine Aggregate (ASTM C 128-88) and AASHTO T 85-91, Specific Gravity and Absorption of Course Aggregate (ASTM C 127-88)	1	18	9.06
9	AASHTO T 164-94 Quantitative Extraction of Bitumen from Bituminous Paving Mixtures and AASHTO T 170-93 Recovery of Asphalt from Solution by Abson Method	1	20	9.75
10	AASHTO T 89-94, Determining the Plastic Limit and Plasticity Index of Soils	1	20	9.75
11	Bituminous Mix Designs by Superpave™, Marshall and Hveem Methods	2	20	10.05
12	AASHTO T 153-90 Fineness of Portland Cement by Air Permeability Apparatus (ASTM C 204-92)	2	20	11.15
13	AASHTO T 99-94, The Moisture-Density Relations of Soils (ASTM D 698) (Standard Proctor) and AASHTO T 180-93, Moisture Density Relations of Soils (ASTM D 1557) (Modified Proctor)	3	17	11.25
14	AASHTO T 100-95 Specific Gravity of Soils	4	19	11.5
15	*New Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate, Drying (ASTM C 566-89) and AASHTO T 265-93. Laboratory Determination of Moisture Content of Soils	2	18	12.06
16	*Existing Method* for AASHTO T 88-93, Particle Size Analysis of Soils	2	19	12.15
17	*Existing Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93, Laboratory Determination of Moisture Content of Soils	1	19	12.35
18	AASHTO T 154-91 Time Setting of Hydraulic Cement by Gillmore Needles (ASTM C 266-89) and AASHTO T 131-93 Time Setting of Hydraulic Cement by Vicat Needle (ASTM C 191-92)	3	20	12.55
19	AASHTO T 22-92, Compressive Strength of Cylindrical Concrete Specimens (ASTM C 39-86)	1	20	14
20	AASHTO T 244-95 Mechanical Testing of Steel Products (ASTM A 370-94a)	2	20	14.1

pliers, and contractors working in the construction industry. Limited information on volumes of tests was obtained by calling firms. These data were extrapolated based on estimates of the number of firms and their sizes relative to the 150 largest metropolitan areas.

PRECISION AND REPRODUCIBILITY OF CURRENT TESTS

One advantage of automation is an increase in the precision and reproducibility of tests. This occurs because the test is conducted in an identical fashion each time and in strict accordance with the test method. Test variability due to the human element is eliminated. Human errors, such as transposition of numbers when writing down data or transferring from one medium to another, are also eliminated. Re-running tests because of operator error will be greatly reduced.

This benefit will be greater for those tests where the current precision or reproducibility are poor. Thus, one of the factors considered for each test is the documented precision of the tests, where available, or judgment of experienced engineers about the precision of a test, where documentation is not available. A judgment was then made during conceptual design about the potential to improve precision and reproducibility. This technical benefit was given a relative rating as part of the prioritization process.

SURVEY RESULTS ON PRIORITIZATION OF CONCEPTUAL DESIGNS

After the conceptual designs were completed, the 20 designs judged by the researchers to be the most feasible for implementation were submitted to the states that had responded to the first survey. The states were asked to comment on the process used by the researchers to analyze financial feasibility and to prioritize the designs based on the needs of their state. Twenty states responded to this survey.

The comments on the financial feasibility analysis can be categorized in five general comment areas. When asked if they analyze financial feasibility the way it was done in this study, six states answered "yes" but offered small variations, and 11 states indicated they do not make a financial evaluation. When asked if the salary and overhead are representative, eight states said "yes" and seven said "no." The responses of states with "no" were evenly divided between being too high and too low. However, several states indicated the overhead assumed was too high. Only two of the six states that do a financial analysis indicated they include an interest rate for the cost of money in their analyses.

Financial barriers discussed in the responses were concentrated around the lack of funding for initial purchases (10 comments) and the cost of maintenance of more complex equipment (three comments). Three states noted that they had excessive operational problems with the automation they have tried. Costs of training were also mentioned.

Technical barriers were seen in the time and effort of getting acceptance of new methods by AASHTO and ASTM (two comments) and concern about the need to automate operator intuition and judgment (two comments).

A need for new attitudes was expressed by four states. Issues included resistance to change and technology, lack of confidence in new procedures, and a union issue of losing positions to automation.

Table 1 shows the prioritizations of the conceptual designs for tests by the states. States were asked to rank their highest priority as a 1 and their lowest priority as a 20. To summarize the information for Table 1, the rankings of all responders were totaled for each conceptual design and an average determined. The high and low rankings are included in Table 1 to show the spread of answers for each conceptual design.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATIONS

INTRODUCTION

Successful implementation of automation in highway-materials testing must consider the technical, financial, and availability issues that affect the use of technologies to automate procedures. Because technologies may be used to automate individual tests—e.g., tests that are typically done in a series on a given sample and tests that are similar but need different samples—it is necessary to look at total systems of laboratory operations. The appraisal must also consider barriers to implementation and possible ways to overcome them. Finally, an implementation plan must address the four audiences that are important decision makers: laboratory managers, manufacturers, engineers who use the information, and regulatory and standards-setting agencies such as AASHTO, ASTM, FHWA, and FAA.

The information obtained from the literature and other sources directed the analysis of the data into a market study of conceptually designed automated tests. The purpose was to find tests that were conducted frequently so that enough laboratories would buy equipment to produce a market large enough to interest equipment manufacturers. The conceptual designs also had to be technically and financially feasible. After considering 48 tests conducted on the broad spectrum of highway construction materials, 28 of the most feasible automation conceptual designs were prioritized. An implementation plan for future action was devised for the 20 conceptual designs considered to have the highest potential.

TECHNICAL APPRAISAL

The researchers looked at the uses of technologies in other industries to evaluate the potential or use in automating existing highway-materials testing. Generally, it can be said the experience in other industries is so extensive that most equipment is well proven. Some newer technologies do not specifically have extensive experience but are being developed in processes that have produced successful equipment in the past. Most industrial uses have requirements for precision and repeatability that exceed the requirements of the highway-materials tests, so meeting test accuracies is not expected to be a problem. The requirements for maintenance-free operations are also high in industrial uses because the equipment is usually a part of a larger process and downtime is very disruptive to significant portions of industrial or commercial operations.

The ability of new technologies to replace current tests was also evaluated. An example of such technology being studied is machine vision to conduct particle evaluations. Other technologies, such as determination of moisture content by infrared methods, will also need study of their application to highway materials. Some additional development of testing methods will be required, as will the adoption of a standard test method for any new test.

FINANCIAL EVALUATION

The literature suggested that financial considerations were the most important factor in the implementation of automation. Thus, the analysis started with a "market" study of the financial feasibility of various tests. Through a survey of state and private laboratories, the tests with the highest volumes were determined. Then an iterative process was used to find conceptual designs most likely to be financially feasible. The process started with a conceptual design of an automated process. The cost for a manufacturer to develop, manufacture, and sell the equipment was estimated so the approximate price of the equipment could be estimated. On the basis of the estimated costs and the estimated savings due to automation, the number of tests required to pay for the cost of automated equipment was estimated. The number of laboratories with enough volume of the particular test was estimated to establish the size of the market. Assuming a manufacturer would capture one-third to one-sixth of the market, the financial feasibility for a manufacturer was evaluated. If the conceptual design was not feasible for laboratories or manufacturers, a new concept was considered. The conceptual designs for automated tests were ranked on their financial feasibility.

Financial Evaluation for a Laboratory

The feasibility of automation for any laboratory will depend on such issues as salary and overhead costs of labor, investment factors such as whether a state includes interest costs in its evaluations, how much time can be saved, the cost to install and train in the laboratory, the initial price of the equipment, and the operating and maintenance costs. To facilitate the financial evaluations, a spreadsheet was developed, which allows input of the variables and computes the number of tests required each year to pay back the investment within a given number of years. This spreadsheet is available on the Internet at ftp://www.brauncorp.com (click on finanaly.wk4) for downloading or on disk for availability by mail. Table 2 shows the information included in the analysis. The initial investment has two categories. The "equipment purchase" would be the price paid to the equipment manufacturer or seller. The "installation in laboratory" category is for the cost to adapt the laboratory to automation and the start-up costs of quality control testing.

An average salary of $14.00 per hour for the 3-year period was used in the financial analyses of all tests. This is an increase from the $13.00 per hour, which was the median reported by states for 1997. It assumes not only normal increases but also a small increase due to projected shortages of people. The assumed total overhead cost of $24.50 per hour was based on limited data from states that calculate and use overhead that includes direct salary costs such as vacation and insurance, unproductive time costs such as training, and the costs of supervision and management. Many states do not use the indirect costs in their overhead evaluations, but those costs are real; to ignore them ignores the real costs of labor and the real savings of automation.

Operational costs seek to compare the day-to-day and yearly costs of using the equipment. The cost of maintenance for automated systems is dependent on the complexity of the system and the quality of the equipment. Equipment manufacturers typically estimate yearly maintenance as a percent of initial equipment cost. Three manufacturers of automated laboratory testing equipment were contacted. They indicated they generally use a range of 3 to 5 percent (total ranges of 2 to 10 percent) of initial cost when estimating the cost of yearly maintenance. The low end of the range is for simple but expensive equipment. The high end is for complex equipment with a low initial cost. Complexity of the software is also a factor. This cost includes calibrations, preventive maintenance, and repairs.

Maintenance has been an important issue in industrial use of automation and has been dealt with successfully for many years. One industrial equipment buyer indicated that they do not track specific maintenance costs because the costs are small enough to be unimportant. They do, however, track equipment downtime, which is more important to them. They indicated that downtime for maintenance varied from 1.9 percent to 5.8 percent of total available time on three typical types of systems, simple to complex.

The researchers also reviewed the maintenance experience of their own laboratory. The yearly cost of maintenance for a large, compression-testing machine used heavily for compression testing of concrete cylinders and block has averaged 1.7 percent of initial purchase price over a period of 12 years since purchase. A gyratory compactor, used in part of the SHRP bituminous mix design process, has had no repairs in

TABLE 2 Financial evaluation of automation of a test

Initial Investment			
Equipment purchase		$120,000	
Installation in laboratory		$35,000	
Total		$155,000	
Future Labor Costs			
Hands-on time saved (hours)		0.9	
Average salary per hour during future time period		$14.00	
Average overhead per hour during future time period		$24.50	
Operational Costs	**Current**	**Future**	
Materials per test	$0.50	$0.50	
Maintenance per test	$0.02	$0.03	
Disposal of waste per test	$0.02	$0.01	
Total per test operational costs	$0.54	$0.54	
Utilities per year	$500.00	$800.00	
Hazardous wastes or other special environmental	$500.00	$0.00	
costs per year	$200.00	$300.00	
Training per year	$100.00	$100.00	
Other	$1,300.00	$1,200.00	
Total yearly operational costs			
Yearly cost savings due to reduction in number of tests redone or due to reduction of risks		$2,000.00	
Payback Analysis			
Payback period (years)		3	
Interest Rate (per year)		8.00%	
Number of Tests per Year to Pay Back Initial Investment			1,675

4 years of steady use. A second gyratory compactor, leased to contractors for field laboratory testing, has had only $10 in repairs over a 2-year period.

"Hazardous waste or other environmental costs" reflects the fact that some current tests have hazardous wastes, which must be disposed of in accordance with regulatory controls. Automation may reduce the material to be disposed of. "Yearly cost savings due to reduction in the number of tests redone or due to reduction of risks" is a category that reflects the savings costs of redoing tests when test errors are recognized. This category also reflects the savings costs due to elimination of materials failures due to test errors that are not recognized. It is also a way to recognize that new test methods may be better at predicting the material behavior, which also reduces risks of material failures.

A 3-year payback period was selected for the financial feasibility. This may be aggressive because most of the equipment will last 10 or more years with appropriate maintenance. A payback period of 5 years is likely very suitable.

An 8 percent interest rate was included in the cost analysis. Most states do not currently include the cost of borrowed money in their analysis. Others use the cost of borrowing through bonding, typically closer to 5 percent at this time.

The resulting value calculated by the spreadsheet is the number of tests conducted per year during the payback period required to offset the cost of automation by the savings from automation.

Number of Laboratories that Might Purchase Equipment

The number of laboratories that would have enough tests to justify purchasing automated equipment was then estimated. Laboratories included in this market identification were federal, state, county, and city materials testing laboratories, commercial materials-testing laboratories, laboratories of materials suppliers, and laboratories in universities and other research institutions.

Information from the responding state highway-materials testing laboratories was taken from the first survey and extrapolated to the rest of the states. The extrapolation considered the number of lane-miles of highways in a state and the geographical location relative to states that had responded. It was recognized that states vary in their approach to testing and, thus, in the possible numbers of tests they would run. However, the extrapolation typically used an average of more than one reporting state and so is thought to be adequately accurate for the purposes of this study.

Information for commercial laboratories was based on the responses received in the first survey and the knowledge of the researchers. To extrapolate the surveys received from commercial laboratories to the rest of the commercial laboratories, information available from Dun and Bradstreet, the American Council of Independent Laboratories (ACIL), and the population estimates of metropolitan areas was used. This information allowed the researchers to estimate the number of firms and their approximate revenues. Instead of estimating the total volume of each test type run by commercial laboratories directly, they estimated the number of potential equipment buyers. The number of potential buyers was estimated by first evaluating the feasibility of automation for the commercial laboratories that responded to the survey relative to their approximate revenue. This was then extrapolated to other laboratories based on their estimated revenues.

Dun and Bradstreet records businesses under Standard Industrial Classification (SIC) Codes assigned by the Department of Labor and lists, among other things, their size by staff and revenue. There is no specific code for laboratories that test highway materials, so it was necessary to interpret businesses from three SIC codes: C 8734-00 (Testing Laboratories); 7389-0200 (Inspection and Testing Services); and 8734-9909 (Soil Analysis). Also, businesses do not always report all the types of services they provide and so may not be listed under a specific SIC code. From personal knowledge of firms with more than $2.5 million in sales in the Testing Laboratories list, the researchers estimated that 20 percent of those firms do construction-materials testing. They used the size distribution of the entire code to estimate the size of firms doing construction-materials testing. On the basis of the Dun and Bradstreet data, they estimate there are a total of 800 to 1,000 firms providing commercial laboratory construction-materials testing and with enough size (at least 10 employees and $0.5 million in sales) to be able to use automation. Many of these firms have multiple laboratories.

The American Council of Independent Testing Laboratories (ACIL) is a trade organization with a specific membership classification, which includes firms that test highway and construction materials. Ninety firms have membership in the Construction Materials Engineering section. During a telephone conversation on January 28, 1998, Cheryl Dodds, the membership director of ACIL, reported they estimate about 10 percent of the available firms are members in that category, indicating an approximate total of 900 firms nationally. Many of these firms have multiple laboratories.

The researchers also estimated the number of laboratories by comparing the number of laboratories in known metropolitan areas and the size of those metropolitan areas to the population sizes of the 254 largest metropolitan areas (population of 100,000 or more). Metropolitan area populations were available from the U.S. Bureau of the Census (*37*). For example, in Minneapolis/St. Paul, which has a population of 2.7 million, there are 10 firms providing construction-materials testing. Their sizes range from $40 million to $100,000 revenues. On this basis, there are approximately 800 to 900 laboratories in the nation.

The total number of sales for a piece of equipment was assumed to be a total of the state laboratories with enough annual volume of tests to meet the payback volume, the number of commercial laboratories estimated to be large enough, and other users that could be identified.

Each feasibility analysis includes a general financial feasibility evaluation of developing and marketing the new test equipment. The feasibility will vary from manufacturer to manufacturer depending on their existing expertise, marketing, and distribution systems. However, the intent of the analysis is to show feasibility and interest those manufacturers who are likely to find it attractive. The analysis assumes there will be more than one manufacturer, in the hope there will be some competition to spur advances in the equipment and to control costs.

Probable Future Use

This section evaluates the potential for increases or decreases in numbers of tests that will be conducted in the future. The evaluations rely on the results from the survey of the states, comments from state managers, and an evaluation of the potential for future new test methods based on the research. The results of the state survey are shown in Table 3.

FEASIBILITY FOR MANUFACTURERS

Manufacturers will evaluate the potential return on their investment (profit) by looking at their cost to develop, market, produce, and sell the equipment, and the volume of sales at assumed prices. There are risks to consider, such as technological barriers, competitors' actions, and the evaluation of the size of the market. In this feasibility study, the cost to develop the equipment was estimated based on a detailed study of two conceptual designs by an engineer experienced in designing and building automation equipment. The rest of the equipment was estimated by comparing to the detailed studies and by comparing to existing equipment already being sold by various manufacturers.

