# ROBOTICS APPLICATION TO HIGHWAY TRANSPORTATION - VOLUME I: FINAL REPORT

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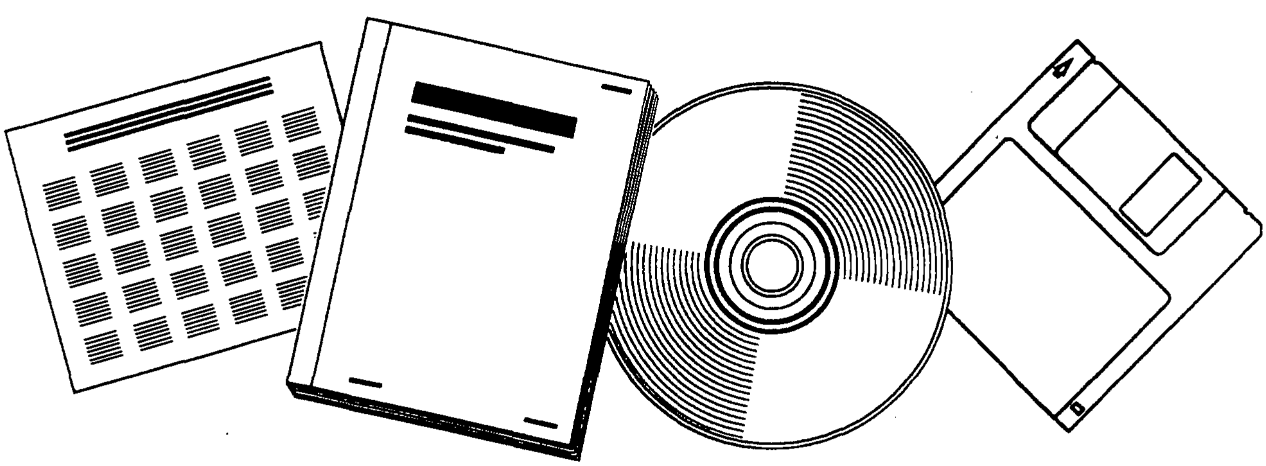

U.S. DEPARTMENT OF COMMERCE
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# Robotics Application to Highway Transportation

## Volume I: Final Report

Research and Development
Turner-Fairbank Highway Research Center
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## FOREWORD

This report, "Robotics Application to Highway Transportation," presents the results of research conducted for the Federal Highway Administration, Office of Advanced Research under an Interagency Agreement with the National Institute of Standards and Technology.

This research concerns the application of robotics to highway construction, maintenance, and operation. It does not include those to the efficient and safe operation of vehicle traffic on highways that are covered by FHWA's special program on Intelligent Transportation Systems.

This report consists of four volumes. This first volume describes the conduct of the research and the final findings. The other three volumes present the resource materials of this research.

Copies of this volume are being distributed to the Federal Highway Administration regional and division offices and to each State highway agency. Additional copies of the documentation are available from the National Technical Information Service, 5280 Port Royal Road, Springfield, Virginia 22161.

Thomas J. Pasko, Jr.
Director, Office of Advanced Research

## NOTICE

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16. Abstract

The National Institute of Standards and Technology, at the request of the Federal Highway Administration, has conducted a study of potential applications of automation and robotics technology in construction, maintenance, and operation of highway systems. The study included a workshop exploring industry perceptions of needs and barriers to adoption, a workshop and a literature search to assess current state of the art practices and trends, and site visits by automation experts to typical highway worksites. Potential technology opportunities were highlighted for short, medium, and long-term efforts in a matrix of intersections between common highway jobs and areas of current technological thrust. From among the opportunities identified, six potential research areas were developed as specific proposals, and subjected to life-cycle cost-benefits analysis. Four were projected to return significant savings by comparison with current practice. Of these, two were identified as also likely to return benefits of significant impact on total highway expenditures and the national economy due to their ability to leverage savings across large numbers of jobs or their effect on a large percentage of highway traffic.

This volume is the first in a series. The other volumes in the series are:

FHWA-RD-94-054 Vol. II: Literature Search
FHWA-RD-94-094 Vol. III: Proposed Research Topics and Cost/Benefit Evaluations by CERF
FHWA-RD-94-095 Vol. IV: Proposals for Potential Research

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| NOTE: Volumes greater than 1000 l shall be shown in $m^3$. | | | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 or (F-32)/1.8 | Celcius temperature | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.71 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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# INTRODUCTION

The National Institute of Standards and Technology, at the request of the Federal Highway Administration, has conducted a study of potential applications of automation and robotics technology in construction, maintenance, and operation of highway systems. The study included a workshop exploring industry perceptions of needs and barriers to adoption, a workshop and a literature search to assess current state-of-the-art practices and trends, and site visits by automation experts to typical highway worksites.

The first volume of this report contains an overview of the study and the methods employed and a summary of the principal results. A second volume contains a bibliographic study and several papers examining selected topics of interest. The third volume presents proposals for particular research possibilities developed by the study panel, and a life-cycle cost-benefits analysis of the proposed research under the assumption that the expected technological goals could be achieved. Additional documents and videotapes included in the various volumes are described in the summary of results.

The study was conducted by a group of automation and robotics experts from academia and government. In addition, some of the panelists additionally had civil engineering backgrounds. The panel sought to gain an indepth understanding of issues and needs in the highway industry through meetings and discussions with contractors, equipment manufacturers, materials suppliers, and State departments of transportation engineers, as well as through visits to highway construction and maintenance sites and highway operations facilities. During the site visits, the panelists also interviewed jobsite supervisors and equipment operators, and other personnel. The panel evaluated the current state of relevant technology out of its own expertise, augmented by a search of the relevant literature and an invited workshop focused on current research in the field, sponsored jointly with the National Science Foundation.

From these resources, the panel identified a variety of highway industry opportunities for automation, and correlated these with research and development opportunities suggested by the current state of the art in automation and robotics. These potential areas of contact were organized into a matrix of research opportunities, which the panel further classified in terms of its estimate of the potential for near-term, medium-term, and long-term efforts to achieve the necessary research or development goals.

A principal goal of the study was to identify a selection of specific research proposals and to evaluate their potential benefit to problem areas of the highway industry. The panel selected six potential research programs for detailed evaluation. Specific research projects were defined, and the technical objectives sought were interpreted in terms of their perceived benefits for highway work. These proposals were submitted to the Civil Engineering Research Foundation (CERF) for a study of life-cycle cost-benefits, under the assumption that the technical objectives could be met. CERF performed the analysis with the assistance of a group of engineering professionals from State DOT's, industry, and academia. Qualitative and quantitative information was gathered and analyzed, and costing was estimated for typical scenarios using current and proposed methods.