It was generally assumed that there would be three or more competitors selling the specific piece of equipment and that they would share the total market. Because certain manufacturers have equipment very similar to the equipment used in the conceptual designs, they would have an advantage in producing new equipment. Also, there will be some transfer of expertise and equipment from one conceptual design to another, which would be an advantage to the cost of development and sales.

CONCEPTUAL DESIGN PROCESS

The researchers evaluated the various technologies they knew or which were discovered in the research to apply them to the tests to be automated. Current or pending uses in other industries were considered for application directly or through adaptation. The initial matching of tests and technologies is contained in Appendix B, "Potential Automation Technologies for Testing." Conceptual designs to automate existing tests or to create new methods were developed from these matches.

It is recognized that other conceptual designs are possible. The scope of this research was not to find the best design but to find designs that could be implemented. Manufacturers will develop the best designs as part of their competition for sales.

To validate the iterative evaluation, the conceptual design and cost estimating process was carried out in detail on the methods to automate compression testing of concrete cylinders and to adapt a bar code labeling system to highway-materials testing. The designs were detailed enough that the equipment could be priced by comparing to similar existing industrial equipment. These detailed conceptual designs also give a picture of the capabilities of automation which exist in other industries. Conceptual designs for other tests were generally not as detailed, but were considered adequate to allow reasonable price estimates.

Conceptual Design of Automated System for AASHTO T 22-92 Compressive Strength of Cylindrical Concrete Specimens

The following sections describe a conceptual design automating the existing test method of AASHTO T 22-92. It is assumed that a laboratory has an existing facility and equipment to handle samples manually from receiving through curing, capping, breaking and discarding. The automation replaces the manual handling and the existing capping equipment. It assumes remodeling of the storage in the curing room and reuse of a compression machine with electronic readout of test results. Figure 3 illustrates the concept.

Receiving the Cylinder

It is assumed that the incoming cylinder has a bar code label attached to the shipping container. The operator would scan the label via a hand-held scanner, which identifies the sample and recalls information such as sample number, date cast, location, required strength, and mix design entered into the computerized control system when the bar code label was printed. If there is no bar code label, the data would have to be entered manually. The system then prints a rugged bar code label suitable for attaching to the wet concrete specimen that will also stay attached to the concrete specimen throughout the storage and handling process. This will require an aggressive adhesive that will not lose its hold during this process.

The operator then removes the concrete cylinder from the mold and places the concrete cylinder onto a conveyor that queues the specimens in a first-in first-out order.

Preparing for Curing Storage

The conveyor then routes the concrete cylinders into a Grinder that accurately grinds off the two ends so that the

TABLE 3 State estimates of future use of tests

Test Name	AASHTO (ASTM) Test Number	Future Use of Tests		
		Less	More	Same
Compressive Strength of Cylindrical Concrete Specimens	T 22-92 (C 39-86)	1	6	16
Slump of Hydraulic Cement Concrete	T 119-93 (C 143-90)	1		13
Air Content of Freshly Mixed Concrete by the Pressure Method	T 152-93 (C 231-97)	1		14
Reducing Field Samples of Aggregate to Testing Size	T 248-89 (C 702-87)		1	17
Bulk Specific Gravity	T 166-93	2	2	19
Particle Size Analysis of Soils	T 88-93	2		20
Penetration of Asphalt Materials	T 49-96	18		6
Materials Finer than 75 μm (No. 200) Sieve in Mineral Aggregates by Washing	T 11-91 (C 136-84a)	1	1	21
Determining the Liquid Limit of Soils, and Determining the Plastic Limit and Plasticity Index of Soils	T 89-94 T 90-94	1	1	19
Quantitative Extraction of Bitumen from Bituminous Paving Mixtures, and Recovery of Asphalt from Solution by Abson Method	T 164-94 (D 2172-95) T 170-93 (D 1856-95a)	8	9	25
Bituminous Thickness and Density of Pavement Core	(D 3549-93a)	3	4	14
Absolute and Kinematic Viscosity of Asphalts	T 201-94 T 202-91	20		5
Sieve Analysis of Fine and Coarse Aggregates	T 27-93 (C 136-84a)	1	3	13
Mechanical Testing of Steel Products	T 244-95 (A 370-94a)		2	15
Specific Gravity and Absorption of Fine and Coarse Aggregates	T 84-95 T 85-91		5	20
Flexural Strength of Concrete	T 97-86	2	2	9
Bituminous Mix Design by Marshall Method		12	1	7
Marshall Stability and Flow	T 245-94	11	1	10
Superpave™ Short- and Long-Term Aging of Pavement Mixes	PP2		16	
Superpave™ Gyratory Compaction	TP 4		22	
Rockwell Hardness of Metallic Materials	T 80-96		2	16
Tension Testing of Metallic Materials	T 68-96			14
Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine	T 96-94 (C 131-89)	1	1	23
Ignition Oven Method for Asphalt Content of Paving Mixtures	TP 53		14	5
The Moisture-Density Relations of Soils (Standard Proctor)	T 99-95		3	20
Thin Film and Rolling Film Oven Tests	T 240-94	2	13	7
The Moisture Density Relations of Soils (Modified Proctor)	T 180-95		2	19
Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate	T 104-94		3	16
Time Setting of Hydraulic Cement by Gillmore Needles and Time Setting of Hydraulic Cement by Vicat Needle	T 154-91 (C 266-89) T 131-93 (C 191-92)	1	2	16
Fineness of Portland Cement by Air Permeability Apparatus	T 153-90 (C 204-96a)	1	3	16
Superpave™ Binder Tests	MP-1		19	2
Flash and Fire Points of Asphalt, Cements, Paints, etc.	T 48-96	1	1	18
Unconfined Compression	T 208-92	1	3	11

(continued on next page)

TABLE 3 *(Continued)*

Test Name	AASHTO (ASTM) Test Number	Future Use of Tests		
		Less	More	Same
Abson Recovery	T 170-93	2	6	14
Mortar Air Content	T 137-96		2	16
Asphalt Specific Gravity	(D 3142)	4	1	16
Sand Equivalent Test	T 176-86 (1996)		7	11
Specific Gravity of Soils	T 100-95 (D 854-83)			21
Total Moisture Content of Aggregate by Drying Laboratory Determination of Moisture Content of Soils	T 255-92 (C 566-89) T 265-93		1	13
Welding Operator Examination				11
Welder Procedure Qualifications		1		6
Fractured Particles in Aggregate	(D 5821-95)		11	5
California Bearing Ratio	T 193-93	3	2	8
Splitting Tensile Strength	T 198-93		2	6
Rapid Chloride Permeability	T 277-93	1	5	3
Resistance of Compacted Bituminous Mixture to Moisture Induced Damage	T 283-89	1	2	3
Unit Weight	T 19-93	1	1	18
Bulk Specific Gravity of Compacted Bituminous Mixtures	T 166-93	2	2	19
Aggregate Flatness and Elongation	(D 4791-95)	1	7	12
Soundness of Aggregates by Freezing and Thawing	T 103-91 (1996)	1	1	7
Hydraulic Cement Compressive Strength	T 106-96		1	1
Carbon/Sulphur Analyzer	(E 1019-94)			1
Organic Content in Soils by Ignition	T 267-86		1	11
Procedure A Chloride Ion Concentration	T 260-95	1		3
Triaxial Testing (unconsolidated)	T 296-94		5	7
Air Voids in Hardened Concrete	(C 457-90)	1	1	3
Test Method for Uncompacted Void Content of Fine Aggregate	TP 33		11	5
Aggregate Durability Index	T 210-95		1	4
Consolidation Properties of Soils	T 216-94		5	9
Charpy V-Notch Impact Testing of Metallic Materials	T 266-96 (E 23-94b)		1	6
Capping Cylindrical Concrete	T 23-93			1
Direct Shear Test of Soils	T 236-92	1	4	9
Density Meter	T 238-86 (1996)			1
Portland Cement Autoclave	T 107-91		1	
Magnetic Coating Thickness	T 65-95			1
Prediction of 7- and 28-day Strengths	T 276-91		1	1
Particle Shape and Texture	TD 33 (D 3398, C 1252)		4	1
Moisture Susceptibility of Bituminous	T 165-91	1	2	3
Resilient Modulus of Bound and Unbound Aggregates and Soils	T 294-94 (SHRP P 46)		2	2
Triaxial Testing (Consolidated)	T 297-94		3	6
Nuclear Asphalt Content	T 287-93	1		1
Lightweight Pieces in Aggregate	T 113-96	1	2	8
Hveem Mix Design		1		
Hveem Stabilometer R-value	T 190-93			3
Cloud Point	(D 2500-91)			1
Potential Alkali-Silica Reactivity	(C 289-94)		2	1
Distillation of Petroleum Products	T 115-84 (1996) (D 86-93)			1
Testing Emulsified Asphalt	T 59-96			1

(continued on next page)

TABLE 3 *(Continued)*

Test Name	AASHTO (ASTM) Test Number	Future Use of Tests		
		Less	More	Same
Specific Gravity of Semi-Solid or Solid Bituminous Materials	(D 3289-90)			1
Distillation of Cut Back Asphalt	T 78-94 (1995)			1
Rebar Bend Test	(D 3963/ D 3963M-93a)			1
Parallel Plate Loading of Bitumen	(D 4989-90a)			1
Organic Impurities in Fine Aggregates	T 21-91 (1996)			1
Softening Point of Bitumen	T 53-96			1
Clay Lumps and Friable Particles	T 112 -91 (1996)			1

cylinder ends are parallel to each other. This is a wet and dirty step, and the water and concrete cuttings must be contained.

After the Grinder has produced a cylinder suitable for testing, the new "rugged" bar code label is attached to the sample. The cylinder is then pushed onto an exit conveyor that routes the sample from the Grinder to the storage system.

Curing Storage

The storage system requires the most special design of the process. Most of the other components of the system are commercially available items that can be purchased and integrated into the overall complete system. The storage system,

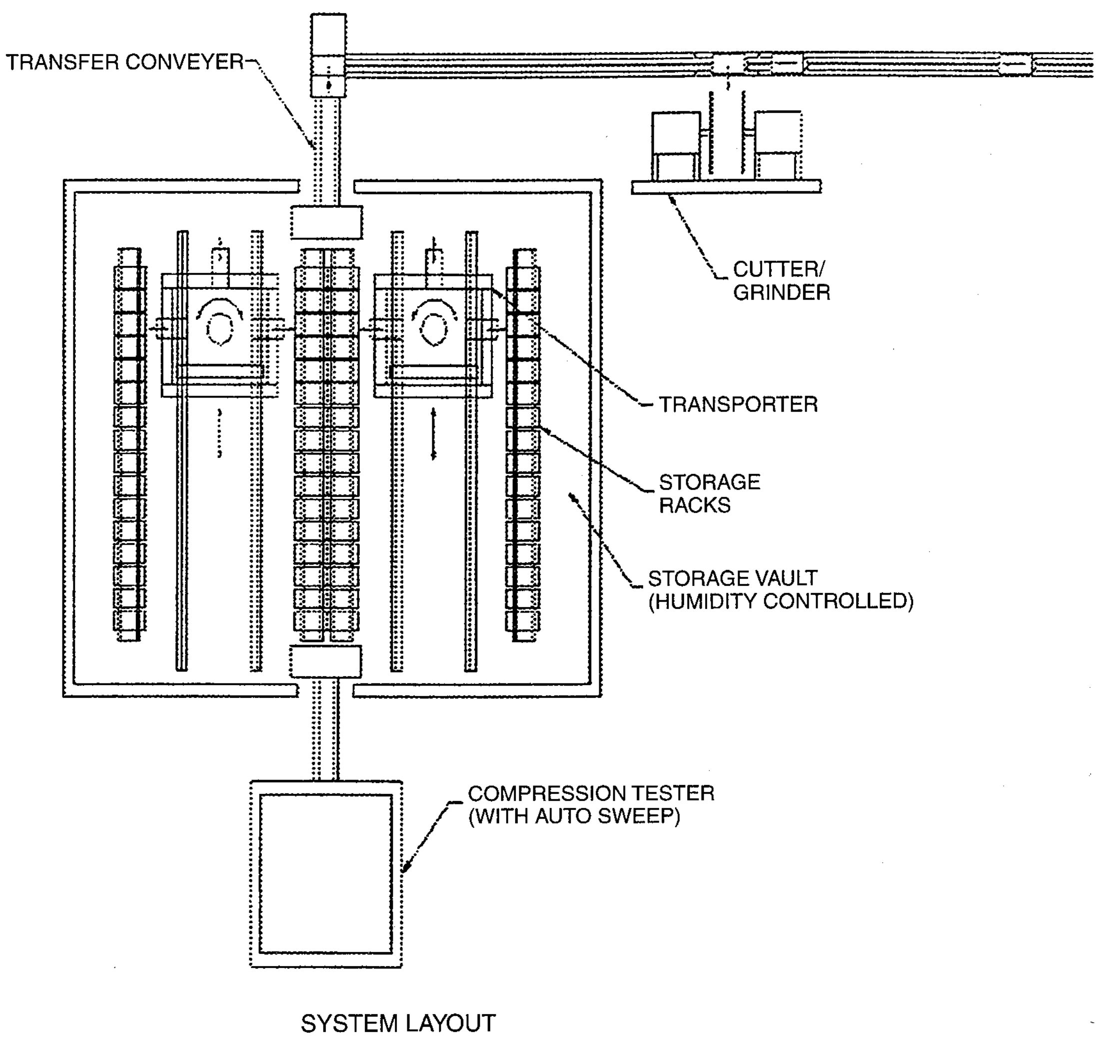

Figure 3. System layout (Source: Factory Systems Engineering Inc.).

however, because of the 100 percent humidity environment, requires some uniqueness in the design.

The input into this storage system is from the Grinder conveyor. The conveyor presents the concrete cylinder, to the pick-up position for the Gantry Transporter. See Figures 4 and 5.

The Gantry Transporter picks up the cylinder, rotates it vertically, and transports the cylinder to a storage location that is determined by the computerized control system. The control system will keep track of all the storage locations available, what samples are in what locations, etc.

Upon reaching the appropriate storage location, the Gantry Transporter will rotate the concrete cylinder to a horizontal orientation, extend its pick-up mechanism and place the concrete cylinder into the storage rack.

The storage rack is planned to be constructed on site, with minimal tooling, and also to be configured to maximize the available space. The design can be flexible to use the available space most effectively. See Figure 6.