Four of the proposals were projected to provide significant economic improvements over current practice. Of these, two were judged capable of providing significant benefits to the national economy and traveling public at large by virtue of the leveraging effect of large-scale highway construction, maintenance, and operations issues on their estimated benefits. Some of the proposals were augmented, modified, or withdrawn following the cost-benefits analysis, and all those remaining were reformulated as specific programs of research in the form of proposals for research support, with specific timelines, efforts, deliverables, and support levels.

# OVERVIEW OF THE STUDY

## ORIGIN

The Office of Advanced Research of the United States Department of Transportation, Federal Highway Administration (FHWA), has the mission "to plan, administer, conduct, and coordinate fundamental research and innovative adaptations for emerging and advanced technologies which have potential for long-range applications in the highway program." In pursuit of this mission, the Office of Advanced Research contracted with the Robot Systems Division of the National Institute of Standards and Technology to conduct a study of the potential applications of automation and robotics technologies to relevant problems in highway construction, maintenance, and operations that might be beneficially advanced by FHWA activities.

## RATIONALE

The Nation's highways are a major component of the national infrastructure. It is widely acknowledged that there is a developing general crisis in the maintenance of the American civil infrastructure. Highways, bridges, sewers, railroads, harbors, and public buildings built in the 1950's and 1960's are wearing out, while Federal spending on infrastructure has fallen from roughly 5 percent of all U.S. budget outlays in the 1960's to less than 3 percent in the late 1980's. The results are starting to show. The U.S. Department of Transportation, for example, estimates that Americans are delayed more than 2 billion hours in traffic on urban highways each year -- delays that cost the nation $35 billion in lost interstate commerce.

Research by David Aschauer, a former senior economist at the Chicago Federal Reserve Bank, concludes that "there is a distinct positive relationship between infrastructure and productivity," and that "the drop-off in infrastructure spending is clearly a significant factor in the nation's sagging productivity growth." U.S. News and World Report says that "even conservative studies suggest that a one-time investment of $20 billion to improve roads, airports, and other core infrastructure would raise the output of the nation's businesses by $13 billion every year thereafter and ratchet up the productivity of existing assets."

Clearly a major investment needs to be made in the American infrastructure. At issue is how to make this investment pay the highest dividend in terms of increased productivity. There are enormous productivity benefits to be derived from the development of improved methods of civil construction to increase the efficiency and reduce the cost of the work required. The single greatest opportunity lies in adapting the principles of industrial automation to the field of civil construction. Successfully accomplished, this would provide an enabling technology that could leverage the existing investment of the civil construction industry in machines and personnel, and could apply as beneficially to repair of existing infrastructure as to new construction. Because essentially similar problems and procedures in highway construction and maintenance span enormous distances and vast amounts of invested capital, the Nation's highway system presents a magnificent opportunity to approach these goals through the solution of a relatively restricted set of problems.

It is overly simplistic to conceive of this in terms of robotics applied to construction machinery; successful accomplishment requires the broad perspective of true automation. The lessons of industrial automation have taught us that robotics are successful only when combined with design for automation, automated planning, integrated materials flow, automated measurement and inspection, standard data base and data exchange formats, and a variety of other technologies now emerging in the U.S., Europe, and Japan as necessary constituents of the automation process. Such a broad-spectrum approach to the automation of the highway construction industry must not only address the problem of the public cost of maintaining the American highway infrastructure, but must have a beneficial effect on the American economy in many other ways as well.

## GENERAL ECONOMIC BENEFITS

Beyond the great benefit of reducing the cost of maintaining the public infrastructure, the following benefits may be expected from rapid application of automation to highway construction:

- Advances in automation for highway construction can revitalize the American highway construction industry and a host of derivative industries. Aided by advanced technology, these industries will not only become more profitable, but will also be more competitive in the global construction market.

- Jobs can be created. The evidence of automation in manufacturing shows that the ultimate result of improved efficiency through automation is to create new jobs, new industries, and jobs requiring more skills.

- Productivity can be increased significantly in a major section of the American economy, thereby contributing significant real growth in gross national product.

- The market for high-technology automated services and equipment created by automation of the highway construction industry will provide a stimulus to lagging U.S. high-technology industries.

- The development of new generations of equipment for automated construction will support American export markets.

A major research initiative addressing these issues, as well as improved automated devices and processes, is required, and could quickly pay substantial dividends in improved efficiency and cost-savings. However, the highway construction industry in the United States consists of many, non-vertically integrated components. Many of these are small subcontractors. Others specialize in various kinds of equipment manufacture or materials handling. In such an environment, no single participant nor industry segment will have the opportunity or resources to develop the necessary technology. The Federal Government, through its laboratories and its agencies for the regulation and oversight of civil construction, does have the necessary breadth of experience and skills to direct and support the development of this technology in the national interest. The Federal Government, directly, and indirectly through subsidies to State and local governments, is also a major consumer of this industry's product. It is thus in a position to accelerate the adoption of new technologies by the industry. Given a problem of this scale, a coordinated program of research, having the necessary scale and breadth to address the issues cited, can only be mounted by a Federal research initiative, in cooperation with the relevant segments of the civil construction industry.

The first objective of such a program must be to identify and provide the range of technologies that must be brought together for a successful transition of the highway construction industry from its present status to that of a high-technology, automated industry. The second objective must be to ensure that the necessary standards and other requirements for integrating these technologies exist. The third objective must be to transfer this technology and its integration effectively into the industry. The present study attempts to begin this process by investigating the opportunities presented by the uniting of current industrial automation technology with current highway construction and maintenance practices. It attempts to identify both targets of opportunity for immediate application of existing technology, and the most highly leveraged opportunities for research that can extend that technology into the highway arena.

## TECHNICAL APPROACH

The current state of the art in robotics and automation has been driven to a very large degree by the requirements and environment of manufacturing applications. At the outset, it was recognized that there are many similarities between problems addressed by automation in factory-based manufacture, and activities common to highway construction, maintenance, and operation. Construction is a form of manufacture. In the case of highways, maintenance is also similar to manufacture, since repair frequently requires that roadways and structures be essentially reconstructed. Maintenance may also require special procedures such as stripping of old paint, which present specialized problems. Operations such as management of traffic around construction sites can have underlying similarities to such traditional problems as managing manufacturing materials flow, however other issues, such as trash collection, appear novel.

Because of the structural similarity of construction equipment to much automated robotic equipment, it is initially tempting to assume that the addition of robotic controls to such equipment in an attempt to convert the construction site to something similar to an automated factory might be a reasonable first approach. Several considerations argue against this. At the level of physical devices, the great difference between the highway-site problem and traditional automated manufacturing problems lies in the degree of structure that can be imposed on the environment. In the factory, the position and orientation of materials is easily regulated, the timing of parts presentation can be controlled, tolerances can be rigidly specified, and the completion-time of operations is invariant. These conditions are hardly ever found in the field.

The technical means to cope with these difficulties exist to greater or lesser degree in current robotics technology. What is required in principle to solve such problems is more elaborate sensing, e.g., machine vision, to ascertain the actual state of affairs, and more flexible and intelligent control systems to correct the devices' actions to compensate for variance in the situation. Unfortunately, these technologies, where they even exist with sufficient capability, are very costly. Real-time vision systems and computers capable of guiding flexible real-time behavior represent substantial investment. In addition, devices that achieve such capability are typically not robust enough for daily field usage. On the other hand, at the organizational level, the problems of planning and scheduling, inventory control, task assignment, resource utilization, data base management, and other tools of automation appear formally quite similar to those routinely encountered in factory automation, provided that the physical means exist to collect information and to project action based on decisions.

In light of these considerations, it was decided that the most reasonable technical objectives for the present study would be:

•To identify highway practices currently within the capabilities of available robotics technology, or reasonable extensions to that technology, in which current highway industry practice is especially costly or difficult, e.g., for reasons of safety or environmental considerations, and which would therefore represent a cost-effective target for even complex physical automation.

•To identify highway practices, e.g., some rebar placement and tying operations, in which the constraints on the environment can be made to approximate those existing in factory environments, and to seek means to apply factory-robotics technology to such situations in a manner that would be cost-competitive with current methods.

•To investigate opportunities for retrofitting existing highway industry practice and devices with minimal-cost sensing and control, including man-in-loop control, in order to collect the information and project the decisionimplementation required to apply factory-level and cell-level automated planning, processmanagement, and control technology in the highway environment.

•To identify opportunities for application or development of robotics technologies not currently employed in factory automation, where highway industry practices present unique new operations or processes that might be automated.

This set of objectives was intended to leverage existing expertise and knowledge accumulated in the factory automation experience of the past two decades, while avoiding the tendency to overgeneralize and fail to recognize the unique challenges of the highway industry. They were further interpreted within the context of FHWA's desire to identify both near-term and long-term opportunities for significant research, and to identify opportunities for stand-alone demonstration projects that could stimulate the interest of the highway industry and state and local governments in automation for highway programs.

Finally, it was intended that the study should focus and build upon the considerable body of work already done in this area and the numerous contributions of other groups that have already studied various aspects of the issue.

## METHODS AND ACTIVITIES

A study panel was assembled from the National Institute of Standards and Technologies (NIST), academia, and industry resources. The makeup of the panel was chosen to reflect a broad-based expertise in various aspects of automation and robotics. In addition, some members of the panel had relevant expertise in highway and general construction areas. One of the principal goals of the succeeding phases of the study was to educate the panel members as broadly as possible in the unique problems of the highway industry. Without such education it was assumed that the recommendations of the automation experts would likely be creative, but naive. Three major objectives of this education phase were: (1) to gain familiarity with current technology, procedures, and practices used in highway construction, maintenance, and operations; (2) to understand the structure of the industry, its current practices and methods of doing business, and the regulatory climate in which it functions, and to try to understand barriers to adoption of automated methods; (3) to review the current state of the art with respect to applications of automation in this industry.

To address the first need, FHWA arranged three field trips for members of the panel. These took place in early 1993 and were hosted by the State departments of transportation (DOT's) of Texas, Georgia, and California. All three visits lasted 2 days and included sitetours, meetings, and discussions. The sites visited illustrated a variety of construction activities, including surveying, several kinds of paving operations, bridge construction and decking, rebar laying, grading and filling, trenching and pipelaying, and materials handling. Maintenance operations included stripping and painting, repaving, bridgerepair, pavement inspection, and traffic control. During the Los Angeles visit, one-half day was spent touring the Los Angeles Traffic Control Center and discussing operational issues. In addition, the panel members viewed videotapes of other sites and operations provided by CALTRANS.

The second need, an understanding of issues in the industry, emerges from the lessons of the past two decades in factory automation projects. The mistakes of the past reveal the ease with which the wrong targeting of problems can nullify the contribution of the most brilliant technical innovation. It is necessary to understand automatable processes in the context of the total chain of production in which they are imbedded, and to understand the economics of their contribution to that context. It is also frequently necessary to consider such nontechnical barriers to adoption as labor displacement, human interfaces, regulatory and safety requirements,and environmental issues to evaluate the true potential, costs, and contributions of potential automation projects.

To help the panel members understand these issues in the highway construction industry, a 1 day workshop was held on November 4, 1992, hosted jointly by NIST and FHWA, and attended by representatives of the highway construction industry, including general contractors, major subcontractors in important specialties, major equipment manufacturers, and materials suppliers. Approximately 70 people were present. The meeting was arranged by NIST's Robot Systems Division, and was moderated by the director of NIST's Building and Fire Research Laboratory. The meeting explored those issues that the industry saw as the principal problems driving their costs, deadlines, and quality control. In addition to the panel members, technical participants from FHWA and NIST as well as other technical experts attended the meeting as consultants. The panel members attempted to categorize and rank the issues raised, and to formulate them into guidance for interpreting the potential impact of the automation opportunities observed in the subsequent site visits.

A second meeting with contractors was arranged by the Texas DOT following the first site visit. At this meeting, the panelists had the opportunity in a small-group format to ask specific questions about the operations they had seen and the potential contribution of automating them. They were able to hear the contractors' viewpoint on the business consequences and barriers to adoption of both specific proposals and general issues of automation. Many issues related to economic incentives and regulatory and labor concerns were discussed.