Retrieval from Curing Storage

The storage plan must accommodate variable storage times, probably 1 to 90 days. Each day the computerized control system informs the Gantry Transporter which samples to

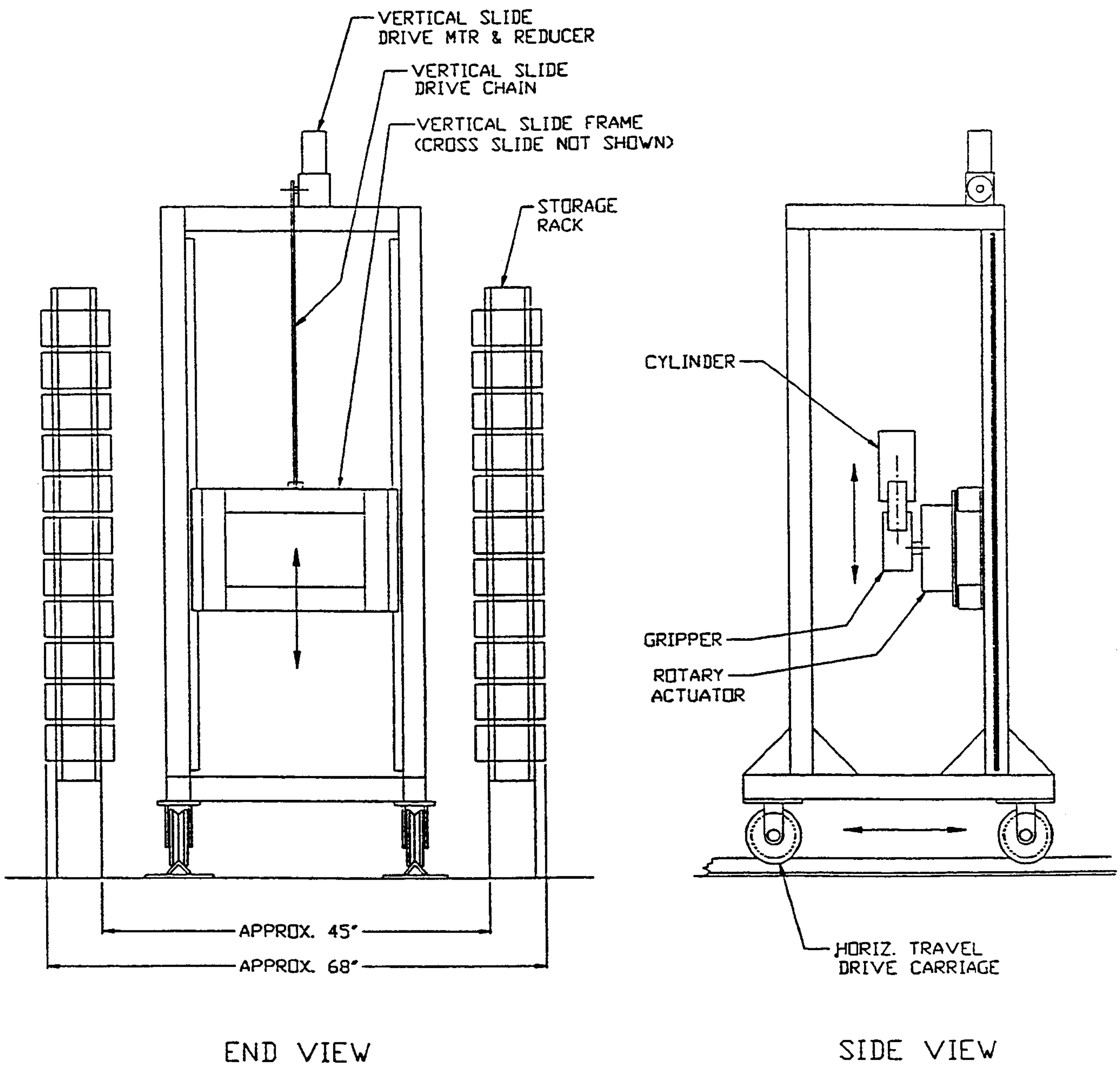

Figure 4. Gantry transporter.

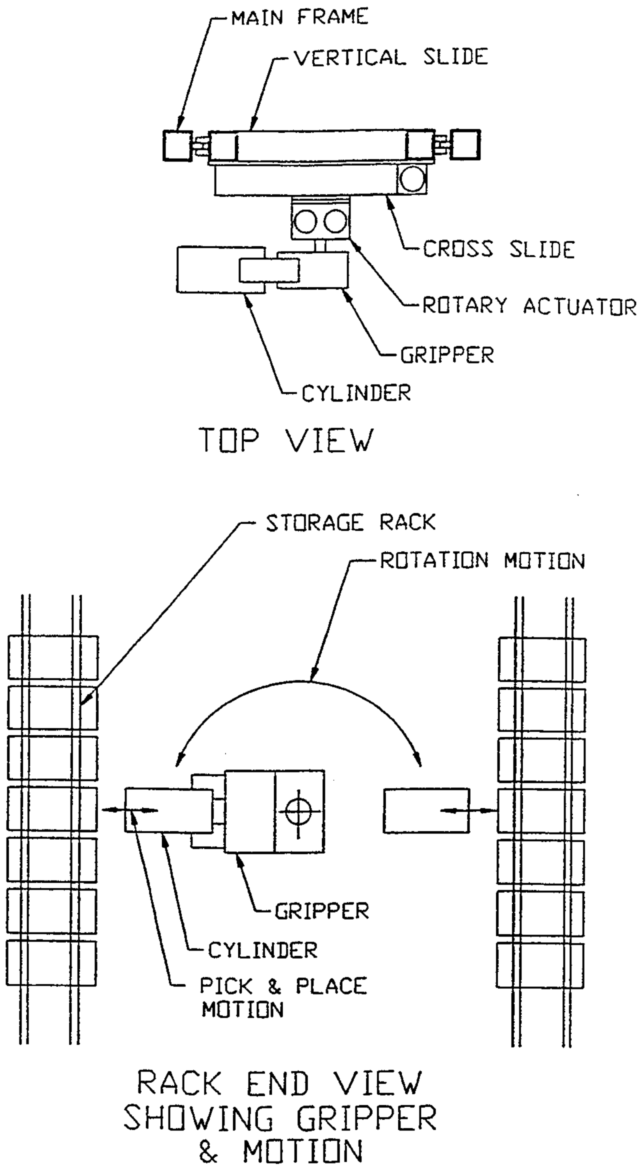

Figure 5. Gantry transporter gripper.

retrieve and what locations they are in. The Transporter goes to the appropriate location and retrieves the concrete cylinder. Upon extraction from the storage location, the Transporter routes the cylinder past a bar code scanner to ensure that the concrete cylinder is the one the system is looking for. The Transporter then delivers the cylinder to another conveyor. This conveyor routes the cylinders and queues them up in front of the automatic compression-testing machine.

Compression Testing

This machine is equipped with an automatic concrete cylinder loading device (available commercially now from the Italian company Technotest, but possibly a special design for this specific application). This device will pick up a cylinder from the conveyor and place the cylinder at the proper orientation and location under the compression ram. The compression testing unit then cycles until the sample has been tested.

As the cylinder breaks, a digital camera, mounted to the side of the compression machine, will take a picture and store that picture digitally in the computer control system. At the end of the shift, a technician can view each picture quickly to ensure that all the samples that were tested during that shift broke suitably, and that no samples need to be disqualified. This camera allows the total system to run without an operator in attendance.

The machine is also equipped with an automatic unloading mechanism for removal of the debris created by the destruction of the concrete cylinder or for saving a cylinder that did not have the expected strength. The debris is swept from the platform of the compression machine into a conveyor that routes the concrete into a dumpster or hold area, thus completing the sequence.

Conceptual Design of Automated System for Bar Code Labeling and Sample Control

The automation of any total operation generally starts with electronic data capture from test equipment and computerized calculations and report generation. The second step is to combine the data handling into an information management system, which makes the data more accessible to users. In a laboratory, this should start with the identification of a sample, ideally when the sample is taken in the field or created in the laboratory. As a sample is taken or created, it should be given a unique number, and the necessary information for tracking, evaluating and reporting the sample should be input to the information management system. The sample should be marked with a unique identification, such as a bar code, so the identification can be read at any time and the information related to that sample brought up on a screen or into an automated testing machine to direct the machine operation.

The scenario for automating this activity envisions handheld computers, which allow input of data about a sample and create a bar code label for the sample. The data would be transferred to a central computer for access by many users, including the laboratory. The laboratory would also have bar code readers at various points in the automated testing processes.

The advantage to the laboratory of automating this test is the time saved from the reduction in data input and the reduction in the number of errors that are inherent in the data input. Electronic transfer of data and reports also saves time for the users of the laboratory services.

The estimated cost to purchase and install an automated system in a laboratory is highly dependent on the system chosen, the extent of automation, and the extent to which the system is available to others. The hardware and software will likely have a price in the range of $50,000 to $100,000 in the

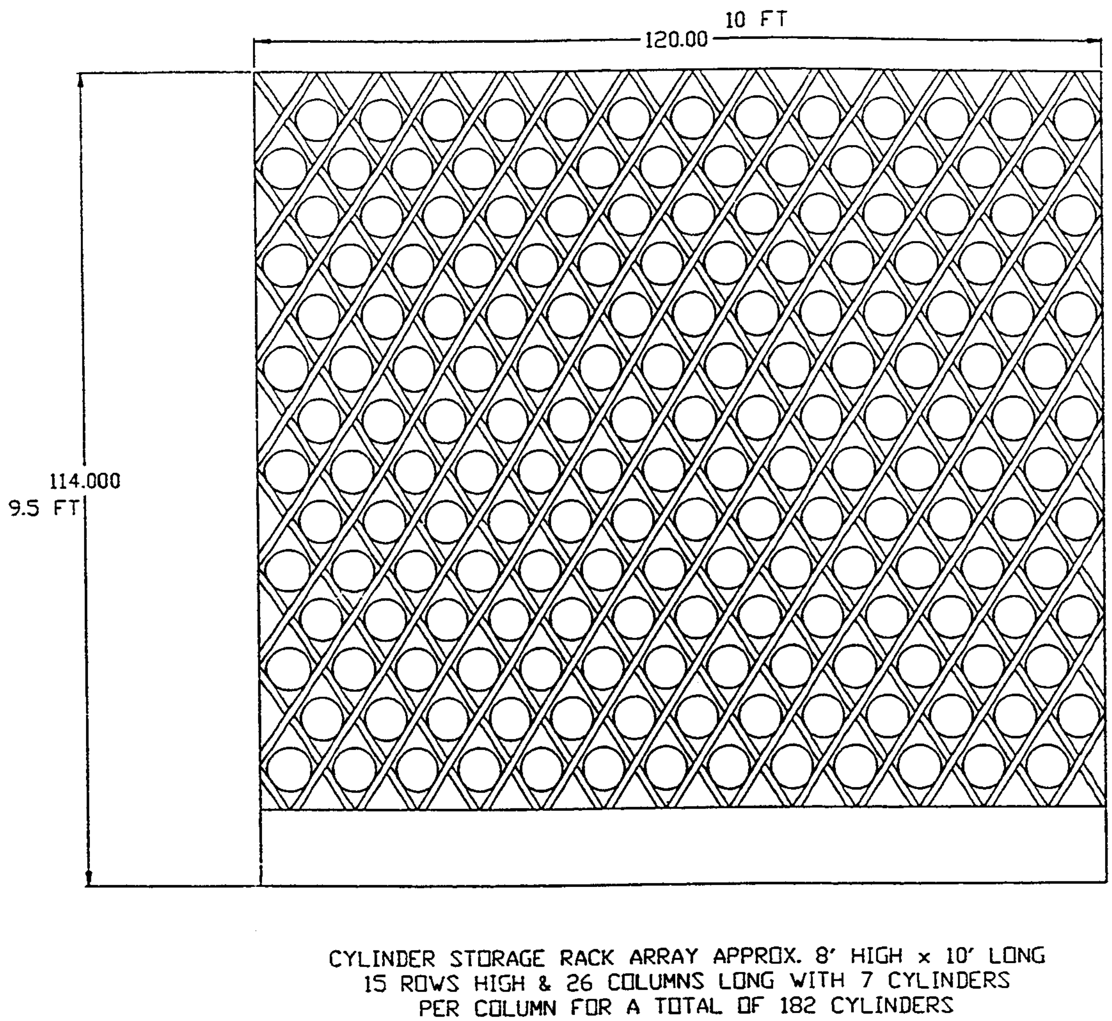

Figure 6. Storage rack.

laboratory. Training costs will be in a similar range. Hand-held units for sampling in the field would be additional.

Justification of a system is difficult because the cost savings extend beyond the laboratory. Time savings must be estimated for each situation, as well as for each user. To a certain extent, laboratories will be forced to install a LIMS, because the rest of the transportation industry will be computerized.

Using current state-of-the-art microprocessor technology, automation of data entry and test result tabulating, storing, reporting, and so on can be accomplished with today's relatively low-cost electronic hardware. The following sections will illustrate two levels of laboratory automation: a minimum system and a complete, state-of-the-art system.

Minimum System

This system is considered to be the lowest level of automation that would result in savings in labor for data entry, tabulating, and reporting. Figure 7 illustrates the components and how they are connected to provide an automated data handling system.

The main components required to provide the minimum system are as follows:

• Standard PC workstation in receiving	\$2,500
• Special software written for this application	\$37,500
• Laser printer	\$800
• Bar code printer	\$2,000
• RF wireless antenna system, in ceiling	\$1,800
• Wireless RF hand-held scanner	\$4,500
Total estimated cost, without installation	\$49,100

Proposed Sequence of Operation

When the samples enter the laboratory, the technician working at the receiving station will identify the incoming

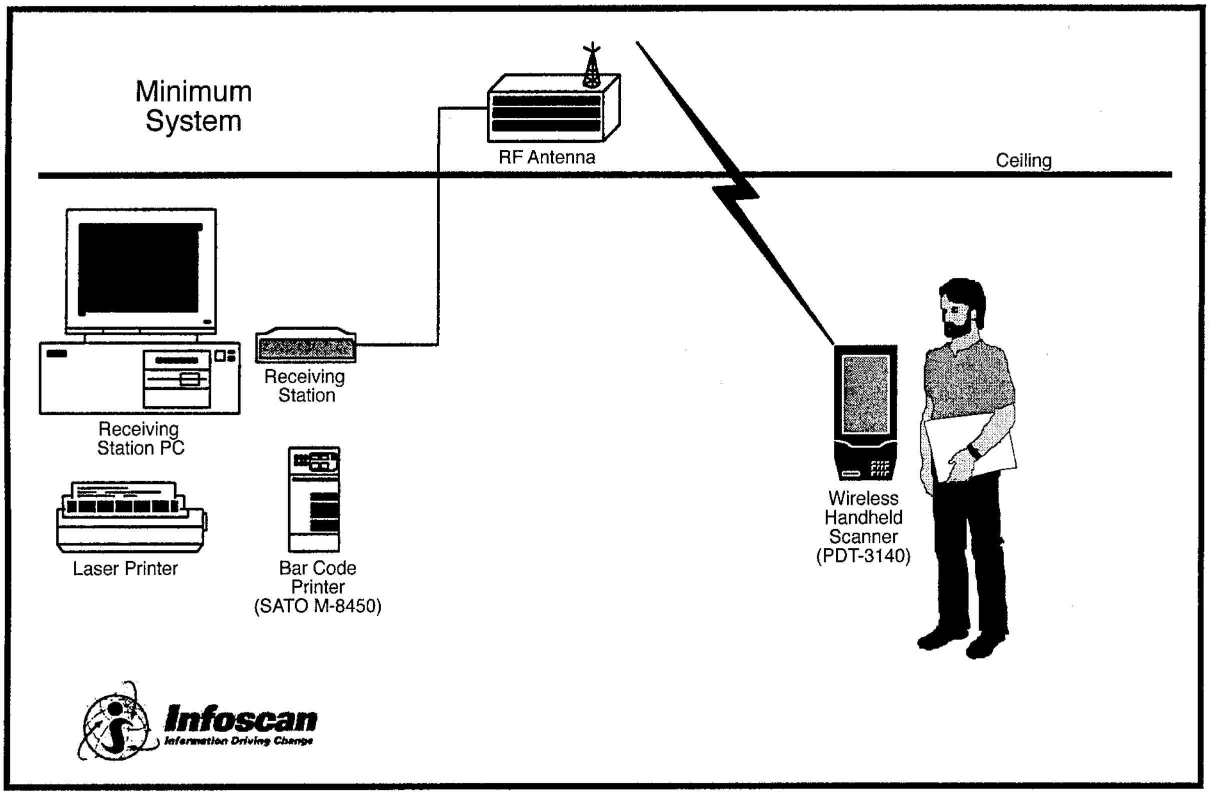

Figure 7. Minimum data entry/labeling system (Source: Factory Systems Engineering Inc.).

sample by manually entering the sample's data sheet into the laboratory's Receiving Workstation PC (personal computer).

The Receiving Workstation PC prints a bar-coded label using the Bar Code Printer. The label is then attached to the incoming sample's container, and the sample is placed in inventory.

When placing the sample in inventory, the technician will identify the sample's storage location by entering the data into the system using a Wireless RF Hand-Held Scanner. (See description of Scanner illustrated later in this report.)

When the Scheduling Program (either automated or manual) requires the sample to be removed from storage, it will display the sample's location in storage. Upon finding the storage location, the technician scans the bar code label (using the Wireless RF Hand-Held Scanner) and the system verifies that the technician has found the appropriate sample.

The Special Software displays the sample's next stop in the testing process. The technician delivers the sample to this location and enters the test location the sample was delivered to by scanning the bar code label identifying the test station.

Before performing the required test, the technician must first scan in the sample's bar code label and indicate to the system that the test is about to begin. The technician then performs the test, and, once completed, enters the test results into the Wireless RF Hand-Held Scanner. The sample's test results are then stored in the PC and the appropriate reports can be printed on the system's Laser Printer when required.

Hardware Descriptions

The following are explanations of and possible candidates for purchase for each of the system's components:

Receiving Workstation PC. This is a standard desktop Personal Computer such as a Compaq® 4640. There are many alternatives here, and many of them will cost less than the $2,500 listed. Some may be as low as $1,500. The key ingredients are one of either Windows® 95, 97, or Windows NT® Operating Systems, with expansion capabilities in sound, modem communications, CD-ROM, multiple hard drives, tape back up drive, and future communication connection to the corporate local area network (LAN).

Special Software. This is software that must be created for this application. There may be several existing software products available in the marketplace today that can be altered, or enhanced, to provide the specific needs of this identified system. The actual cost (estimated at $37,500) for the completed software package will depend upon the total quantity of systems sold utilizing the software. At the $37,500 price tag, a total sales volume of 20 units was considered. If the total sales volume of units is greater, the price tag will obviously be less.

Laser Printer. This is a standard Hewlett Packard® Laser Printer.

Bar Code Printer. This is a special printer that is specifically designed for printing bar code labels where a thick layer of pressure-sensitive adhesive is present. Most printers will not feed heavily coated paper; thus, the need for a special printer.

RF Wireless Antenna System. This antenna system is required for the computer to communicate with the Wireless RF Hand-Held Scanner. The antenna is typically mounted above the ceiling tiles so its maximum range is a 500- to 600-ft radius for a 900 MHz system, or 200 to 300 ft for a 2.5 GHz system. The speed of transmission of information is 2.7 times faster for the 2.5 GHz units than the 900 MHz units.

Wireless RF Hand-Held Scanner. This unit is the key component to the overall system. The unit is small enough to attach to a technician's belt (or waist), yet powerful enough to perform as an operator interface between the technician and the computer. Because of the 500- to 600-ft range for a single antenna mounted in the ceiling, this Wireless RF Hand-Held Scanner is the technician's critical link to the computer for requested information and data input to the computer without actually being at the computer's keyboard. With this device, the technician can move around carrying the keyboard within the antenna's range. If there is a need for more than one technician to perform remote data input/output, several Wireless RF Hand-Held Scanners can be used simultaneously.

Optimum System

The optimum system involves a wider range of electronic communications equipment and a more complete state Local Area Network (LAN). It also employs the use of cellular telephone communications with the Lab Automation Server (computer). Figure 8 shows the conceptualized equipment.

In addition to the items identified in the Minimum System, the following items are needed to provide an Optimum System; a system that provides the maximum return for the dollars invested:

- Lab automation server $7,500
- More complex software for remote cellular communications 50,000
- Optional field unit consisting of:
  - Wireless RF Hand-Held Scanner, with modem 5,000

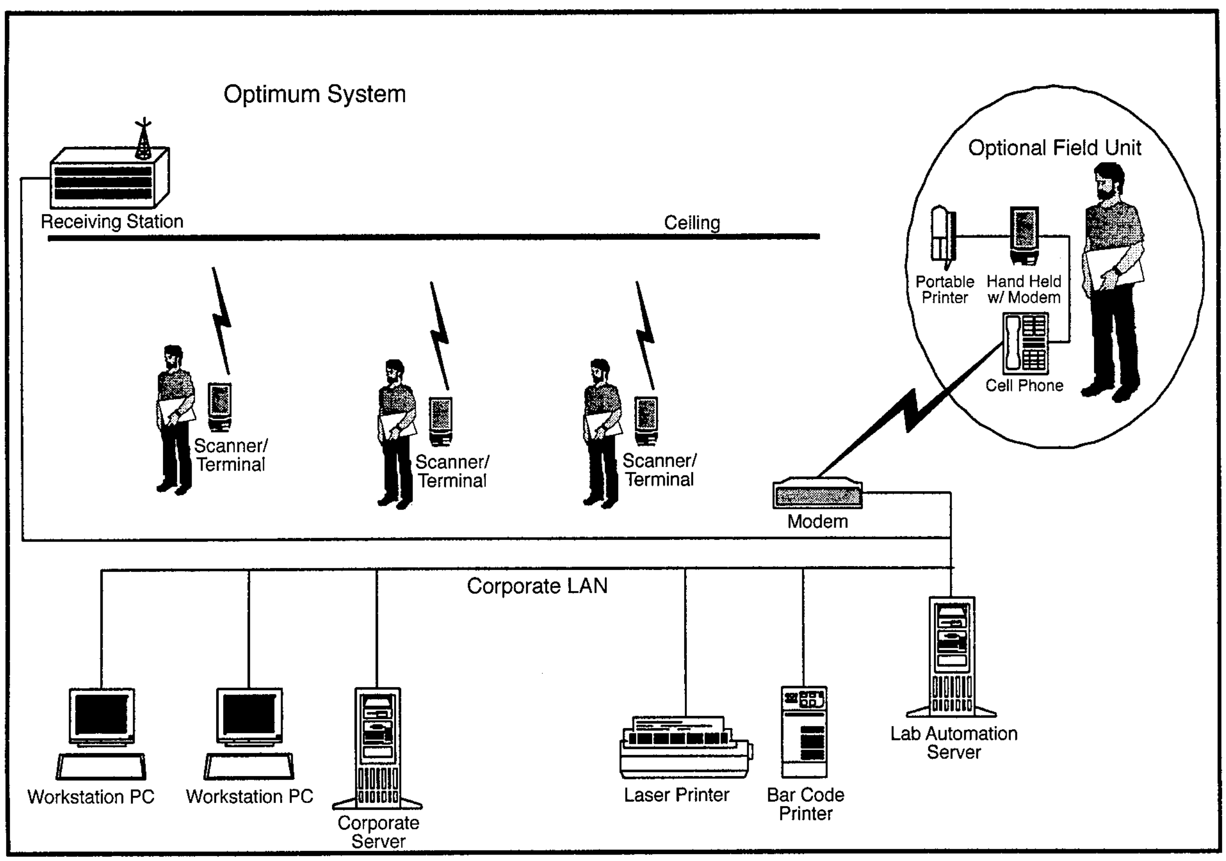

Figure 8. Optimum data entry/labeling system (Source: Factory Systems Engineering Inc.).

- Portable printer for printing bar code labels. 1,000
- Cell phone 500

Total estimated cost, without installation $64,000

- Additional Wireless Hand-Held Scanners . . . . $4,500 each

Proposed Sequence of Operation

The Optional Field Unit provides the field crew with the ability to create bar code labels on the job site and transmit the data, via telephone, to the laboratory. Once the sample is placed in the container for shipment, the operator inputs the specific data for the sample into the Hand Held RF Scanner Terminal. The project information can be scanned via the Scanner from a printed data sheet previously generated in the laboratory. The appropriate bar code label is then printed by the Portable Printer (which can be attached to the operator's belt). The operator attaches the label to the sample's container.

Once the complete set of samples has been labeled, the operator can connect to the Lab Automation Server and transmit all of the data regarding the just labeled samples to the Lab Automation Server. With this information, the Server can place the samples in the system for scheduling and notify the receiving departments what to expect and when.

At the Receiving Workstation, the operator scans the bar code label that was generated in the field to identify the sample and the rest of the information previously transmitted from the Field Unit is retrieved.

The remaining sequence of operation is the same as that described in the Minimum System.

Connecting the Lab Automation Server to the Corporate Server allows tremendous information communication throughout the organization.

PRIORITIZATION OF CONCEPTUAL DESIGNS FOR IMPLEMENTATION

Conceptual designs, which appear to be financially feasible, have been prioritized to focus implementation plans on a limited number of designs. This will allow implementation with limited resources and demonstrate the advantages of automation so that future automation will occur as a natural result of meeting needs. The prioritization criteria are shown in Table 4.

The prioritization ratings from the feasibility analyses were arrayed in a spreadsheet (see Table 5) for rating and review. The factors that could be expressed in finite units, such as number of sales or dollars, were expressed directly. Factors that were relative, such as "Attractiveness to Manufacturers" and "Potential for Implementation," were rated on scales of 5 or 10 (best) to 0 (poorest).

The Total Projected Number of Sales was taken from the Feasibility Evaluations as the mid-point in the projected range of sales. The Number of Agencies Purchasing was also taken from the Feasibility Evaluations.

The Projected Savings to Agencies was estimated by multiplying the labor savings per test multiplied by the number of tests per year multiplied by 3 years to get the amount saved, and then subtracting the cost of the initial investment. This is thought to give an approximation of value of the conceptual designs beyond "break-even."

A rating for the Attractiveness to Manufacturers was established by first developing a ratio of the potential income of a manufacturer (projected market sales times the estimated unit price taken from the Financial Evaluation) divided by an estimate of the development and sales costs. Then a rating was assigned with consideration for other factors such as the potential of design reuse from one test method to others.

TABLE 4 Prioritization criteria to evaluate conceptual designs

Financial Criteria	
Total projected Number of Sales	Number of Agencies Purchasing
Projected Savings to Agencies	Attractiveness to Manufacturers
Technical Suitability	
Potential to Reduce Number of Tests	Ability to Meet Tolerance
Potential to Improve Precision	Reduction in Turn-Around Time
Potential to Reduce Risk of Material Failure	
Potential for Implementation	
Potential of Existing Tests	Potential of Tests With New Technology
Estimated Time to Implement	Barriers
Priorities Expressed by States in Second Survey	

TABLE 5 Prioritization of conceptual designs

TEST DESCRIPTION	AASHTO/ASTM No.	FINANCIAL CRITERIA								TECHNICAL SUITABILITY					'POTENTIAL FOR IMPLEMENTATION			NON-FINANCIAL PRIORITIZATION SCORE
		Total Projected No. of Sales (all buyers)	No. of Agencies Purchasing	Projected Savings to Agencies ($1,000)	Estimated Unit Price ($1,000)	Potential Manufacturer's Income ($1,000)	Projected Costs to Develop ($1,000)	Potential Income / Cost to Develop	Attractiveness to Manufacturers (10 - 0)	Potential to Reduce No. of Tests (5 - 0)	Ability to Meet Tolerances (5 - 0)	Potential to Improve Precision (5 - 0)	Reduction in Turn-Around Time (hours)	Potential to Reduce Risk of Failure (5 - 0)	Existing Tests (10 - 0)	New Technology (10 - 0)	Estimated Time to Implement (5 - 0)	
Compressive Strength	T 22-92	350	35	16,404	150	6,500	200	32.5	10	1	5	3	2	0	10		5	34
Moisture Content - Existing	T 255 and T 265	150	40	902	15	300	100	3	6	1	5	2	1	0	10		5	29
Moisture Content - New	T 255 and T 265	275	50	1,377	10	400	100	4	6	1	3	2	2	0		7	3	22
Reducing Field Samples	T 248	750	40	1,583	2	200	50	4	6	0	5	3	0.5	1	7		5	27
Sieve and Wash - Existing	T 27 and T 11	200	30	8,145	65	1,950	200	9.75	10	1	5	1	1	0	7		4	28
Sieve and Wash - New	T 27 and T 11	200	30	9,578	75	2,250	200	11.25	10	1	4	1	1	0		7	3	26
Particle Size Analy - Exist.	T 88	60	20	617	45	450	100	4.5	5	1	5	2	1	0	8		4	25
Particle Size Analysis -New	T 88	200	35	2,670	40	1,200	100	12	10	1	5	3	24	0		10	4	33
Los Angeles Rattler	T 96	5	5	(81)	30	125	50	2.5	1	0	5	1	0.5	0		10	5	22
Atterberg Limits	T 89 and T 90	300	40	4,344	60	2,700	100	27	10	0	5	5	0.5	2	7		4	33
Proctors	T 99 and T 180	100	10	736	60	720	100	7.2	5	1	5	5	0.5	1	7		4	28
Sp. Grav. and Absorption	T84 and T85	225	40	2,265	30	1,500	50	30	10	1	5	5	2	2		7	3	33
Slump and Air Content	T 119 and T 152	75	10	(162)	25	250	100	2.5	2	0	5	5	0	2	5		4	23
Air Content - New method	T 152	200	50	(4,558)	100	10,000	2,000	5	4	3	2	5	0	5		4	1	24
Fineness of Cement	T 153	40	15	415	20	200	5	40	8	2	5	3	1	2		10	4	34
Time Setting of Cement	T 154 and T 131	225	40	6,330	15	450	100	4.5	4	3	5	3	1	0	7		4	26
Soundness of Aggregate	T 104	75	25	58	30	300	50	6	4	0	5	2	1	0	7		4	22
Resistance to Moisture	T 283	30	15	313	55	275	100	2.75	1	0	5	3	0	0	6		3	18
Extraction/Recovery	T 164 and T170	50	45	16,991	40	320	50	6.4	5	0	5	2	2	0	7		4	23
Bituminous Mix Designs	Superpave and other	40	30	957	150	1,500	100	15	8	2	5	4	6	3	6		4	32
Bulk Spec. Grav. - Existing	T 166	100	35	4,314	45	900	100	9	6	1	5	2	0.5	0	5		3	22
NCAT Oven Extract./Grad.	TP 53, T27, T11	65	30	509	30	450	100	4.5	5	2	5	1	2	0	6		4	23
Thickness/Density of Core	D 2726	20	15	2,438	75	750	200	3.75	3	0	3	3	0.5	0		5	3	17
Superpave Binder Tests		70	30	1,418	75	1,500	100	15	8	1	5	1	1	0	6		4	25
Mech. Testing of Steel	T 244	65	40	7,595	60	600	150	4	4	2	5	1	2	0	5		5	22
Specific Gravity of Soils	T 100	70	25	400	10	300	25	12	8	0	5	3	2	0		10	4	30
Fractured/Flat/Shape Agg.	D 5821, D4791, SHRP	20	10	43	65	650	200	3.25	3	1	5	5	1	2		5	3	24
Gyratory Compactor	TP 4	175	50	2,387	10	200	25	8	8	0	5	0	1	0	8		5	26

The rating for Potential to Reduce Number of Tests was based on an evaluation of the current tests and the impact of the automation on how often the tests would be used.

The rating for Ability to Meet Tolerances was also based on an estimate of the automation capabilities. This was not a significant differentiating factor because many of the automation scenarios use the existing test equipment. It is also true that most industrial uses of automation involve tighter tolerances than tests for highway materials.

Likewise, the rating for Potential to Improve Precision was based on the precision of current tests expressed in the test methods or audit results such as from AASHTO's laboratory certification program, and an estimate of the capabilities of automation and the fact that most industrial uses have a higher degree of precision and repeatability than highway materials tests. This was only a significant differentiator for a few new technologies.

Ratings for the Potential for Implementation of Existing Tests and New Technology are based on an evaluation of the difficulty to apply automation in scenarios that use existing test methods and those that use new test methods based on new technologies. The two categories are mutually exclusive.

A rating was assigned to the Estimated Time to Implement based on an evaluation of how long it would take to have a test scenario successfully implemented, as measured by at least one manufacturer producing and selling the automated equipment, and equipment sales of 20 percent of the predicted market. The ratings were assigned according to the times shown in Table 6.

A Non-Financial Prioritization Score is calculated by adding all the judgment ratings for the scenario.

The conceptual designs were then ranked in descending order generally based on four weighted factors:

- States' preferences (25%),
- Number of agencies purchasing (20%),
- Projected savings to agencies (25%),
- Attractiveness to manufacturers (30%), and
- Non-financial prioritization score (20%)

The resulting rankings of tests are shown in Table 7.

The final prioritization did not follow the scoring exactly. Some intuitive changes were made to reflect logical relationships. For example, the conceptual design for determining aggregate particle size and shapes, Priority 5, was ranked higher than its score because it can be combined with the conceptual design for Priority 1.

It should be noted that the rankings are not quantitatively precise. Differences between some designs are small, and a change in the weighting system would change the rankings of some of the designs. However, for purposes of this research, the rankings are adequate to define those for which implementation is feasible.

The complete feasibility analyses of the design concepts, which were in the top 20 priorities are included in Appendix C, "Feasibility Analyses for Prioritized Conceptual Designs" (not published herein).

APPLICATIONS IN LABORATORIES

It is anticipated that most laboratories will adopt automation in stages as money becomes available. There may be an opportunity, where a laboratory is being newly constructed, to go immediately to maximum automation. But this will be the exception to the general experience. On the basis of past experience, laboratories will likely purchase individual pieces of automated equipment that provide computerized analysis and data transfer. These pieces of equipment will then be hooked into a local area network (LAN) of computers for faster, easier transfer and sharing of data. The computerized equipment will be connected in test cells to eliminate the human interface needed to conduct batteries of tests. Finally, bar code, or other forms of labeling, equipment will then be added to speed data input and sample control.