The third portion of the effort to understand the background of the problem, a review of the current state of the art, was first addressed by mounting a literature search and a technical workshop. A search was conducted of trade association publications and journals, online data bases, the Library of Congress, and university libraries. Several hundred directly relevant and closely related items were identified which applied to FHWA concerns or closely related topics. Items that were related to research on technologies that could be applied to FHWA concerns, but that did not specifically refer to such applications, were omitted as this would potentially have included all research literature on automation, machine vision, robotics, and similar fields. As a check on the search strategy, a list of keywords was developed from the literature discovered, and a second contract was let to a search specialist from the Institute for Scientific Information, who performed a 3 day breadth-oriented search on the keywords from their data base, which covers most of the world's publications. This search returned 2500 items, of which most were false positives. No important or not marginally relevant items were returned that were not in the original search. It was concluded that the initial search has found the majority of the relevant material. Copies of the search were made available to the panelists early in the study.

To further understand the current state of relevant technology, a second workshop was conducted in late April 1993. This workshop focused on current research, and the attendees consisted primarily of academic and industrial scientists from the automation and civil engineering communities. The workshop was sponsored jointly with the National Science Foundation. The first day focused specifically on issues relating to highway construction maintenance and operations. The second and third days focused on technologies rather than applications, and covered the general area of robotics and automation applied to earthmoving, tunneling, site characterization, excavation, and materials handling. Many interesting papers were heard, and it was the consensus that most participants substantially benefitted from exposure to the current state of the art across a broad inter-disciplinary front. On the evening of the first day, a discussion session was held at which the panel presented their preliminary proposals for highway automation projects to the participants for criticism and comment. A lively discussion ensued that resulted in several improvements to the proposed studies.

## PROPOSALS AND EVALUATION

The ideas stimulated by these activities were summarized in a matrix of perceived opportunities for near-term to long-term efforts, categorized by area of highway concern and area of automation technology. Out of these general areas perceived to have high potential payoff in terms of match between current or anticipated levels of automation technology and benefits to the highway industry, the panel selected a number of specific problems. These problems were selected to cover a representative range of timescales and scope.

Individuals or small groups of the panelists then proposed research programs that in their opinion would address these issues. These pre-proposals focused on the nature of the research and the expected benefits to the highway industry. To evaluate the actual potential benefits of the proposed research programs and to attempt to assign an estimated dollar value to these benefits, the Civil Engineering Research Foundation (CERF) was given a contract to identify appropriate experts in the civil engineering community and assess their reactions to the proposals and to perform other studies as necessary to draw conclusions on the expected benefits. CERF prepared questionnaires and descriptive mailings in consultation with NIST, evaluated responses, and held meetings with representative respondees for indepth discussion of the issues. CERF performed an analysis of these results that was given as feedback to the panel of automation experts. Based on this feedback, the panel made revisions that seemed appropriate to the proposals and prepared final forms of the proposals, including estimates of time and cost for the proposed work.

At the same time, an analysis was developed of important factors for evaluation of true costs and benefits, which obviously may include many factors other than those amenable to a strict accounting interpretation. The proposals, the CERF report, and the evaluation factors together constitute a principal result of the study and are presented in detail in the other volumes of this report.

## RESULTS

The principal results of the study, contained in several volumes of this report were:

- A bibliography of the current relevant literature, including a brief review of some of the major projects covered in the literature.

- A general summary of the panel's impressions of the current state of the ``fit" between automation and robotics technology and the needs and problems of the highway industry. The issues highlighted are summarized in the matrix of technological opportunities. Problems foreseen in adoption are also discussed.

- Several specific areas are further discussed in papers that report more broadly on the relevance of these issues as a guide to further discussion of research needs. These represent topics that were found by the panel to be of broad importance across many issues of automation in the highway industry. In addition, this section contains a report that survey the state of exoskeleton technology with respect to possible applications for highway construction and maintenance workers.

- The proposals for research programs in selected technologies, together with the CERF analysis of benefits and the study of evaluation criteria.

- A set of final proposals for particular research programs with specific deliverables and time scales.

# SUMMARY OF RESULTS

This section provides a guide to the various documents comprising the study, and a brief summary of their principal conclusions. In the first part, some global impressions that were obtained by members of the panel over the course of the study and that are not directly contained in any one document are presented as a general guide and framework for interpretation of particular findings in the other sections of this report.

## GENERAL FINDINGS

The members of the study panel participated in a number of events focused on educating the panel with respect to current practice and state of the art in the highway industry, and with respect to the perceived needs and concerns of persons in all phases of that industry. These events included a workshop at which the panel members were able to interact with industry representatives, including contractors, materials suppliers, equipment manufacturers, and State DOT personnel. At the workshop, general sessions explored the reactions and concerns of the attendees to many issues in automation of their areas of expertise; smaller discussion groups provided brainstorming on particular topics. During three field trips, members of the panel visited highway worksites and observed a variety of common activities in construction, maintenance, and operations. On these field trips, the panel members had the opportunity to speak with foremen, equipment operators, and other workers on the job. Discussions were held with local contractors and with local State DOT engineers.

Out of these activities, the panel formed a number of impressions concerning issues and conditions in the highway industry with respect to automation. These impressions were influential in guiding the panel's technical proposals that are presented later in the report, but are not specifically contained in those proposals.

## BARRIERS TO ACCEPTANCE

The success of an automation revolution in the highway industry depends on widespread adoption of new technology. A number of current conditions appear to act as barriers to acceptance of new technology. In general, it is beyond the panelists' expertise to propose solutions to these problems, however, it is worthwhile to point them out so that others may be motivated to address them.

• **Regulatory Climate:** The panel was repeatedly told of problems presented by conflict of proposed technologies with a variety of Federal, State, and local regulations. The industry is highly regulated and, in many cases, the regulations have been written in a manner that implicitly assumes the current model of industry practice. Such regulations present a barrier to the introduction of new practices, methods, and technologies. Of particular concern are regulations that have been written as to actually incorporate references to specific, current technology in setting standards for acceptance; procedures for testing and inspection; or safety-related requirements.

• **Structure of the Industry**: The American highway industry is horizontally structured. Typically, contractors, subcontractors, equipment manufacturers, and materials suppliers are all independent businesses. This contrasts with the situation in countries such as Japan, where a construction corporation is frequently a verticallystructured business that may develop and produce its own equipment. As a result, American equipment manufacturers are reluctant to spend development costs on new equipment that may present too high a risk for the small contractors who are their principal customer base. The American highway industry was characterized as an industry in which, "Everyone is trying hard to be second." The fragmented nature of the industry makes firms unwilling to adopt technology that has not already been proven to be profitable by someone else. This indicates a potential importance for demonstration projects as a means of speeding adoption of new technologies.