It seems logical that test cells will be valuable for aggregate testing, bituminous mix designs and testing, and metals testing.

ADDRESSING BARRIERS TO AUTOMATION

Financial Barriers

Published discussions of the automation barriers indicate that financial issues generally drive the need for automation and are the greatest barriers to implementing automation.

TABLE 6 Ratings of estimated time to implement

Estimated Time to Implement (years)	Assigned Rating
1	5
2	4
3	3
4	2
5	1
5+	0

TABLE 7 **Final prioritization of conceptual designs**

Final Priority	Conceptual Design to Automate or Replace Existing Test Methods	Score
1.	*New Test Methods* for AASHTO T 27-93, Sieve Analysis of Fine and Coarse Aggregates (ASTM C 136-84a) and AASHTO T 11-91, Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing (ASTM C 117-90*)	121
2.	AASHTO T 84-94, Specific Gravity and Absorption of Fine Aggregate (ASTM C 128-88) and AASHTO T 85-91, Specific Gravity and Absorption of Coarse Aggregate (ASTM C 127-88)	118
3.	AASHTO T 89-94, Determining the Plastic Limit and Plasticity Index of Soils	118
4.	*New Test Methods* of AASHTO T 88-93, Particle Size Analysis of Soils	117
5.	ASTM D 5821-95 Fractured Particles in Coarse Aggregate, ASTM D 4791-95 Flat or Elongated Particles in Coarse Aggregate and AASHTO TP 33 Fine Aggregate Particle Shape	62
6.	TP 4 Superpave™ Gyratory Compaction of Bituminous	110
7.	AASHTO T 248-95, Reducing Field Samples of Aggregate to Testing Size (ASTM C 702-93)	95
8.	AASHTO T 22-92, Compressive Strength of Cylindrical Concrete Specimens (ASTM C 39-86)	95
9.	Superpave™ Binder Tests	100
10.	AASHTO T 164-94 Quantitative Extraction of Bitumen from Bituminous Paving Mixtures and AASHTO T 170-93 Recovery of Asphalt from Solution by Abson Method	99
11.	Bituminous Mix Designs by Superpave™, Marshall and Hveem Methods	98
12.	AASHTO T 153-90 Fineness of Portland Cement by Air Permeability Apparatus (ASTM C 204-92)	91
13.	AASHTO T 100-95 Specific Gravity of Soils	90
14.	*New Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93, Laboratory Determination of Moisture Content of Soils	84
15.	AASHTO T 99-94, The Moisture-Density Relations of Soils (ASTM D 698) (Standard Proctor) and AASHTO T 180-93, Moisture Density Relations of Soils (ASTM D 1557) (Modified Proctor)	67
16.	*Existing Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93, Laboratory Determination of Moisture Content of Soils	84
17.	AASHTO T 154-91 Time Setting of Hydraulic Cement by Gillmore Needles (ASTM C 266-89) and AASHTO T 131-93 Time Setting of Hydraulic Cement by Vicat Needle (ASTM C 191-92)	75
18.	AASHTO T 244-95 Mechanical Testing of Steel Products (ASTM A 370-94a)	71
19.	*Existing Method* for AASHTO T 88-93, Particle Size Analysis of Soils	66
20.	TP 53 Ignition Oven Method for Asphalt Content of Paving Mixtures and AASHTO T 27 Sieve Analysis of Fine and Coarse Aggregates and AASHTO T 11-91 Materials Finer than 75-μm (No. 200) sieve in Mineral Aggregates by Washing	8

The responses of the state laboratory managers reveal the same thing.

In states where the budget for equipment is separate from the budget for staff and the two are not related, an investment in equipment that will save labor does not get emphasized over other equipment requests. This barrier will be difficult to overcome because it requires changing a state's budgeting process, or at least getting a variance from the process. However, a part of the implementation plan includes arguments for recognizing the value in the budgeting process and relating the investment to the State and Department goals.

Indirect costs of staff, such as time spent in meetings or in training, time spent by supervisors and managers directing and reviewing the staff, recruiting costs and resignation costs, are often not included in budgeting. Budgets can be successful without identifying these costs, but not including them in evaluating the benefits of automation understates the benefits of reducing the time spent on testing. The implementation plan will identify these costs and the experience of those states who do break out the costs.

Most states do not include the cost of money in the cost evaluation of acquiring equipment. States that do, generally use the interest rate of borrowing on bonding. This understates the expense of the investment and overstates the benefit. However, the implementation plan will point out this cost.

The feasibility evaluations for this report used a payback period of 3 years. The equipment is expected to last much longer, 5 to 10 years, or even more depending on the equipment. Thus, a payback period of 5 years could likely be justified. This would decrease the number of tests required per year to pay back the investment. This is a point the implementation plan will communicate.

The cost of yearly maintenance on automated equipment is a concern expressed by several laboratory managers. As noted in the discussion of financial analyses, the cost of maintenance, expressed as a percent of initial cost, is similar to manual equipment.

Laboratory managers are used to doing their own maintenance on equipment and are concerned that they will not have staff knowledgeable about maintenance of automation. Maintenance in industrial applications is routinely provided by warranties on the equipment, service contracts from the manufacturers, or service contracts with local companies. Local companies are being created to provide service for automated equipment, similar to companies that were created to provide service to electric typewriters, then copy machines, and now computerization.

Technical Barriers

The accuracy and reproducibility of the automated equipment and tests may need to be proven in demonstration projects and in test methodology development. For equipment that automates existing test methods, this should be relatively easy and may be self-evident. New test procedures will need to address this barrier in the test development and demonstration paths of implementation. As noted earlier, the levels of precision needed in a highway-materials testing laboratory are not as demanding as in much of industry, so real problems with accuracy are not likely. However, the perception and doubts of those not familiar with automation will need to be addressed.

Several state laboratory managers expressed concern about the potential for higher maintenance and greater downtime of automated equipment. There is some information available about the amount of downtime experienced with various types of automated equipment, and manufacturers will need to be prepared to convince buyers that their equipment is reliable.

Depending on the automated process design, additional training will likely be required for staff to learn to operate and maintain the equipment. For some tests, where automation replaces extensive human activities that must be learned, the new training will be in lieu of prior training. Training on electronic communications, computers and sample labeling equipment particularly will be needed.

Attitudes

The implementation plan will include considerable effort to provide education as to the benefits and realities of automation and to allay fears about the use of new technologies. An attitude of "doing it the way we have always done it" is not expected to be as much a problem as it might have been in the past, because there is increasing pressure from taxpayers to accomplish more with less money and a desire on the part of managers and staff to respond. However, the implementation plan will communicate the benefits in ways that will address the need to adopt beneficial changes. This will not be change for the sake of change, but change to gain certain benefits.

IMPLEMENTATION PLAN FOR AUTOMATION

For successful implementation, four audiences must be convinced that the new equipment is beneficial.

1. Manufacturers must believe there will be a large enough market to invest in profitably. There should be a large enough market to spread the price of development over a number of machines.
2. Decision makers at user laboratories (highway agencies, commercial firms, materials suppliers, etc.) must believe their investment will pay back satisfactorily.
3. Engineers that use the data must believe that the new equipment is as accurate as the existing equipment.
4. Regulatory and standards-setting agencies (AASHTO, ASTM, FHWA, FAA, Corps of Engineers and others) must believe it is worthwhile.

The implementation plan will address those audiences in ways tailored to their interests, emphasizing the issues most relevant to them. The plan will be conducted in a combination of media to get the message to as many people as practical.

A detailed implementation plan is included in Appendix D, "Implementation Plan for Automating Highway-Materials Testing." This plan assigns conceptual designs to one of three paths.

Plan with Three Paths

The implementation plan incorporates three paths as the conceptual designs are in varying states of readiness for actual use (See Figure 9). Designs that automate existing test methods and have a clear financial feasibility need only an education effort to make the four audiences aware of the benefits and feasibilities of automation in general and of the specific conceptual designs. A second path is needed where the benefits of automating existing test methods are not adequately defined by available information. A demonstration task will be necessary to validate opinions and assumptions. After a successful demonstration task, a slightly different education path would be used to implement the technology. A third path is required for tests using new technology to replace old tests. It will be necessary to first develop the test methodology, conduct ruggedness evaluations, and get the test approved by AASHTO. This will also provide data necessary to validate opinions and assumptions about the financial benefits. A somewhat different education effort will then be needed for complete implementation.

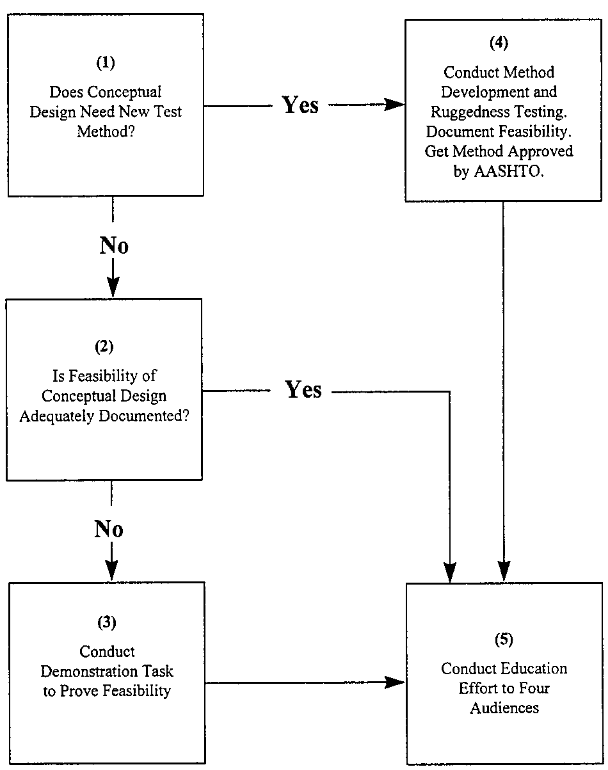

Figure 9. Implementation plan paths.

The recommended paths for implementation of the prioritized conceptual designs are shown in Table 8.

Education Phase

The education process of all paths will include a general discussion of the benefits and feasibilities of automation and how to automate a laboratory. The availability of existing equipment will be publicized. The earliest efforts for implementation will be for those automation designs using existing test methods and clear benefits. The education effort of this path will benefit subsequent efforts for those tests needing demonstration projects or methodology development.

Specific information about conceptual designs ready for implementation will be presented in education of the first path. The automation will be described in words and drawings. Then data from this report will be used to document the technical and financial feasibility for laboratories and manufacturers. The potential barriers and ways to overcome them will be discussed.

The communications will present analysis techniques, which laboratory managers can use to document the needs and benefits specific to their laboratory, for presentation during their budget requests. The techniques will include computerized versions of the analysis for them on disk, CD-ROM, and an Internet site.

Audience participation will be stressed to generate credibility of the research, answer questions, solicit and overcome objections, and improve future presentations.

Being able to demonstrate to all audiences that there is a well thought out, organized implementation plan will be important to the acceptance of the investment risks the manufacturers and decision makers must make.

This education effort will take advantage of several media: presentations at industry and association meetings; papers published in appropriate journals; videos for use by individual decision makers or in selected audiences; and Internet sites for general information and analysis techniques that laboratory managers can download and use for their specific situations.

Demonstration Tasks

There are conceptual designs in which it is not clear from the documentation that the combination of tests and technologies will be beneficial. A demonstration task will be required to further evaluate and document the projected benefits. A demonstration task would require final design of an automated process and construction of a prototype machine. The prototype machine would be operated for a sufficient time to go through "ruggedness" testing of the new process to demonstrate precision and bias. This may require changing the process or test design. It would also give information on operating costs and machine reliability.

TABLE 8 Implementation paths for prioritized conceptual designs

Implementation Path	Prioritized Conceptual Designs (from Table 7. Final Prioritization of Conceptual Designs)	
Education of Four Audiences	Priority 6. TP 4 Superpave™ Gyratory Compaction of Bituminous	Priority 10. AASHTO T 164-94 Quantitative Extraction of Bitumen from Bituminous Paving Mixtures and AASHTO T 170-93 Recovery of Asphalt from Solution by Abson Method
	Priority 7. AASHTO T 248-95, Reducing Field Samples of Aggregate to Testing Size (ASTM C 702-93)	Priority 17. AASHTO T 154-91 Time Setting of Hydraulic Cement by Gillmore Needles (ASTM C 266-89) and AASHTO T 131-93 Time Setting of Hydraulic Cement by Vicat Needle (ASTM C 191-92)
	Priority 9. Superpave™ Binder Tests	
Demonstration Project Followed by Education of Four Audiences	Priority 8. AASHTO T 22-92, Compressive Strength of Cylindrical Concrete Specimens (ASTM C 39-86)	Priority 16. *Existing Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93, Laboratory Determination of Moisture Content of Soils
	Priority 11. Bituminous Mix Designs by Superpave™, Marshall and Hveem Methods	Priority 18. AASHTO T 244-95 Mechanical Testing of Steel Products (ASTM A 370-94a)
	Priority 15. AASHTO T 99-94, The Moisture-Density Relations of Soils (ASTM D 698) (Standard Proctor) and AASHTO T 180-93, Moisture Density Relations of Soils (ASTM D 1557) (Modified Proctor)	Priority 19. *Existing Method* for AASHTO T 88-93, Particle Size Analysis of Soils
Develop New Test Methodology and Gain Acceptance Followed by Education of Four Audiences	Priority 1. *New Test Methods* for AASHTO T 27-93, Sieve Analysis of Fine and Coarse Aggregates (ASTM C 136-84a) and AASHTO T 11-91, Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing (ASTM C 117-90*)	Priority 12. AASHTO T 153-90 Fineness of Portland Cement by Air Permeability Apparatus (ASTM C 204-92)
	Priority 2. AASHTO T 84-94, Specific Gravity and Absorption of Fine Aggregate (ASTM C 128-88) and AASHTO T 85-91, Specific Gravity and Absorption of Coarse Aggregate (ASTM C 127-88)	Priority 13. AASHTO T 100-95 Specific Gravity of Soils
	Priority 3. AASHTO T 89-94, Determining the Plastic Limit and Plasticity Index of Soils	*Priority 14. New Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93, Laboratory Determination of Moisture Content of Soils
	Priority 4. New Test Methods for AASHTO T 88-93, Particle Size Analysis of Soils	Priority 20. TP 53 Ignition Oven Method for Asphalt Content of Paving Mixtures and AASHTO T 27 Sieve Analysis of Fine and Coarse Aggregates and AASHTO T 11-91 Materials Finer than 75-μm (No. 200) sieve in Mineral Aggregates by Washing
	Priority 5. ASTM D 5821-95 Fractured Particles in Coarse Aggregate, ASTM D 4791-95 Flat or Elongated Particles in Coarse Aggregate and AASHTO TP 33 Fine Aggregate Particle Shape	

Funding for demonstration tasks may come from a variety of sources, including NCHRP. There are other federal and state funding sources. Some funding sources require a matching contribution from a manufacturer or sales company who would have the opportunity to use the information exclusively.

Test Methodology Development and Acceptance

New test methods will require development of the methodology in a format that can be tested for "ruggedness," which can be submitted to the appropriate committees in AASHTO and ASTM for acceptance. Most engineers want to specify test methods that have the credibility conferred on tests accepted by AASHTO or ASTM. Regulatory agencies such as FHWA also rely on the validity of test methods accepted by AASHTO and ASTM.

This path is an expansion of the demonstration task in that it will require finalizing the test design, proving the test validity, and obtaining adequate support from AASHTO and ASTM committees to get the test method approved. A manufacturer or sales company would likely be involved in design and finance of this process.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

To achieve implementation of automation in highway materials testing, it is necessary to find or create automated equipment for tests that are conducted in enough volume in enough laboratories to result in the purchase of relatively large numbers of the test equipment. This will make it feasible for equipment manufacturers to invest in developing and selling the equipment. Further, some technology transfer will be required to make the availability and advantages known to laboratory managers.

Research has indicated that financial considerations have been the most critical factor in creating a need for automation in industrial applications and are perceived as most important by highway-materials testing laboratory managers. A second factor has been the improvement in test precision and reproducibility, which indirectly affects the financial costs of testing and of constructing and maintaining highways.

An automated testing need must also result in a market of sufficient size to attract equipment manufacturers. Investment in developing and selling the equipment should have a return that is equal to or better than the return achievable with other types of equipment.