• **Contracting Practices**: In typical practice, a multitude of small independent contractors are involved in any large project. Often this includes not only firms specializing in different phases of project activities, but also firms of the same sort operating in different geographic areas, such as sections of right of way. This is not a great problem as long as overall project optimization is not attempted on short and intermediate time scales. However, one of the greatest benefits of automation in manufacturing has been just such "real-time" optimization made possible by computerized measurement and control. Site-wide project integration, a major tool of automation for efficient operations, will be impeded by contracting practices that build islands of independent responsibility into project organization.

The panel was frequently told that current contracting procedures, even where incentive clauses have been tried, often provide little incentive for the contractors to expend money to adopt new methods that provide such benefits as greater efficiency, reduced waste, reduced traffic disruption, improved quality, or even reduced time to completion. In particular, little incentive appears to exist for contractors to adopt methods that may reduce project life-cycle costs, as opposed to initial costs. In part, these practices appear to arise from the lack of methods, until now, for giving contractors viable means to achieve these results.

The panel noted that many important tools and technologies for automation, particularly automated methods for design, planning, measurement, and electronic information transfer are already commercially available to the highway industry, but are not widely adopted. While certain groups are making use of such methods, industry penetration appears to be much slower than is typical in the manufacturing sector. Factors such as those just mentioned, rather than any lack of applicability of automated methods to the industry, may explain this phenomenon.

### Industry Needs

The results of the industry workshop focused the panel members' attention on a number of perceived needs of the highway industry that were further amplified in the sitevisits and other discussions. In general, these are not so much different in kind from concerns to which automation has been applied in other industries as it is different in emphasis and importance. This was a principal influence on the panelists' recommendations from among the multitude of possible projects and technologies that could be considered. Some of the chief issues that were pointed out were:

• **Safety**: Highway construction, operations, and maintenance are inherently dangerous environments. Moreover, the unstructured nature of these environments compared to the typical factory environment makes control of dangerous conditions far more difficult. Aside from humanitarian concerns, injury represents a major economic issue in terms of lost productivity, health care costs, workers compensation, liability, litigation, and insurance. Automated methods for sensing and detecting danger, reacting to and controlling dangerous conditions, and removing humans from inherently dangerous situations are desired. This concern creates a niche for fully automated devices and teleoperated devices where they might not be otherwise justified on economic grounds of increased efficiency or quality.

• **Labor**: Labor costs were reported to be a more significant factor in the highway industry than in the manufacturing industries, perhaps in part due to the already automated nature of most large manufacturing industries. At the same time, the typical jobs performed by human labor in highway tasks is far less structured than is the case in factory situations. As a result, it is not likely that current or foreseeable automation technology will be able to provide any wholesale reduction in the highway labor force through devices that directly replace humans. Rather, opportunities exist for increasing the efficiency of human labor through automated assistance. Possibilities range from automated planning for efficient use of workforce to teleoperated devices with partial automation of operator functions.

- **Equipment**: The industry is generally attuned to the value of improved equipment. However, a general consensus appeared to be that there is a great reluctance on the part of contractors or equipment rental firms to invest heavily in radical new technologies, and a disinclination to abandon existing heavy investments in current equipment. There are exceptions where a particular problem is seen as inadequately addressed by existing equipment, and these provide opportunities for the adoption of wholly new equipment technologies. However, in general, industry representatives expressed a desire for improved equipment technology in the form of add-ons or attachments that could be retrofitted to existing equipment. This matches well with current automation technology that can provide sensing, computer control, and enhanced operator interfaces that are easily retrofitted to existing equipment at costs that are low in proportion to heavy equipment costs once development has been amortized.

- **Operational Efficiency**: This was seldom mentioned explicitly by the panel's industry contacts. However, it became the panel's consensus that a variety of specific issues repeatedly mentioned were facets of an overall need for enhanced efficiency of operations. Opportunities for automation technology addressing these needs include techniques of design for automation, automated planning and scheduling, dynamic as opposed to static optimization of operations, computerized site integration, automated materials tracking, network access to design and scheduling data bases, and a variety of similar technologies used for a long time in other industries.

These and other less frequently mentioned industry needs formed a background perception of the problems and opportunities facing automation of the highway industry as the panel considered possible specific problems and technologies in a search for recommended research and development programs.

## POTENTIAL AUTOMATION TECHNOLOGIES FOR RESEARCH

Working from the perspective developed in the workshops and site visits, the panel discussed the spectrum of technologies that might be fruitfully applied to the highway industry, both today and after various amounts of future research and development effort. The views and recommendations of the panel were compiled by Dr. Arthur Sanderson and summarized in two figures discussed here.

The matrix in Table 1 presents in graphic form the intersection that the panel found between areas of potential application for robotics and automation in highway construction, maintenance, and operations on the one hand, and the state of current technology on the other. The potential areas for research are broken down in Table 2 into near-term, medium-term, and long-term opportunities. near-term implies that the basic technologies exist today, and that the effort required would be to integrate and apply these technologies to specific highway problems of interest to FHWA. Near-term work is thought to be feasible in an 18-month time frame. Medium-term work indicates that the panel believes that most technologies required for the application are available, but that some research is required for further technological development. This indicates that the general principles are thought to be understood and applicable to the task, but that some gaps in our understanding will have to be filled, and problems in application remain to be identified and solved. Experimentation will be required. Medium-term work is estimated to require a timeframe of up to 3 years. Long-term work represents feasible targets for indepth research studies aimed at

Table 1: Potential Applications/State of Current Technology for Robotics and Automation in Highway Construction, Maintenance, and Operations

| TASKS/PROCESSES | SENSING & INSPECTION | | | | LARGE-SCALE ROBOTICS | | | | TELEOP AND HUMAN INTERFACE | | | INTEGRATION DESIGN, PLAN AND SCHEDULING | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Vision | Misc. Sensory | Site Locating | Data Base | Earth Moving | Material Handling | Assmbly Paint | Driving/ Nav. | Lg.Scale Teleop | Manipul. Enhance | Inspec- tion | Design | Planning | Schedul- ing | Intelligent Control |
| Project Design | | | | X | | | | | | | | X | X | X | X |
| Planning and Scheduling | | | | X | | | | | | | | X | X | X | X |
| Site Layout | | | X | X | | | | | | | | X | X | X | X |
| Grading | X | X | X | X | X | | | X | X | | | | | | X |
| Paving | X | X | X | X | X | | | X | X | | | | | | X |
| Trenching/Pipes | X | X | | X | X | X | | | X | X | | X | X | X | X |
| Retaining Walls | | | | X | | X | | | X | | | X | | | X |
| Concrete Construction | | | | X | | X | | | X | | | X | | | X |
| Rebar Assembly | X | | X | X | | | X | | X | X | | X | X | X | X |
| Bridge Assembly | X | | X | X | | | X | | X | X | | X | X | X | X |
| Site Materials Handling | | | X | X | | X | | | X | X | | X | X | X | X |
| Locating Utilities | X | X | | X | X | | | | | X | X | X | | | X |
| Road Surface Inspection | X | X | | | | | | X | | | X | | | | X |
| Crack Sealing | X | | | | | | X | X | | | X | | | | X |
| Bridge Inspection | X | X | X | X | | | | | X | X | X | | X | | X |
| Road Striping | X | X | X | | | | X | X | | | X | X | | | X |
| Paint Rem & Application | X | X | X | X | | | X | | X | X | X | X | | | X |

Table 1: Potential Applications/State of Current Technology for Robotics and Automation in Highway Construction, Maintenance, and Operations (Continued)

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Snow Plowing** | | X | | | | | | X | | X | | X | X | X | X |
| **Cutting Grass & Brush** | X | X | | | | | | X | X | X | | | X | X | X |
| **Trash Collection** | X | | | | | X | | | | X | | X | X | X | X |
| **Traffic Cone - Place/Pick** | X | X | | | | X | | X | | X | | X | X | X | X |
| **Underwater Inspection** | X | X | | X | | | | | | X | X | X | X | X | X |
| **Underwater Construction** | X | X | X | X | X | X | X | | X | X | | X | X | X | X |
| **Tunneling** | | X | X | X | X | X | | | X | X | | X | X | X | X |
| **Safety/Security/Rescue** | X | X | X | | | | | X | X | X | | X | X | | X |

Table 2: Near-Term, Medium-Term, and Long-Term Opportunities

1. **SHORT TERM**
   - Tying rebar -- especially on concrete beds.
   - Weighing concrete to monitor flow during concrete paving.
   - Improve pipe manipulation in trench -- reduce human hazard.
   - Safety sensors around machines.
   - Exploit current database standards.
   - Add force feedback to machines.
   - Expert systems for project costing.
   - Automated planning and scheduling of rebar assembly operations.

2. **MEDIUM TERM**
   - Site location system -- enhance human operator.
   - Automated pipe laying and filling in trench.
   - Real-time monitor of compaction -- soil and asphalt.
   - Site layout and materials flow scheduling system.
   - "Soft" links between machines for control and integration.
   - Graphical display of project information system -- human interface and monitoring.
   - Prototype project information system -- linked to design database.
   - Road surface visual inspection.
   - Apply design-for-assembly to rebar structures.
   - Computer aids to traffic rerouting during job planning.
   - Demonstration of two-machine cooperative manipulation.
   - Tomographic inspection of bridge columns.
   - Machines with exchangeable tools.
   - Demonstration of concurrent engineering bridge designed for inspection and maintenance.
   - Study of safety issues related to humans in the workspace of automated systems.

3. **LONG TERM**
   - Automatically guided vehicles using site location system.
   - Common database exchange format for site, materials, and operations.
   - Real-time control of compaction.
   - Integration of design database to planning and scheduling -- Project Information Systems.
   - Multimachine coordination by networking and distributed control.
   - Automated on-site assembly of rebar structures.
   - Bridge inspection and repair.
   - Life-cycle concurrent engineering for construction, maintenance, and repair of selected projects, e.g. bridges, trenches and piping.
   - Design with improved, smart and environmentally sound, materials to enhance automation and maintenance.

discovering new and improved methods that will extend our technology in the directions required to apply it to the indicated problems. Time estimates for this sort of work must be open-ended, but the areas selected indicate those where the panel's professional opinion is that the research should be successful within 5 years.

## LITERATURE SEARCH

In order to determine which efforts have already been made or are under way, NIST contracted for a literature search that was completed early in the program and made available to the panel. The bibliography developed was updated throughout the course of the study. The bibliography, together with a discussion highlighting some significant representative published efforts, is presented as a volume of this report.

In general, it was found that when the search excludes general research in automation technologies *per se*, such as "machine vision" or "artificial intelligence," and instead focuses on research and development aimed specifically at highway applications, the literature is surprisingly sparse. Even using a fairly broad definition of articles of interest, the literature appears to be comprised of several hundred published studies within the 10-year cutoff period. This was confirmed with a broadly defined computerized search of the entire technical literature base, which yielded thousands of studies, only a few of which were both relevant and not contained in the initial directed search.

A second result is that a majority of the issues that the panel found to be likely candidates for research have been addressed in one form or another by others, not always with great success. On the one hand, it is encouraging that the panel's perception of significant intersections between technological possibilities and highway industry needs is confirmed in the perception of others. On the other hand, it is discouraging that these efforts have not had more impact. Two conclusions that may be drawn from this are that careful consideration must be given to cost/benefits analysis of any proposed study, and that the effort cannot end with a successful research outcome. The sponsoring agency must follow through with an active program to inform and assist the highway industry in adopting the results of demonstrably successful and cost-effective programs.

## SPECIFIC OPPORTUNITIES

Six specific proposals were put forward by the panel for evaluation of actual benefits. These problems have both long- and short-term aspects and, in several cases, the proposed work spans more than one time frame, with various benefits appearing at each stage. Some represent potential individual research programs, others represent possible large demonstration projects by consortia of investigators. They represent a selection, from the areas of study indicated in the matrix presented above, which the panel members felt were the most timely from the standpoint of a "quick hit" wherein the current state of the art in automation appears to mesh with significant issues in highway construction and maintenance. The proposals were presented and discussed at a special session of the technological workshop on automation for highway issues held by the panel in May 1993, and were revised on the basis of that discussion before presentation for cost/benefit analysis.

These proposals are summarized here, and their rational and anticipated benefits are indicated. The volume of proposals presented to the Civil Engineering Research Foundation for analysis contains a more detailed discussion of each proposal, prepared by various members of the panel.