Until now, automation in highway materials-testing laboratories has been slow to develop. Interest has been generated recently by the increasing need to provide more and better roadways with less money. Ways of increasing efficiencies and effectiveness are more actively sought. However, there is limited knowledge of the capabilities and advantages of automation among the managers of highway materials-testing laboratories. Thus, a program of technology transfer that increases awareness of the automation benefits will be a catalyst for improvements in laboratories.

This research has evaluated the market for highway materials-testing automation and the availability of technologies that will automate the testing. The information has been combined in conceptual designs of automated equipment and implementation plans. The implementation plan items have been prioritized for future action based on the financial feasibilities of laboratories to buy and manufacturers to produce equipment and on the needs expressed by managers of state highway materials laboratories.

SUGGESTED RESEARCH

The implementation plan discussed in Chapter 3 and detailed in Appendix D should now be carried out. Laboratory managers, manufacturers, engineers who use the test information, and standards-setting and regulatory agencies need to be made aware of the potential of automation of laboratories and feasibilities of the conceptual designs. There is adequate documentation to promote investment in manufacturing and sales and the purchase of automated equipment. There are significant opportunities to improve the financial and technical performance of highway-materials testing laboratories and, with good transfer of the knowledge gained in this research project, testing agencies can take advantage of those opportunities.

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APPENDIXES A AND C

UNPUBLISHED MATERIAL

Appendixes A and C as contained in the research agency's final report are not published herein. For a limited time, copies of the report containing those appendixes are available for loan on request to NCHRP, Transportation Research Board, Box 289, Washington, D.C., 20055. The available appendixes are as follows:

APPENDIX A: Reported Annual Volume of Tests from States

APPENDIX C: Feasibility Analyses for Prioritized Designs C.1–C.20

APPENDIX B

POTENTIAL AUTOMATION TECHNOLOGIES FOR TESTING

Test Name	Test Number	Automation Technologies
Laboratory Moist Curing and Compression Testing of Concrete Cylinders	T 22-92 T 126-93	material handling, robotic manipulator, water jet cutting system, machine vision for evaluating size, shape and break, computerized data handling, computer operated testing machine
Laboratory Moist Curing and Flexural Testing of Concrete Beams	T 97-86	use same technologies as above, possibly in a test cell that does both tests
Splitting Tensile Strength of Cylindrical Concrete Specimen	T 198-93	use same technologies as above, possibly in a test cell that does both tests
Slump of Hydraulic Cement	T 119-93	robotic manipulator, machine vision and laser measurements with computerized data handing
Air Content of Hydraulic Cement	T 152-93	Automate existing test procedure in test cell with Slump and possibly Cement Content and Water Content for Water/Cement Ratio with: robotics, machine vision for reading test results and computerized data handling
Air Content of Hydraulic Cement	T 152-93	Develop new test method using one of various nondestructive scanning techniques to give air content and L_{bar} measurement and water/cement ratio, with neural network software for evaluation and reporting
Weigh Batching of Aggregate for Test Specimens	T 248-89	material handling, automated splitters, sieving, and weighing,
Reducing Field Samples	T 248-89	same as above
Bulk Specific Gravity	T 166-93	Develop new test method(s) using nondestructive scanning techniques or GeoPyc™ 1360 Envelope Density Analyzer
Sieve Analysis of Fine and Coarse Aggregate	T 27-93	Automate using existing automated equipment and materials handling
Sieve Analysis of Fine and Coarse Aggregate	T 27-93	Adapt, or continue adaptation of, x-ray or laser-based particle sizing methods
Extraction and Gradation of Asphalt Cement Concrete	TP 53 T 27-93 T 11-91	Combine NCAT ignition oven method of determining asphalt content with automated gradation (where asphalt or aggregate are not needed for other testing)
Extraction and Gradation of Asphalt Cement Concrete	TP 53 T 27-93 T 11-91	Combine existing automated machines for centrifugal extraction with new automated gradation methods
Specific Gravity and Absorption of Fine and Coarse Aggregate	T 84-95 T 85-91	Develop new test method with AccuPyc 1330 Pycnometer™ helium displacement technology
Material Finer Than 75 μm Sieve	T 11-91	Adapt, or continue adaptation of, x-ray or laser-based particle sizing methods, in conjunction with gradation
Atterberg Limits	T 89-94 T 90-94	robotic manipulator, machine vision to judge completion, moisture probe in lieu of oven drying, "expert system" to adjust moisture content of trial samples, soil/water mixing under high air pressure to speed conditioning
Thickness and Density of Pavement Core	(D 3549-93a)	machine vision or laser-based methods to determine thickness and volume, electronic weighing, machine vision to identify layers for cutting a core into layers, water jet or laser cutting
Marshall Mix Design		test cell to conduct the various tests, robotic manipulator, expert system for decisions on proportioning (mix design)

Test Name	Test Number	Automation Technologies
Marshall Stability and Flow	T 245-94	robotic manipulator, computer controlled test machine
Superpave™ Mix Design		test cell of related tests, robotic manipulator, existing automated equipment, expert system for decisions on proportioning (mix design)
Superpave™ Gyratory Compaction	TP 4	part of test cell of related tests or stand-alone, robotic manipulator, existing automated equipment
Superpave™ Binder tests	MP 1	part of test cell of related tests or stand-alone, robotic manipulator, existing automated equipment
Ignition Oven Asphalt Content	TP 53	robotic manipulator, existing automated oven redesigned to fit robotics, possibly part of test cell of related tests
Soundness of Aggregate	T 104-94	test cell of related tests, robotic manipulator, automated environmental chamber with ventilating ovens
Soundness of Aggregate	T 104-94	develop new test
Thin Film and Rolling Film Oven	T 240-94	test cell of related tests, robotic manipulator
Mechanical Testing of Steel Products	T 244-95	test cell of related tests, robotic manipulator, water jet or laser cutting tools, existing automated sample preparation tools
Rockwell Hardness	T 80-96	part of test cell of related tests, or stand-alone robotic manipulator, existing semi-automated test equipment
Tension Testing of Metallic Materials	T 68-96	part of test cell of related tests, or stand-alone robotic manipulator, existing semi-automated equipment
California Bearing Ratio	T 193-93	part of test cell of related tests, robotic manipulator, existing semi-automated equipment
Standard Proctor	T 99-95	part of test cell of related tests or stand-alone cell, existing semi-automated equipment, or develop hydraulic- or air-operated rammer, robotic manipulator, moisture probe for approximate moisture contents, particle size determination and expert system to select trial moisture contents, software to evaluate results and draw curve
Modified Proctor	T 180-95	same as Standard Proctor
Aggregate Abrasion	T 96-94	existing Los Angeles Machine, automated particle sizing, automated weighing, robotic manipulator
Gillmore or Vicat Needles	T 154-91 T 131-93	part of test cell of related tests, use existing semi-automated equipment, or develop new test equipment that simulate existing equipment using servo-controlled load application of needles, robotic manipulator, automated sample preparation
Air Permeability Fineness	T 153-90	Develop new test method based on particle sizing methods of other industries
Rapid Chloride Permeability	T 277-93	Develop new test method based on Diffusivity tests
Abson Recovery	T 170-93	include in test cell for extraction by centrifuge method
Specific Gravity of Fine Grained Soils	T 100-95	Develop new test based on helium displacement technology
Fractured Particles in Aggregate	(D 5821-95)	machine vision and neural network software
Lottman Stripping	T 283-89	automate existing test procedure, reducing test tolerances

Test Name	Test Number	Automation Technologies
Flatness and Elongation	(D 4791-95)	machine vision and neural network software
Fine Particle Shape	TP 33	machine vision and neural network software
Moisture Content	T 255-92 T 265-93	basic test of several test cells or methods, robotic manipulator, electronic weighing, enhanced ovens

APPENDIX D

IMPLEMENTATION PLAN

CHAPTER D-1. INTRODUCTION

Problem Statement

NCHRP Research Project 4-25, Implementation Plan for Automating Highway-Materials Testing (NCHRP 4-25), has evaluated ways to automate laboratory testing and created conceptual designs of 20 automated highway-materials test processes. To successfully implement this research, equipment manufacturers, laboratory managers, engineers who use the test information, and standards-setting and regulatory agencies that approve the processes of materials testing must be made aware of the benefits of automation and the new processes. These four "audiences" must be convinced that it will be beneficial to invest in the manufacturing and purchase of the new equipment so that manufacturers will make and sell the equipment and laboratories will buy and use it.

Objective

The objective of this plan is to effect the implementation of automation in highway-materials testing laboratories to improve service to the highway construction and maintenance industry. This will be accomplished by educating the highway construction industry and all laboratories that use similar test equipment about (a) the benefits of automation, (b) the equipment already available, (c) the feasibility of the new equipment in the conceptual designs, and (d) the methods to overcome barriers to automation. The benefits must be demonstrated with documented analyses adequate to cause favorable decisions by manufacturers and laboratory managers. Audiovisual materials that facilitate individual decision making will also be created and provided. Successful completion of this objective will result in the industry wide adoption of the new equipment and methods such that savings to the state laboratories will exceed the investment in the new equipment and in the research that has created the new test processes.

Tasks

To accomplish the objective, the following tasks are envisioned.

Education Phase

Conceptual designs that automate existing test methods (without changing the actual test method) will not go through the extensive approval procedure required for AASHTO and ASTM test methods. The education phase will be all that is required.

Task 1. Prepare and distribute two short videos presenting the benefits of general automation in the laboratory, existing automated equipment, the proposed automated test processes developed in NCHRP Project 4-25, and how to overcome barriers to automation. One video will address the interests of laboratory managers and engineers who will use the test results. A second video will be directed at the decision makers in companies, which might manufacture and sell the new equipment.

Task 2. Prepare and distribute a computerized "knowledge-based expert system" analyzing the benefits of the new equipment in specific laboratory situations and presenting the benefits visually. This will facilitate the decision-making processes and provide documentation for budgeting decisions in laboratories.

Task 3. Present papers and talks at appropriate conferences and publish articles in appropriate industry magazines and journals to increase awareness of the possibilities and benefits and to begin the process of getting new test methods accepted by AASHTO and ASTM. Appear at trade shows with demonstrations.

Demonstration Phase

If it is not clear from the feasibility documentation that a combination of existing test methods and technologies to automate them will be beneficial, a demonstration task will be required to further evaluate and document the projected benefits. With adequate documentation from a demonstration task, the design will be presented to the audiences using Task 3 of the educational phase.

Task 4. Prepare work plans for tasks to demonstrate the feasibility of the conceptual designs that use new technologies to automate existing test methods. Identify specific funding sources and make applications for funding.

Task 5. Conduct demonstration tasks, finalizing design of the demonstration equipment and documenting the feasibility of the design. Prepare documentation for Task 3 of the educational phase.

Development Phase

The conceptual designs that create new test methods using new technologies will have to be developed in detail to establish a test methodology, demonstrate its precision and bias characteristics, and document its feasibility. The new test method will have to be taken through the approval processes of AASHTO and ASTM.

Task 6. Prepare work plans for development tasks to establish specific test methodologies, demonstrate the feasibilities of the conceptual designs which use new technologies for automated new test methods, and coordinate the acceptance of the new methods by AASHTO and ASTM. Identify specific funding sources and make applications for funding.

Task 7. Conduct the development tasks, developing the new test methods, proving their feasibility and obtaining acceptance by AASHTO and ASTM. Prepare documentation for Task 3 of the educational phase.

Measurement Phase

Task 8. Measure success of the total automation effort and report to NCHRP. Success will be judged by the number of new test procedures adopted and put into use, the number of new pieces of equipment sold, and an estimate of the savings to laboratories by this automation.

CHAPTER D-2. FINDINGS OF FEASIBILITIES OF AUTOMATION

Summary of Research of NCHRP Project 4-25

The research of NCHRP Project 4-25 identified several opportunities to automate highway-materials testing. There are two ways to achieve automation—automating existing test methods and developing new methods using automation technologies. The technical and financial feasibilities of the various matches of technologies and test methods were studied. Conceptual designs were identified, which appear to be technically and financially feasible. Barriers to automation were identified, and methods to overcome them were recommended.

The technical feasibility study assumed that the automated test would have to be as accurate and repeatable as the existing test method. The financial feasibility study analyzed each design to determine if equipment manufacturers would invest in development and sales and if laboratories could justify purchase of the equipment. The financial feasibility study included a "market study" to evaluate which tests will be conducted with enough frequency to warrant automation.

The financial study was an iterative process of:

- Developing a conceptual design for an automated test process;
- Estimating the cost savings per test for the automated method;
- Estimating the probable sale price of the equipment;
- Projecting the number of laboratories that could save enough money to justify buying the equipment; and
- Evaluating if the potential number of sales at the assumed price would be enough to cause one or more equipment manufacturers to invest in the development and sales of the equipment.

Data for the technical and financial studies were gathered by a literature search and two surveys of state and commercial laboratories and others that do highway-materials testing. The first survey collected data on frequency and duration of tests, existing and planned automation, salary costs, and other data. The second survey identified the priorities of state laboratories from a selection of 20 conceptual designs for automated tests.

After studying 48 types of materials tests, conceptual designs of automation were created for 28 combinations of technologies and tests. From those, 20 were prioritized as being most feasible for implementation.

The detailed findings of the feasibility studies are included in Appendix C. A summary of each of the studies is presented in the following paragraphs.

Priority No. 1. Automation *by New Test Methods* for AASHTO T 27-93, Sieve Analysis of Fine and Coarse Aggregates (ASTM C 136-84a) and AASHTO T 11-91 Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing (ASTM C 117-90*)

Automation by new methods will use machine vision methods to determine the larger particle sizes and a method to separate the small particles and wash them through the number 200 sieve. Alternatively, the small particles could be measured in another piece of equipment suitable for silt and clay-sized particles. The machine vision equipment could also be used to do tests for fractured particles in aggregate, flatness and elongation, and fine particle shape (Priority No. 5).

This automation will reduce hands-on time and operator errors. There could also be limited gains in precision by eliminating operator error.

Total estimated investment = $85,000
Estimated equipment cost = $75,000. Estimated installation cost = $10,000.
Estimated Hands-on Time Savings per Test = 0.75 hour (45 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 950
Estimated U.S. market for pieces of equipment = 140 to 285

Priority No. 2. Automation *by New Test Methods* of AASHTO T 84-94, Specific Gravity and Absorption of Fine Aggregate (ASTM C 128-88) and AASHTO T 85-91, Specific Gravity and Absorption of Coarse Aggregate (ASTM C 127-88)

The scenario for automating these tests uses two types of available machines from other industries. At least two companies manufacture equipment that uses gases (generally helium) or powders to permeate the pore spaces in the aggregates or soils. Gases are used for true specific gravities, and powders are used for bulk or apparent specific gravities. Some method development is still needed for saturated, surface-dry measurements of aggregates. Some sample preparation is needed for these machines but less than for the existing methods.

This automation will reduce hands-on time and total elapsed time. There should be gains in precision by increasing operator repeatability and inter-laboratory reproducibility.

Total estimated investment = $30,000
Estimated equipment cost = $30,000. Estimated installation cost = $0.
Estimated Hands-on Time Savings per Test = 1.5 hours (90 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 22
Estimated U.S. market for pieces of equipment = 150 to 300

Priority No. 3. Automation of AASHTO T 89-94, Determining the Plastic Limit and Plasticity Index of Soils

The scenario for automating this test is to use a small robot to prepare the specimen and move it from station to station for measuring performance (rolling a thread or dropping the liquid limit cup) and measuring moisture content. Machine vision will evaluate the specimen performance (the size of the thread and the closure of the groove of soil) during the tests. Moisture content will be determined automatically.

This automation will reduce hands-on time and operator errors. There should be significant gains in precision by eliminating operator bias and error. This test could be more meaningful with better precision and, therefore, would be used more often by engineers.

Total estimated investment = $65,000
Estimated equipment cost = $60,000. Estimated installation cost = $5,000.
Estimated Hands-on Time Savings per Test = 1.67 hours (100 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 430
Estimated U.S. market for pieces of equipment = 235 to 370

Priority No. 4. Automation *by New Test Methods* of AASHTO T 88-93, Particle Size Analysis of Soils

There are a number of methods being researched to determine the percentages of silt and clay-size particles in soils and aggregates. At least one test method, using a type of X-ray vision, is said to be ready for developing an AASHTO approved method. It requires sample preparation similar to the hydrometer test, but the test process beyond sample preparation occurs in approximately 20 min and is relatively hands-free. Total elapsed time for this test is reduced from 48 hours (for a complete test) to 2 hours.