### Site Integration

The primary objective of this work would be to substantially reduce the construction time on highway projects, perhaps by as much as 50 percent, through the use of automation techniques now employed in manufacturing. Computerized design data bases exist today that can be used as the basis of automated planning, scheduling, and logistical control of materials and resources. Advanced control techniques can be used to dynamically reschedule the equipment on a site, as well as to coordinate the arrival of materials and relocation of men and equipment based on the current state of the site. In the short term, using design data bases, survey data bases, and onsite data entry, it is possible to do real-time global optimization of projects with man-in-the-loop interfaces, including equipment deployment and scheduling, and delivery of materials. Other advantages would include reduced materials waste and automated collection of data for as-built data bases. The fundamental requirement is gathering and distributing information in a timely manner to optimize work for the entire site rather than just a small part of it.

Longer-term efforts could extend to semi-automated control of grading and materials placement directly from plans and survey data through advanced operator interfaces, or to automated sensing and control of interactions between pieces of equipment, such as between trucks and concrete spreaders/asphalt pavers, or between front-end loaders and bulldozers or graders.

### Automated Bridge Decking

The goal of this work would be to substantially reduce time and manpower required to deck or re-deck bridges, while improving quality and reducing the need for rework. The aim of this proposed national demonstration project would be to show that it is possible to incrementally add automated capabilities to today's technology in order to achieve this goal. Existing screeds used in bridge work already provide a basic, globally-referenced, physical platform. With this device as the common integrating target, researchers at many institutions could work towards implementing automated functions such as:

- Subgrade inspection using photometric, range, and strain-gauge sensors.

- Computer-aided design, organization, and tracking of rebar.

- Laying down rebar, either individually or in sheets, including laying down the supports needed for the rebar.

- Automated tying of rebar.

- Monitoring concrete supply flow with respect to the subgrade profile and the design specification by use of optical, ranging, and strain-gauge sensors.

- Inspection of the concrete slab immediately behind the screed to automatically correct pits or voids, and control overall deck profile to conform to specifications.

- Other floating and tining operations automatically carried out and inspected.

### Automated Trenching and Pipelaying

This proposal would attempt to automate most phases of the trenching and pipelaying process through the use of sensors, automation controllers, and smart end-effectors for equipment. The advantages that would result from accomplishing these objectives include: (1) the automation of all in-trench operations to remove humans from the trench, which would greatly increase safety, and permit the cutting of minimum-width trenches to reduce time and decrease interference with adjoining structures, utilities, or landscape; (2) the reduction of damage to buried utilities; (3) increased efficiency of machines and operators; (4) reduction of survey and site layout time; and (5) automatic creation of as-built data bases for future utility maps. The proposed research would bring together, in one specific application area, many of the automation concepts from manufacturing that can be applied to construction work in the field. In addition, it proposes specific retrofittable devices that can be used to increase the versatility of traditional equipment such as backhoe excavators. The inherent safety problems of trenching operations suggest this as a high-profile area for potential demonstrations of automated technology.

### Bridge Inspection and Maintenance

This proposal would develop improved alternatives to "Snoopers" for positioning and manipulating automated bridge inspection and maintenance operations. Elimination of workers from paint-stripping environments, and improved containment of lead-based paint and shot are examples of potential advantages of automation. In the short term, advanced control techniques can provide coordinated motion for devices adapted from existing machines. In the longer term, new forms of robotic devices could be designed for delivery of many inspection and maintenance services. Such machines would be programmed from data bases describing each bridge. The bridge data bases would be developed originally from as-built data bases, which in turn would be developed during construction by noting deviations from as-designed data bases generated during design. Each time a bridge is repaired or otherwise modified, an new as-is data base would be generated. These as-is data bases would constitute the input from planning and scheduling bridge repair, and for programming the robots to perform various functions such as inspection, paint stripping, and repainting.

Advanced robotic devices might be able to crawl along over and under bridges, automatically performing routine inspection, paint stripping, and repainting chores. Large bridges might have specially designed robots. Robots might be specially designed for classes of smaller bridges. Such robots might crawl along a bridge and its associated support structures and monitor a number of parameters that are a measure of the health of the bridge, such as macroscale deformations, acoustic emissions, ultrasonic echo examination, paint condition, and chemical detection of corrosion.

### Automated Pavement Inspection and Repair

Currently, human experts are required to visually inspect road surfaces. Many attempts have been made to apply machine vision to this process due to the very large amount of inspection that must be performed, but none has yet been sufficiently successful. The objective of this proposal is to develop an inspection system for roadway defects, such as cracks, with performance better than that of human inspectors. The minimum detectable crack size would be less, so that preventive maintenance could be carried out earlier, leading to increased savings in repairs. Quantitative measures of performance, detection rate, and false-alarm rate could be accurately characterized. The goal would be to carry out the inspection (and, for defects of limited severity, the repair) at highway speeds. Much more roadway than the currently limited sample could be inspected, and, if repair could be carried out simultaneously, inspection and repair would become a one-pass operation with no need for road closing.

### Temporary Bridging

Deployment of modular temporary bridging systems by automated means could provide several classes of benefits associated with different timeframes of technological development.

**Near Term:** Temporary bridging for traffic diversion around bridge repairs can be placed with increased speed and efficiency by integrating existing new technologies for modular bridging with recently developed robot crane technology that provides stable control of heavy lifting in six degrees of freedom.

**Mid Term:** Rapid and ecologically noninvasive bridging of wetlands during construction of new bridging could be accomplished with further extension of these technologies. The suspended Stewart platform crane technology can emplace lightweight modular bridging over ecologically sensitive sites with little or no footprint. The net benefit would include elimination of costly reconstruction of damaged habitats, as well as minimal ecological intrusion.

**Long Term:** Movable temporary bridging to carry traffic over highway repair sites is an idea with a long history. Until recently, the technology to make such proposals realistic has not existed. It now appears that combinations of recent developments in deployable bridging structures and robotic lifting and positioning technology make it reasonable to attack this problem in a serious manner. If this can be achieved, very substantial benefits to the economy would result from minimizing lost commuter time and delay of goods and services due to traffic congestion at repair sites.

## COST/BENEFIT ANALYSIS

A booklet containing the above overviews of the proposed projects and their complete texts, together with a brief review of the mission of the study program, was presented to the Civil Engineering Research Foundation (CERF) for analysis. This booklet is included as a volume of this report.

The CERF findings, also included as a volume of this report, present in detail the methods employed and the results obtained. The methods included questionnaires and surveys of knowledgeable experts, followed by an indepth analysis of a specific real-life scenario for each proposed program's results under the assumption that the research could be brought to a successful conclusion. In addition, CERF obtained more qualitative information concerning perceptions of relevant professionals with regard to the need and desirability of the proposed results.

The experts participating in the CERF study included industry professional engineers from industry, engineering faculty of academic departments, and State DOT engineers. They attempted, in each case, to arrive at estimates of the cost of adoption of the proposed technologies, and to place an estimated value on the expected benefits. It is difficult to make such an estimate when it is attempting to address aspects beyond simple initial cost. The greatest cost savings of proposed new technologies may be attributable to increased life span due to more uniform construction quality, or hours saved in movement of goods or workers due to decreased traffic disruption. The estimates must then be treated with caution, however, they represent the professional judgment of knowledgeable engineers.

### Savings Relative to Current Practice

In summary, the CERF analysis found four of the studies to have significant potential benefits based on the scenarios investigated. In order of potential savings over current practice, these were:

1. Automated pavement inspection and crack sealing.
2. Automated bridge inspection and maintenance.
3. Automated bridge deck construction.
4. Site integration.

This rank ordering could be significantly affected by the assumptions and scenarios used:

The pavement inspection and sealing proposal depends heavily on the ability to successfully seal transverse cracks at speeds of several miles per hour. The CERF experts accepted this assumption, but recommended that this technology be demonstrated before other aspects of the proposal are pursued.

The bridge deck construction proposal was evaluated based on a relatively small bridge. It is probable that it would show greater potential savings over current practice on larger bridges.

The site-integration proposal showed a 20 percent savings over current practice. However, the scenario evaluated, an asphalt resurfacing project, involved relatively repetitive, stereotyped procedures progressing serially along a stretch of road. This is arguably a worst-case scenario for demonstrating potential savings from this approach. More complex and heterogenous projects might show significantly higher savings.

### Overall Benefits to the Industry and the Economy

The evaluation based on savings over current practice must be weighted by the percentage of highway industry effort subject to improvement. When the results are adjusted on this basis, the relative ordering of the proposals by benefit changes. Bridge construction and inspection, while important problems, represent a relatively small proportion of total expenditures for highway construction, maintenance, and operations. Inspection and sealing of highways, on the other hand, must be continuously carried out on essentially the entire national highway system, and involves significant costs to the economy through delay of traffic. Site integration, which offers a smaller per project percentage of savings, is nonetheless a technology applicable to virtually all highway industry activities so that the total potential savings become enormous.

Taking these factors into account, the CERF study estimates that the total benefit of site-integration technology for highway construction and maintenance is in the range of $8 to 16 billion per year for the United States. Automated highway inspection and crack-sealing, in addition to direct cost savings, has potentially high returns in reduction of indirect costs by proper maintenance of the nation's highway system. Among these are reduced fuel consumption, reduced transportation costs, reduced vehicle repair, and increased safety. While it is almost impossible to attach a reliable dollar estimate to these benefits, it is clear that they represent potentially enormous benefits to the economy through the sheer numbers of vehicles and persons affected.

After weighting the potential contributions in this fashion, the CERF study highly recommended two proposals for further development:

1. Site Integration.
2. Automated Pavement Inspection and Crack Sealing.

Automated bridge inspection and maintenance, and automated bridge deck construction were considered potentially beneficial, although of lesser overall economic impact.

Automated Trenching and Pipelaying, and Rapid Temporary Bridging were not considered by the CERF respondents to provide substantial benefits. (However, the analysis of the pipelaying was based on the conclusion that it could not fully eliminate the need to have men in the trench, a point that the author of the proposal has addressed in the revised final proposal, and which should be taken into further consideration.)

## FINAL PROPOSALS

Following the CERF analysis, the authors of the technology proposals prepared specific research and development proposals with detailed budgets and deliverables for consideration by FHWA. In the case of some of the proposals, this is essentially the addition of a level of time and effort statement and a proposed budget for the technological development contained in the proposal presented to CERF. In the case of other proposals, a more specific near-term scenario was developed for evaluating and demonstrating a particular application of the technology; for example, a bridge construction project was proposed as a means of evaluating the site integration concept.

The final proposed projects present a spectrum of opportunities from relatively small to quite large efforts, and from relatively risky research to integration of existing technologies. In general, the funds requested for research are insignificant by comparison with either the adoption costs of the technologies by industry, or with the potential benefits of a successful adoption. However, they may still be relatively large with respect to available research funds. In this regard, they offer a range of opportunities for funding, and many offer flexible options for staged funding of phases of a project over time.

## OTHER ITEMS INCLUDED

It should be recognized that the final proposals presented here each represent only one idea concerning possible approaches to one of the intersections between needs and technology identified by the study panel. It is hoped that the study in its entirety will serve to identify many potentially fruitful areas for research funding and will help to stimulate many others to advance proposals for other approaches and areas of research. To this end, several other documents generated in the course of the study are included as general results even though they do not bear directly on the proposed studies.

- **White Papers**: Several panel members prepared "white papers" addressing issues in automation with potential relevance to highway issues from a more general perspective, including such topics as Design for Automation, Automated Planning and Scheduling, and Robotics and Teleoperation. A review of the current status and potential applications of powered human exoskeletons is also contained in this section.

- **Technology Workshop**: FHWA, NIST, and the National Science Foundation jointly sponsored a 3 day invitational workshop to review current progress in technology for automation of construction and site preparation. The first day of this conference was devoted to technology for highway construction, maintenance, and operations. A summary of the proceedings of this day, and abstracts and viewgraphs of the presentations are included in this report. The proceedings of the entire 3 day workshop will be published at a later date by the National Science Foundation.

- **Evaluation Criteria**: The CERF report focused, by design, on evaluation by attempts to assign dollar values to costs and benefits. However, CERF attempted to identify other issues in industry perception of the proposed study and, in general, it is recognized that assessing the real social and economic costs and benefits of such projects is difficult at best, and frequently dollar value may be a poor measure. An independent effort was commissioned by FHWA to devise a procedure for identifying evaluation criteria. The results of this effort were not ready in time to apply them to the proposals contained in this report, but they may be useful in evaluating future proposals. This study is included as an auxiliary document of relevance to the study.

- **Videotapes**: Several videotapes were generated during the study and are included as part of the report. These include the full proceedings of both workshops and a set of tapes of typical highway operations contributed by CALTRANS.

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