This automation will reduce hands-on time and operator errors. There could be limited gains in precision by eliminating operator error.

Total estimated investment = $45,000
Estimated equipment cost = $40,000. Estimated installation cost = $5,000.
Estimated Hands-on Time Savings per Test = 1.5 hour (90 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 330
Estimated U.S. market for pieces of equipment = 150 to 230

Priority No. 5. Automation *by New Test Methods* of ASTM D 5821-95 Fractured Particles in Coarse Aggregate, ASTM D 4791-95 Flat or Elongated Particles in Coarse Aggregate and AASHTO TP 33 Fine Aggregate Particle Shape

These three tests can be automated using machine vision and neural net software to evaluate particle shapes. The software can be "taught" to make the distinctions required. Samples are passed in front of a camera in a manner that presents them individually to the camera. As noted above, this test may be combined with Priority No. 1.

The advantages of this automation include a reduction in hands-on time and an increase in precision, operator repeatability and inter-laboratory reproducibility.

Total estimated investment = $65,000
Estimated equipment cost = $60,000. Estimated installation cost = $5,000.
Estimated Hands-on Time Savings per Test = 1.2 hours (70 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 500
Estimated U.S. market for pieces of equipment = 10 to 30

Priority No. 6. Automation of TP 4 Superpave™ Gyratory Compaction of Bituminous

As this test becomes routine in laboratories, the need to reduce operator time will be valuable. Equipment manufacturers, who are already competing for improvement, will be able to include automated handling of the bituminous mix so that an operator will need only to place the mix supply in a hopper and come back to remove the extruded, weighed specimens. A small robot will place the mix in the mold, move the mold into place for compaction, remove the mold, extrude and weigh the compacted specimen, and repeat the process.

The advantage of this automation is the reduction of hands-on time from 3.0 hours to 1.0 hour.

Total estimated investment = $10,000
Estimated equipment cost = $10,000. Estimated installation cost = $0.

Estimated Hands-on Time Savings per Test = 2.0 hours (120 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 45

Estimated U.S. market for pieces of equipment = 75 to 275

Priority No. 7. Automation of AASHTO T 248-95, Reducing Field Samples of Aggregate to Testing Size (ASTM C 702-93)

This test is a good candidate for automation because it is labor intensive and common to a number of other laboratory tests on aggregates and mix designs of bituminous and portland cement concrete. It has the potential of being a standalone operation or being incorporated in a test cell for a number of tests. The concept automates the existing test as the machine conducts repeated splitting of a sample. A technician places a sample in the machine to start the process and selects the number of splitting cycles. Optionally, there is a means of heating the equipment to facilitate splitting bituminous mixtures for testing during mix designs.

The advantages of automating this test are primarily the time savings, but there can be a limited increase in precision because the machine will always split the sample without segregation.

Total estimated investment = $2,000

Estimated equipment cost = $2,000. Estimated installation cost = $0.

Estimated Hands-on Time Savings per Test = 0.08 hour (5 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 275

Estimated U.S. market for pieces of equipment = 550 to 940

Priority No. 8. Automation of AASHTO T 22-92, Compressive Strength of Cylindrical Concrete Specimens (ASTM C-39-86)

Automation of this test concentrates on the sample-handling aspects and uses existing compression-testing machines and curing chambers (some remodeling of the curing chamber and test layout is assumed). Sample handling uses conveyors and a computer-directed Gantry Transporter to move cylinders from receiving in and out of curing to testing and disposal. Grinding the ends replaces capping, except where neoprene pads are used. The machine will remove the cylinder from the mold, measure it, grind the ends (this step may be bypassed where neoprene pads are used if the ends meet specifications), and place the cylinder in a computer-controlled location in the curing chamber. On the day when testing is required, the computer-controlled Gantry Transporter retrieves the sample and places it on a conveyor to the compression testing machine. The cylinder is moved from the conveyor to the compression testing machine automatically. The testing machine photographs the cylinder after the break and discards the cylinder if the test passes, or puts it in a hold area if it fails.

Automation will improve precision by eliminating operator error and automatically evaluating the statistical process control of the system. Eliminating capping is an environmental benefit. The system can be expanded to include flexural strength testing of AASHTO T 97-86, T 177-81, or T 198-93 and other sizes of compression samples.

Total estimated investment = $155,000 (does not include compression machine or curing chamber)

Estimated equipment cost = $120,000. Estimated installation cost = $35,000.

Estimated Hands-on Time Savings per Test = 0.90 hour (54 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 1,675

Estimated U.S. market for pieces of equipment = 220 to 450

Priority No. 9. Automation of Superpave™ Binder Tests

The scenario for automating this test is to use a robot to move the specimens between stations of existing test equipment. The system can run 24 hours a day without operator involvement.

The advantages of automating this test are a reduction in hands-on time from 5.0 hours to 0.5 hours and the ability of the system to run 24 hours a day.

Total estimated investment = $85,000

Estimated equipment cost = $75,000. Estimated installation cost = $10,000.

Estimated Hands-on Time Savings per Test = 4.5 hours (270 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 180

Estimated U.S. market for pieces of equipment = 40 to 100

Priority No. 10. Automation of AASHTO T 164-94 Quantitative Extraction of Bitumen from Bituminous Paving Mixtures and AASHTO T 170-93 Recovery of Asphalt from Solution by Abson Method

The key concept in this system is use of a small robot rather than an operator to tend the two tests. An operator will place a sample in the queue for the robot to pick up to start the test. The robot will connect the two tests by collecting the solvent/asphalt mixture from the extraction test and transferring it to the Abson Recovery test. The robot will add solvent and cycle the extract to the Abson equipment, weighing as necessary.

The advantages of automating this test are a reduction in hands-on time and improved repeatability.

Total estimated investment = $40,000

Estimated equipment cost = $40,000. Estimated installation cost = $0.

Estimated Hands-on Time Savings per Test = 8.5 hours (510 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 50

Estimated U.S. market for pieces of equipment = 40 to 70

Priority No. 11. Automation of Bituminous Mix Designs by Superpave™, Marshall and Hveem Methods

The scenario for automating the Superpave™ procedure includes a sophisticated robot to retrieve aggregate and asphalt from a designated storage oven, combine and mix them correctly, subject them to the aging oven, move them to a compactor or to testing for theoretical specific gravity, and move compacted samples to moisture conditioning for the moisture sensitivity testing. Sample weighing and temperature controls are a part of the process. The specific compaction and testing will be done by existing equipment having SHRP and AASHTO approved methods, but other parts will be adapted to the automation process. The robot will be flexible to accommodate two or three mix design procedures and to accommodate future changes in the mix design procedures.

This operation will run without human attention 24 hours a day, reducing hands-on time and total elapsed time. There should be improvements in the mix designs because of increased repeatability and lack of operator errors.

Total estimated investment = $140,000

Estimated equipment cost = $100,000. Estimated installation cost = $40,000.

Estimated Hands-on Time Savings per Mix Design= 4.5 hours (270 min)

Estimated Annual Number of Mix Designs to Pay Back in 3 Years = 350

Estimated U.S. market for pieces of equipment = 20 to 50

Priority No. 12. Automation of AASHTO T 153-90 Fineness of Portland Cement by Air Permeability Apparatus (ASTM C 204-92)

Automating this test uses a new test procedure with automated equipment from industrial measurements of powders. It is currently being used for production controls at some cement plants. It will require some methods development, but with the existing experience that should not take long.

The advantages of automating this test are reduced operator time and improved precision, operator repeatability and inter-laboratory reproducibility.

Total estimated investment = $20,000

Estimated equipment cost = $20,000. Estimated installation cost = $0.

Estimated Hands-on Time Savings per Test = 0.7 hour (40 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 400

Estimated U.S. market for pieces of equipment = 30 to 55

Priority No. 13. Automation of AASHTO T 100-95 Specific Gravity of Soils

This is a good test for automation since it uses equipment currently in use in the powders industry. A gas (typically helium) is used to measure the volume of the solids instead of water. Method development is underway. The equipment can be set up with an automatic feed to allow it to run continuously without operator attention. This feature may not be valuable for this test.

The equipment should reduce the hands-on time from 2 hours to 0.5 hour. A quicker test may increase the number of tests conducted. Precision will be increased.

Total estimated investment = $10,000

Estimated equipment cost = $10,000. Estimated installation cost = $0.

Estimated Hands-on Time Savings per Test = 1.5 hours (90 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 60

Estimated U.S. market for pieces of equipment = 40 to 100

Priority No. 14. Automation *by New Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93, Laboratory Determination of Moisture Content of Soils

Automation by a new test method can replace the part of the existing test process that weighs, dries, and re-weighs the sample. However, a new test method may be easier to incorporate in other automated test cells to be a part of many other tests. Unless the test sample is part of another automated test, a technician will place a sample in a test container, place the container in the test machine, and remove it when the test is done. If part of another test cell, a robot will place and retrieve the sample or the machine will move to the sample.

This automation will reduce hands-on time and operator errors. There could be limited gains in precision because operator error is eliminated. Shortening the elapsed time for conducting the test to seconds instead of minutes or hours will be valuable to busy laboratories.

Total estimated investment = $10,000

Estimated equipment cost = $10,000. Estimated installation cost = $0.

Estimated Hands-on Time Savings per Test = 0.05 hour (3 min)

Estimated Annual Number of Tests to Pay Back in 3 Years = 1,350

Estimated U.S. market for pieces of equipment = 190 to 340

Priority No. 15. Automation of AASHTO T 99-94, The Moisture-Density Relations of Soils (ASTM D 698) (Standard Proctor) and AASHTO T 180-93, Moisture Density Relations of Soils (ASTM D 1557) (Modified Proctor)

The scenario for automating these tests adapts the commercially available "automatic" hammers to a robot which performs sample preparation, mixing, molding and moisture content determination. It is assumed that a technician will prepare the overall sample by drying it, sieving out the large aggregate if needed, and moisture conditioning clays. Selecting the test method and specific procedure will instruct the robot which hammer and mold to use and how to compact the samples. A new method of determining moisture content is included in the test cell to reduce the elapsed time.

This automation will reduce hands-on time and total elapsed time. There should be gains in precision by increasing operator repeatability and inter-laboratory reproducibility.

Total estimated investment = $65,000
Estimated equipment cost = $60,000. Estimated installation cost = $5,000.
Estimated Hands-on Time Savings per Test = 1.5 hours (90 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 480
Estimated U.S. market for pieces of equipment = 60 to 145

Priority No. 16. Automation *of Existing Test Methods* for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265, Laboratory Determination of Moisture Content of Soils

These tests are used extensively in the lab and are a part of many other tests. Thus, automation should have great benefits.

Practical automation of the existing test methods will be limited to the part of the process that weighs the wet sample, dries the sample, and weighs the dry sample (with electronic display of results and electronic transfer of data if there is a Laboratory Information Management System (LIMS) system). Unless the test sample is part of another automated test, a technician will place a sample in a test container, place the container on a shelf in an oven having multiple shelves, and enter the tare weight of the container in the oven computer. The oven shelves will have electronic weighing devices that record the weight of the container and soil (as in the Ignition Furnace method of determining asphalt content). The oven computer will determine when a test is complete and compute the moisture content.

This automation will reduce hands-on time and operator errors. There could also be limited gains in precision because the oven will determine when samples are dry.

Total estimated investment = $15,000
Estimated equipment cost = $15,000. Estimated installation cost = $0.
Estimated Hands-on Time Savings per Test = 0.05 hour (3 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 2,700.
Estimated U.S. market for pieces of equipment = 105 to 200

Priority No. 17. Automation of AASHTO T 154-91 Time Setting of Hydraulic Cement by Gillmore Needles (ASTM C 266-89) and AASHTO T 131-93 Time Setting of Hydraulic Cement by Vicat Needle (ASTM C 191-92)

After preparation of the sample, testing will be conducted by an automated machine having load sensors, movement measurements, and the ability to change the position of the needles over the test specimen of cement. One piece of equipment can be set up to run either test.

The advantages of this automation are the reduction in hands-on time from 3.0 hours to 0.5 hour and improved operator repeatability and inter-laboratory reproducibility.

Total estimated investment = $15,000
Estimated equipment cost = $15,000. Estimated installation cost = $0.
Estimated Hands-on Time Savings per Test = 2.5 hours (150 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 65
Estimated U.S. market for pieces of equipment = 150 to 300

Priority No. 18. Automation of AASHTO T 244-95 Mechanical Testing of Steel Products (ASTM A 370-94a)

Automation will include a number of tests in this series. A robot will take a specimen from a queue, move it to a machining station, then to the appropriate test station. Often, machining may be done at a prior location. The system can run 24 hours a day without operator attention. It is assumed that the equipment for actually doing the machining and tests is already owned by the laboratory.

The advantages of automating these tests is the savings from reduced hands-on time.

Total estimated investment = $70,000
Estimated equipment cost = $60,000. Estimated installation cost = $10,000.
Estimated Hands-on Time Savings per Test = 2.5 hours (270 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 300
Estimated U.S. market for pieces of equipment = 40 to 75

Priority No. 19. Automation *of Existing Method* for AASHTO T 88-93, Particle Size Analysis of Soils

The sample will be prepared manually, as it currently is, to the point where it is introduced to the dispersion method. A small robot will handle the prepared soil sample through the dispersant mixing and placement into the sedimentation cylinder. The robot will also insert the hydrometer, take readings, and remove the hydrometer until the next reading. Finally, the robot will empty the sedimentation cylinder into a number 200 sieve for final gradation testing in another test cell, or for manual testing.

This method will not decrease the total elapsed test time and will continue to use unhandy glass cylinders and hydrometer. The advantage is that it is an accepted test procedure and will not have to go through a test development and acceptance.

This automation will reduce hands-on time and operator errors. There can be limited gains in precision by eliminating operator error.

Total estimated investment = $50,000
Estimated equipment cost = $45,000. Estimated installation cost = $5,000.
Estimated Hands-on Time Savings per Test = 1.0 hour (60 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 370
Estimated U.S. market for pieces of equipment = 35 to 80

Priority No. 20. TP 53 Ignition Oven Method for Asphalt Content of Paving Mixtures and AASHTO T 27 Sieve Analysis of Fine and Coarse Aggregates and AASHTO T 11-91 Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing

This test is a good candidate for automation by using a robot to prepare the sample, place it in the ignition oven, and connect the two tests so the aggregate from the ignition oven is placed in the particle size analyzer. The particle size analyzer may be either sieving or a new automated method. The financial analysis assumes the laboratory already has the ignition oven and particle size analyzer.

The advantages of automating this test are the reduced hands-on-time, an ability to conduct tests 24 hours a day, and better working conditions as the technician does not have to work with the very hot materials.

Total estimated investment = $35,000
Estimated equipment cost = $30,000. Estimated installation cost = $5,000.
Estimated Hands-on Time Savings per Test = 0.9 hour (55 min)
Estimated Annual Number of Tests to Pay Back in 3 Years = 375
Estimated U.S. market = 45 to 85

CHAPTER D-3. IMPLEMENTATION PLANS

Introduction

For successful implementation, four audiences must be convinced that automation and the new equipment is beneficial.

1. Decision makers at user laboratories (highway agencies, commercial firms, materials suppliers, etc.) must believe their investment will pay back satisfactorily.
2. Manufacturers must believe there will be a large enough market to invest in profitably. There should be a large enough market to spread the price of development over a number of machines.
3. Engineers that use the data must believe the new equipment is as accurate as the existing equipment.
4. Standards-setting and regulatory agencies (AASHTO, ASTM, FHWA, FAA, BLM, Corps of Engineers, and others) must believe it is worthwhile.

The implementation plan will address those audiences in ways tailored to their interests, emphasizing the issues most relevant to them. The plan will be conducted in a combination of media to get the message to as many people as practical.

The implementation plan incorporates three paths as the conceptual designs are in varying states of readiness for actual use. Designs that automate existing test methods and have a clear financial feasibility need only an education effort to make the four audiences aware of the benefits and feasibilities of automation in general and of the specific conceptual designs. A second path is needed where the benefits of automating existing test methods are not adequately defined by available information. A demonstration task will be necessary to validate opinions and assumptions. After a successful demonstration task, a slightly different education path would be used to implement the technology, different because the timing would follow the first educational efforts of Tasks 1 through 3 of this plan. A third path is required for tests using new technology to replace existing tests. It will be necessary to first develop the test methodology, conduct ruggedness evaluations, and get approval of the test by AASHTO. This will also provide data necessary to validate opinions and assumptions about the financial benefits. A somewhat different education effort will also be needed for complete implementation.

The education phase and preparing the work plans for the demonstration and development tasks (Tasks 1 through 4 and 6) could be an extension of the research of NCHRP 4-25. Conducting the demonstration and development tasks could also be an extension of NCHRP 4-25, particularly for those new tests which are the five highest priorities for implementation and are under some development now. Or, some of the demonstration or development tasks could become new projects because of the need for more extensive funding.

Education Phase

The education phase of all paths will include a specific discussion of the technical and financial benefits and feasibilities of automation and how to automate a laboratory. This will include computerization of testing, Laboratory Information Management Systems (LIMS), and sample identification and tracking methods, such as bar codes. Existing automated equipment will also be publicized. The earliest efforts for implementation will be for those automation designs using existing test methods and clear benefits. Table D-1 lists the conceptual designs that are ready for implementation using the educational phase only.

The education effort of this path will benefit available equipment and subsequent efforts for those tests needing demonstration tasks or methodology development.

TABLE D-1 Implementation of conceptual designs by educational phase

Conceptual Design to Automate Testing	Assigned Priority (among 20 tests)
TP 4 Superpave™ Gyratory Compaction of Bituminous	6
AASHTO T 248-95, Reducing Field Samples of Aggregate to Testing Size (ASTM C 702-93)	7
Superpave™ Binder Tests	9
AASHTO T 164-94 Quantitative Extraction of Bitumen from Bituminous Paving Mixtures and AASHTO T 170-93 Recovery of Asphalt from Solution by Abson Method	10
AASHTO T 154-91 Time Setting of Hydraulic Cement by Gillmore Needles (ASTM C 266-89) and AASHTO T 131-93 Time setting of Hydraulic Cement by Vicat Needle (ASTM C 191-92)	17

Specific information about the conceptual designs ready for implementation will be presented in these education efforts of the first path. The automation will be described in words and drawings. Then data from the NCHRP Project 4-25 report will be used to document the technical and financial feasibility for laboratories and manufacturers. The potential barriers and ways to overcome them will be discussed.

The communications will present analysis techniques that laboratory managers can use to document the needs and benefits specific to their laboratory, for presentation during their budget requests. The techniques will include computerized versions of the analysis for them on disk, CD-ROM, and an Internet site. The analysis will lead them, using their own data or "default" data from the survey of state laboratories in NCHRP Project 4-25, and present the output in tables and graphs suitable for inclusion in written or oral reports.

Audience participation will be stressed during presentations to generate credibility of the research, answer questions, solicit and overcome objections, and improve future presentations.

Being able to demonstrate to all the audiences that there is a well thought out, organized implementation plan will be important to the acceptance of the investment risks the manufacturers and decision makers must make.

The specific approaches for the tasks identified in Chapter D-1 follow.

Task 1. Prepare and distribute two short videos presenting the benefits of general automation in the laboratory, existing automated equipment, the proposed automated test processes developed in NCHRP Project 4-25, and methods to overcome barriers to automation.

The researchers will create two videos using engineers, technical editors, a video consultant, and small panels of the targeted audiences to develop a script that will be 10 min or less, stressing the benefits and addressing the concerns which the audience may have.

Manufacturers and laboratories will be called to obtain names of potential recipients of these videos and to prepare them for implementing the automation proposed by NCHRP Project 4-25. At least 10 videos would be distributed to equipment manufacturers and 100 videos to governmental and private laboratory managers. From NCHRP Project 4-25 it is felt that there is a potential market of approximately 400 laboratories large enough to benefit from automation. Videos will also be offered through Technology Transfer Centers and in announcements in publications of National Association of County Engineers, American Public Works Association, and FHWA.

It is felt that this task should be initiated first so the videos are available when the talks and papers are presented as part of Task 3.

Task 2. Prepare and distribute a computerized "knowledge-based expert system" for analyzing the benefits of the new equipment in specific laboratory situations and presenting the benefits visually.

A knowledge-based expert system for analysis and decision making regarding the purchase of automated equipment will be created as a tool to facilitate favorable decisions. It is felt that this will reduce the barrier of too little time to consider, analyze, and document the decision so purchases can be budgeted. It will also reduce the barrier of inadequate analysis that underestimates the existing costs of personnel. The Principal Investigator and the Automation Engineers will work with a programming consultant and a small panel of potential users to develop a user-friendly system.

The analysis process will include financial, technical, and risk issues for decisions on individual machines or on systems of related machines. The system will be established with default values for factors such as salaries and required time to conduct the tests. The default values will be taken from the appropriate average or median values determined in NCHRP Project 4-25. The system will allow changing those values to fit the individual laboratory and to run "what-if?" analyses.

This task should also be initiated quickly so the system is available when the talks and papers are presented.

This system will be made available in disk and CD-ROM format and on the Internet. The researchers would keep track of those who receive it for follow-up on how the system was used and what decisions were made.

Task 3. Present papers and talks at appropriate conferences and publish articles in appropriate industry magazines and journals to increase awareness of the possibilities and benefits and to begin the process of getting new test methods accepted by AASHTO and ASTM.

The Principal Investigator and Automation Engineers will present talks and publish papers in the appropriate conferences, magazines, and journals to create an interest in the new test procedures and automation. The papers will emphasize benefits and ways to overcome possible barriers to implementation. The Principal Investigator will give a paper and attend relevant committee meetings at one TRB Annual Meeting, two meetings of the AASHTO Highway Subcommittee on Materials, and four regional meetings of the American Council of Independent Testing Laboratories. The Principal Investigator will also have trade show booths with the videos and expert system at TRB and other meetings. Papers or articles should be published in National Association of County Engineers, American Public Works Association, FHWA, Corps of Engineers, Society of Manufacturing Engineers, Robotics International, and the American Institute of Motion Control publications.

NCHRP Project 4-25 identified the conceptual designs shown in Table D-1 as being ready for implementation using the educational phase only. It is recommended that this work be done as an extension of the work of NCHRP Project 4-25. It can begin immediately after acceptance of the Final Report of that study. It is likely that the savings from those five will exceed the costs of the initial study and this extension. Thus, the sooner the implementation can be publicized, the sooner the benefits can be realized. Success with the initial group of automated tests will generate enthusiasm for continuing automation efforts.

The knowledge of the study in NCHRP Project 4-25 will be extremely valuable in continuing the process of implementation. It will allow an efficient transfer of that knowledge into the publications, videos, and computerized decision system that are needed to develop awareness and cause favorable acceptance of the automation concepts among the four audiences to be reached.

Demonstration and Education Phase

There are some conceptual designs for which the documentation does not clearly show that the combination of tests and technologies will be financially beneficial. A demonstration task will then be required to further evaluate and document the projected benefits. A demonstration task will include final design of an automated process and construction of a prototype machine. The prototype machine will be operated for a sufficient time to go through "ruggedness" testing of the new process to demonstrate precision and bias. This may require changing the process or test design. It will also give information on operating costs and machine reliability. Table D-2 identifies the conceptual designs which are thought to need a demonstration task.

Funding for demonstration tasks may come from a variety of sources, including NCHRP. There are other federal and state funding sources. Some funding sources require a matching contribution from a manufacturer or sales company that would have the opportunity to use the information exclusively.

Task 4. Prepare work plans for demonstration tasks to demonstrate the feasibility of the conceptual designs that use new technologies to automate existing test methods.

As an extension of NCHRP Project 4-25, the researchers will prepare work plans for demonstration tasks for the six conceptual designs shown in Table D-2. The work plans will identify the objectives to be accomplished, tasks required, the research approach proposed, and an anticipated budget. The plans will also include suggested funding sources for each project and the steps needed to seek the funds.

The objectives of these tasks can be generally described as building and operating the automated test equipment described in the conceptual design; evaluating and documenting the precision and bias of the test equipment; and determining the costs to build, operate, and maintain the equipment. This will allow an evaluation of the benefits of automation as compared with the existing test methods and an educational effort to implement use of the equipment.

The tasks will include the following:

- Prepare a final design from the conceptual design;
- Build and operate the test equipment in a production laboratory;
- Record costs to operate, including personnel time, training, maintenance, downtime, materials per test, utilities, and other costs;
- Record accuracy of tests by new and old methods, and any changes in frequency of testing facilitated by automation;
- Compare results to conducting the tests by the existing methods; and
- Present results to appropriate committees, meetings and publications.

The plans will describe the means and methods (approach) for accomplishing the tasks and the anticipated costs in adequate detail to identify the funds needed and justify funding. Potential funding sources that will be most likely to accept the project should also be identified. Sources will include

TABLE D-2 Implementation of conceptual designs by demonstration phase

Conceptual Design to Automate Testing	Assigned Priority (among 20 tests)
AASHTO T 22-92 Compressive Strength of Cylindrical Concrete Specimens (ASTM C 39-86)	8
Bituminous Mix Designs by Superpave™, Marshall and Hveem Methods	11
AASHTO T 99-94 The Moisture-Density Relations of Soils (ASTM D 698) (Standard Proctor) and AASHTO T 180-93 Moisture Density Relations of Soils (ASTM D 1557) (Modified Proctor)	15
Existing Test Methods for AASHTO T 255-92 Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93 Laboratory Determination of Moisture Content of Soils	16
AASHTO T 244-95 Mechanical Testing of Steel Products (ASTM A 370-94a)	18
Existing Method for AASHTO T 88-93 Particle Size Analysis of Soils	19

NCHRP, FHWA, individual state highway agencies, equipment manufacturers, Small Business Innovation Research grants, and cost-sharing funding (a manufacturer and a federal source) through federal laboratories such as Argonne National Laboratory.

Task 5. Conduct demonstration tasks, finalizing design of the demonstration equipment and documenting the feasibility of the design.

This task will be dependent on the results of Task 4 as to who will conduct the demonstrations, when and how, and from what funding. It is anticipated that two or more of the conceptual designs can be accomplished under an extension of NCHRP Project 4-25. The conceptual designs for AASHTO T 22-92 Compressive Strength of Cylindrical Concrete Specimens (ASTM C 39-86) and for the Bituminous Mix Designs have a relatively high priority. The conceptual design for AASHTO T 22-92 has been carried out to considerable detail, which will make the demonstration project progress faster and provide results quicker.

Test Methodology Development and Acceptance Phase

New test methods will require development of the methodology in a format that can be tested for "ruggedness" and can be submitted to the appropriate committees in AASHTO and ASTM for acceptance. Most engineers want to specify test methods that have the credibility conferred on tests accepted by AASHTO or ASTM. Regulatory agencies such as FHWA also rely on the validity of test methods accepted by AASHTO and ASTM.

This path is an expansion of the demonstration phase in that it will require finalizing the test design, proving the test validity, and getting adequate support from AASHTO and ASTM committees to get the method approved. Table D-3 identifies the conceptual designs that will require a developmental phase before they can be implemented.

Task 6. Prepare work plans for development tasks to establish specific test methodologies, demonstrate the feasibilities of the conceptual designs that use new technologies for automated new test methods, and coordinate the acceptance of the new methods by AASHTO and ASTM. funding.

As with Task 4, this task should be an extension of NCHRP Project 4-25 to facilitate the rapid development of the test methods which are the top five priorities (see Table D-3 and the other four test methods).

The task will be identical to Task 4 except for the addition of the general objective for creating a new test method and getting it accepted by the appropriate AASHTO and ASTM committees. Additional tasks in the work plan will be required to identify the needs for "ruggedness" testing of precision and bias and to take responsibility for documenting the test methodology in a format acceptable to AASHTO and ASTM.

It is possible that the NCHRP IDEA program could be an additional funding source for these conceptual designs. The first five priorities certainly meet this program's focus on high-payoff concepts that accelerate the development and deployment of advanced technologies, as may the other four concepts.

Task 7. Conduct the development tasks, developing the new test methods, proving their feasibility and obtaining acceptance by AASHTO and ASTM.

This task is similar to Task 5 except for the addition of the need to conduct ruggedness testing of the test methodology and move the test procedure through the acceptance processes of AASHTO and ASTM. Like Task 5 in the demonstration phase, Task 7 in the development phase can be done as an extension of NCHRP Project 4-25 or parts of it continued in other projects after the work plans of Task 6 are prepared.

TABLE D-3 Implementation of conceptual designs by developmental phase

Conceptual Design to Automate Testing	Assigned Priority (among 20 tests)
New Test Methods for AASHTO T 27-93, Sieve Analysis of Fine and Coarse Aggregates (ASTM C 136-84a) and AASHTO T 11-91, Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing (ASTM C 117-90*)	1
AASHTO T 84-94, Specific Gravity and Absorption of Fine Aggregate (ASTM C 128-88) and AASHTO T 85-91, Specific Gravity and Absorption of Coarse Aggregate (ASTM C 127-88)	2
AASHTO T 89-94, Determining the Plastic Limit and Plasticity Index of Soils	3
New Test Methods of AASHTO T 88-93, Particle Size Analysis of Soils	4
ASTM D 5821-95 Fractured Particles in Coarse Aggregate, ASTM D 4791-95 Flat or Elongated Particles in Coarse Aggregate and AASHTO TP 33 Fine Aggregate Particle Shape	5
AASHTO T 153-90 Fineness of Portland Cement by Air Permeability Apparatus (ASTM C 204-92)	12
AASHTO T 100-95 Specific Gravity of Soils	13
New Test Methods for AASHTO T 255-92, Total Moisture Content of Aggregate by Drying (ASTM C 566-89) and AASHTO T 265-93, Laboratory Determination of Moisture Content of Soils	14
TP 53 Ignition Oven Method for Asphalt Content of Paving Mixtures and AASHTO T 27 Sieve Analysis of Fine and Coarse Aggregates and AASHTO T 11-91 Materials Finer than 75-μm (No. 200) sieve in Mineral Aggregates by Washing	20

Measurement Phase

The final work of the implementation is to measure and report on the success of the research. This will be accomplished in Task 8. Measuring the success of the NCHRP Project 4-25 effort will be valuable in justifying continued research.

Task 8. Measure success of the total automation effort and report to NCHRP.

It is recommended that NCHRP Project 4-25 be extended to provide (1) a survey of contacts at equipment manufacturers to find out if they are developing equipment and to help them identify potential markets and (2) a survey of laboratory managers to find out how many are buying equipment and their experiences. This survey should be accomplished 1 year after Task 3 is completed. It will be limited to existing automated equipment and those conceptual designs that can be implemented without new test methodologies.

The results of the measurements and experiences of the manufacturers and laboratories will be reported to NCHRP for possible publication. Early indications of successes will be valuable in encouraging others to automate.

Implementation of a conceptual design will be considered successful if it results in:

- At least one manufacturer producing and selling the proposed automated equipment,
- Equipment sales of 20 percent of the predicted market within 1 year after the equipment is available, and
- Equipment sales of 50 percent of the predicted market within 3 years after the equipment is available.

Measuring these results will require a limited amount of work over an extended time period. It may only be practical to measure the results one year after the equipment is available under an extension of NCHRP Project 4-25. A small research project can be conducted at a time approximately 3 years after the development tasks are completed for the top five priorities.

CHAPTER D-4. CONCLUSIONS AND SUGGESTED RESEARCH

Conclusions

This implementation plan includes the information necessary to transfer and disseminate information about the value of automation of highway-materials testing, the technologies determined to be feasible for use in highway-materials testing and the steps necessary to adapt these technologies. This information needs to be in the hands of laboratory managers, engineers and manufacturers to facilitate the use and manufacturing of the automated equipment.

Suggested Research

A continuation of NCHRP Project 4-25 is recommended to achieve implementation of the automation through the tasks identified in this implementation plan. The Principal Investigator and Automation Engineers have familiarity with the information obtained. This will be beneficial in carrying out the tasks of implementation. It is estimated that $150,000 will be required to accomplish Tasks 1 through 4 and 6 as recommended in the plan. Demonstration tasks for AASHTO T 22-92 Compressive Strength of Cylindrical Concrete Specimens and Bituminous Mix Designs are estimated to be an additional $350,000. Developmental tasks for the top five priorities are estimated to be an additional $550,000. It is possible that funding from manufacturers or state laboratories can be incorporated in the total funds.

(Additional research may also be appropriate to demonstrate the feasibility or develop the methodologies of other test methods. This research can be an extension of NCHRP Project 4-25 or funded from other sources.)

The **Transportation Research Board** is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research results. The Board's varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation