Preface

An important function of the Transportation Research Board (TRB) is to stimulate research that addresses problems facing the transportation community. In support of this function, TRB technical committees identify problems, and develop and disseminate research problem statements for use by practitioners, researchers, and others. The problem statements listed below were developed by the TRB committee noted above. These problem statements should not be considered comprehensive; they may only represent a portion of overall research problems identified by committee members.

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I. Problem 1: Improved Test Methods for Construction Quality Control

II. Problem Statement

Test methods used for quality control and acceptance of highway construction work have changed relatively little over the past decades. Such quality control and acceptance operations typically rely on manually-performed tests with poor repeatability and even poorer reproducibility. Oftentimes the ASTM precision statements for such tests indicate testing error levels that may equal or even exceed specification tolerances. For instance, the “d2s” reproducibility error for determining the optimum moisture content of compacted soils is between 1.8 and 2.9 percent (per ASTM D 698). However, the Oklahoma Department of Transportation’s Standard Specifications require embankment
soils to be compacted to within plus-or-minus 2.0 percent of optimum moisture. This is despite the fact that, according to the published ASTM precision statement, two separate laboratories’ determination of optimum moisture can differ by two percent or more and still be considered within the normal or “acceptable” range of testing errors.

Although precision measurement technology has advanced tremendously over the past two decades, construction-related measurements have, by and large, not benefited from these technological advances. In that regard, the Oklahoma Department of Transportation (ODOT) and the Transportation Research Board’s Committee on Emerging Technologies in Design and Construction (AFH30) jointly believe that research is necessary to help bridge the gap between high-technology and the need for improved methods of construction quality control. As such, ODOT and AFH30 propose that NCHRP sponsor multiple open-ended research projects aimed at demonstrating the feasibility of adapting cutting-edge technologies to improve measurement reliability in the field of construction quality control.

ODOT and AFH30 recommend that NCRHP issue a single open-ended solicitation with the possibility of multiple awards. The solicitation should state the goal in relatively broad terms, so as to encourage the submission of truly innovative ideas (e.g. “demonstrate the feasibility of new methods for improving measurement reproducibility for key parameters related to construction quality in transportation”). As such, the solicitation should strike a balance between completely open-ended solicitations, such as those of the NCHRP IDEA program, and the intentionally-narrow research commonly funded by NCHRP and others.

III. Research Objective

The objective of this research is to bridge the gap between recent improvements in measurement technologies (e.g. precision sensors, rapid-frequency sampling techniques, low-cost / high-resolution analog-to-digital electronics, automation techniques, etc.), and the needs of state DOTs for reliable construction quality control measurements.

It is envisioned that the research program could progress as follows:

1. Phase I Feasibility Studies (with multiple awards anticipated),
2. Invitation(s) to Submit Phase II Proposals (for those projects showing exceptional Phase I results),
3. Phase II Research (Prototype Development / Implementation), and
4. Field Testing and Validation by Interested DOTs.

IV. Funding and Time

ODOT and AFH30 recommend award of up to five Phase I projects at $100,000 each (12 month duration) and up to two Phase II projects at $500,000 each (24 month duration), for a total program cost of up to $1.5 million (depending upon the number and size of Phase 1 and Phase 2 projects actually awarded).
V. Urgency, Payoff Potential, and Implementation
Much attention has been paid to increasing real-time, non-destructive testing of hot-mix asphalt (HMA) pavement, but relatively little has been paid to other types of construction. When the monetary investment between HMA construction and all the combined aspects of PCC and embankment construction are compared, there is no comparison. Millions of dollars each year are spent on testing PCC for a myriad of uses. Similarly, millions are spent each year testing embankment.

Implementation for the DOTs would come through testing the identified technologies to determine which ones would improve their construction process. Also, DOT Research Departments would know which technologies show the best potential for funding for further development. Each DOT would then be free to use or support the development of any they choose and to write any specifications for the new technology that would best suit their needs. Of course, if AASHTO (the NCHRP Panel) so desires, writing of specifications for use of the most promising technologies could be made part of the research project.

I. PROBLEM 2: Nondestructive Testing Technology for Quality Control and Acceptance of Embankment and PCC Construction

II. RESEARCH PROBLEM STATEMENT
Test methods used for in-place quality control and acceptance of highway construction work have changed little in past decades. Such quality control and acceptance operations typically rely on manually-performed tests. For instance, Portland cement concrete (PCC) properties are tested by such methods and instruments as the roll-o-meter, the slump test, and the breaking of cylinders and beams. PCC pavement is measured for smoothness by a rolling straight-edge or a profilograph. Embankment is measured for density by the nuclear density gauge and for profile by surveying instruments. Steel samples are selected and stretched to the breaking point. Many of these tests are done at a remote site, which delays the use of the products in the ongoing construction.

Oftentimes the ASTM precision statements for such tests indicate testing error levels that may equal or even exceed specification tolerances. For instance, the “d2s” reproducibility error for determining the optimum moisture content of compacted soils is between 1.8 and 2.9 percent (per ASTM D 698). However, the Oklahoma Department of Transportation’s Standard Specifications require embankment soils to be compacted to within plus-or-minus 2.0 percent of optimum moisture. This is despite the fact that, according to the published ASTM precision statement, two separate laboratories’ determination of optimum moisture can differ by two percent or more and still be considered within the normal or “acceptable” range of testing errors.

Over the past five years, nondestructive testing (NDT) methods, including lasers, ground-penetrating radar, gamma and beta technologies, infrared and seismic
technologies, and acoustic and supersonic sound wave technologies have been significantly improved and dropped in price. These technologies have shown potential for use in the quality control and acceptance of many different highway construction activities.

The primary beneficiaries of this research will be the Construction and Materials Testing sections of AASHTO-member Departments of Transportation.

III. RESEARCH OBJECTIVE
This research will investigate the application of existing NDT technologies for measuring the quality of several different highway construction activities. Promising NDT technologies will be assessed in the lab and on field projects for their ability to evaluate the quality of these activities in real-time, during or immediately after placement in order to allow the owner to accept the entire product at the completion of the activity. The results will identify NDT technologies ready and appropriate for implementation in routine, practical quality control and acceptance operations.

The objectives of this research are to (1) conduct a field evaluation of selected NDT technologies to determine their effectiveness and practicality for quality control and acceptance of selected work items, including, but not limited to PCC, PCC pavement, embankment, post-tensioned concrete bridge members, and aggregate base and (2) based on the field evaluation results, recommend appropriate test protocols. The first phase of the project will identify existing NDT technologies with potential for in-situ testing of selected materials and workmanship, including, but not limited to, those construction products listed in (1). In selecting NDT technologies for field evaluation in Phase II, emphasis will be placed on those judged ready and appropriate for implementation in highway construction.

IV. ESTIMATE OF PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding

<table>
<thead>
<tr>
<th>Phase</th>
<th>Funding</th>
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<tr>
<td>Phase I</td>
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<tr>
<td>Phase II</td>
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Research Period

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<th>Phase</th>
<th>Duration</th>
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<td>Phase I</td>
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<tr>
<td>Interim Review</td>
<td>2 Months</td>
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<tr>
<td>Phase II</td>
<td>25 Months</td>
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<tr>
<td>Final Review</td>
<td>3 Months</td>
</tr>
<tr>
<td>Total Time</td>
<td>36 Months</td>
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V. URGENCY, PAYOFF POTENTIAL, AND IMPLEMENTATION
Much attention has been paid to increasing real-time, non-destructive testing of hot-mix asphalt (HMA) pavement, but relatively little has been paid to other types
of construction. When the monetary investment between HMA construction and all the combined aspects of PCC and embankment construction, there is no comparison. Millions of dollars each year are spent on testing PCC for a myriad of uses. Similarly, millions are spent each year testing embankment.

NCHRP 10-65 is an ongoing research project that is going to identify the most promising technologies for testing HMA pavement “behind the paver.” In other words, the HMA is tested in place, where it will remain. This proposed research would do the same for other types of construction.

Implementation for the DOTs would come through testing the identified technologies to determine which ones would improve their construction process. Also, DOT Research Departments would know which technologies show the best potential for funding for further development. Each DOT would then be free to use or support the development of any they choose and to write any specifications for the new technology that would best suit their needs. Of course, if AASHTO (the NCHRP Panel) so desires, writing of specifications for use of the most promising technologies could be made part of the research project.

I. Problem 3: Automated As-Builts

II. Research Problem Statement

Most transportation agencies have major construction and upgrade projects sited close to or in conjunction with existing facilities. It is often a challenge to find, acquire or develop electronic records and drawings of the older existing facilities with which the new construction will be integrated. Even if electronic records exist, they are often only 2D plan, elevation, and cross-section drawings. These are often inadequate for public hearings which are increasingly necessary. Visualizing or communicating, based on 2D drawings, the way a major upgrade or new facility will be integrated with existing facilities is difficult for most people. It is becoming widely recognized that 3D drawings and renderings pay off many times over in the planning phases for communication purposes, but also in the contracting, construction and operations phases as well. Developing 3D drawings of existing facilities and their surroundings is becoming economically attractive with the advent of 3D LADAR scanning technology and consulting services that render the 3D scanned point clouds into CAD representations. In addition, exciting new technologies are emerging that use sparse range point scanning with conventional robotic total stations to develop 3D CAD models in a fraction of the time taken with LADAR scanning approaches. Both the LADAR scanning and sparse point cloud approaches are becoming efficient enough that they may be attractive for also developing immediate post-construction as-builts in conjunction with traditional techniques for updating drawings during the course of construction due to changes. In addition, new temperature sensing technologies for concrete maturity testing, embedded corrosion sensors, and GPS may add dimensions of
information such as precise strength development, roughness, etc. to the as-built records that will be useful for subsequent asset management purposes.

III. Research Objective

The objective of this research is to evaluate the existing automated as-builts technologies. Several sub-objectives will be addressed including:

1. Review the state-of-the-art in automated as-built technology via product and literature reviews.
2. Assess the extent of their usage in the private and public sectors as well as other advanced markets such as Europe and Japan.
3. Develop a model for the integration of automated as-built capabilities into project delivery processes, asset management processes, and facilities operations processes. This should include definition of resulting project and management performance improvement metrics.
4. Identify the automated as-built technology providers. Characterize and estimate their impact on project and management performance using the metrics developed and based on representative benchmarking sites.
5. Produce implementation guidelines for the adoption of automated as-built technology.
6. Deliver a final report including documentation and products.

IV. Estimate of Problem Funding and Research Period

**Recommended Funding:**
Management and technical skills will be required to complete the proposed work successfully. Vendors of automated as-built technologies will have to be contacted and their participation in performance and benchmarking tests will have to be arranged. Some travel will be required, and benchmarking sites will have to be developed. This study will therefore require approximately $300,000 to complete

**Research Period:**
It is estimated that this work could be completed in 2 to 2.5 years.

V. Urgency, Payoff Potential, and Implementation

Payoff of this research would be immediate and substantial. Appropriate and beneficial use of automated as-built technology could begin with little integration effort, however complete exploitation of the benefits will result after a learning and process integration period.

VI. Person(s) Developing the Problem

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III. Problem 4: Use of 4D-CAD for Planning, Designing, and Constructing Transportation Projects

IV. Research Problem Statement

As transportation projects become more complex to design and build, it is important to take advantage of appropriate innovative technologies for reducing project cycle time. One technology that has received wider acceptance in the design and construction industry during the past a few years is 4D-CAD. This approach involves the combination of 3D design data with the added dimension of time. Considerable benefits and significant savings have been reported from owners and contractors for applying this technique as a construction planning tool for complex industrial and commercial projects. However, application of the technology on roadway construction projects is still rare. With the lowering cost of computing power and growing popularity of 3D CAD, the benefit-to-cost ratio of using 4D-CAD on transportation construction is becoming more and more attractive.

4D-CAD systems originated from the construction of processing, power, and offshore plants where 3D modeling has long been used for checking space conflicts of the complex piping systems. According to Sheppard (2004), 4D modeling efforts might have begun as early as 1973. The first commercially available software was Construction Systems Associates’ PM-Vision, which was released in 1984. However, due to the high computing cost at that time, the system was not widely accepted in the architecture/engineering/construction (AEC) industry. Bechtel, the leading contractor of
industrial plants of the U.S., also developed a 3D computer aided engineering system called Walkthru. Jacobus Technology, Inc., established in 1991 by two former employees of Bechtel, developed and marketed a 4D simulation system called Construction Simulation Toolkit. CIFE (Center for Integrated Facility Engineering) of Stanford University used this software and its later versions, also with the help of AutoCad (for 3D modeling) and Primavera (for scheduling), to apply 4D-CAD in addressing construction planning issues (Collier et. al. 1996, Fischer, 2000).

Koo and Fischer (2000) classified functions of 4D-CAD systems into three categories: 1) visualization, 2) integration, and 3) analysis. Other researchers (Collier et. al. 1996, Fukai 2000, Riley 2000, Webb et. al. 2004, Williams 1996) also showed that the technology can significantly improve the communication of the construction plan to other project stakeholders. Mckinney et al. (1996) classified 4D-CAD technology into two distinctive generations: Visual 4D-CAD and Collaborative 4D-CAD. According to them, Visual 4D-CAD produces a 4D animation for designers to evaluate and review the schedule they propose. While 4D-CAD can effectively communicate completed construction plans, it did not address how the schedule was developed since it merely links the 3D-model with existing schedule. Because of this, the researchers proposed “Collaborative 4D-CAD” as a tool to improve the construction design process. In recent years, virtual reality (VR) –based construction planning is gaining popularity among construction researchers. With the implementation of 3D modeling in prevalent commercial CAD systems, several prototypes of VR based construction planning tools were proposed by researchers (Whyte et. al. 2000, Waly et. al. 2003, Xu et. al. 2003, Clayton et. al. 2002, Li et. al. 2003, Chau et. al. 2004).

A number of specific construction challenges have been addressed by researchers to improve 4D-CAD as a construction planning tool. Akinci et. al. (1997) conducted productivity and cost analysis using 4D modeling. Riley (2000) studied the role of 4D modeling in trade sequencing and production planning. O’Brien (2000) proposed 5D-CAD modeling by expanding 4D-CAD models to include multi-project resource management functions for specialist contractors. Li et al. (2003) studied the application of virtual reality technology to experiment with innovative construction operations. Chau et al. (2004) used 4D-CAD technology to address building construction site utilization issues. Besides construction planning, 4D-CAD and virtual reality also proved to be a very effective tool for education in architectural and construction engineering majors (Jaafari et. al. 2001, Clayton et. al. 2002).

Beside research activities, commercial software for 4D modeling has become very mature after decades of development. Currently active 4D modeling products and vendors include fourDscape™ from Balfour Technologies’, Navigator™ from Bentley Systems, ConstructSim™ from Common Point, PM-Vision™ from Construction System Associates, and SmartPlant™ series of Intergraph. Recognizing the benefits of 4D-CAD, more and more building projects used this technology during the construction process.

Research at Stanford University estimated that 4D-CAD helps avoid up to 45 percent of change costs, leading to a minimum of 4 to 6 percent overall project cost savings.
Benefits from applying 4D-CAD systems in other types of commercial constructions include (Fischer 2000):

- Less field interference;
- Less rework;
- Higher productivity;
- Fewer change order;
- Less cost growth;
- Fewer request for information.

While great achievements have been made in applying 4D-CAD to the construction of industrial facilities and commercial buildings, little has been done in road and bridge construction. This may be due to limited computer support for construction planning of transportation construction projects. Also, many construction planners are familiar with 2D paper drawings, and are not ready to embrace a new tool. As a result, missing items during the bid preparation are common for many contractors, which translates into higher contingency factors in bids. With the proven benefits revealed by the early research into 4D-CAD, the investigation of the application of 4D-CAD in construction planning for transportation projects should provide improvements over current methods.

V. Research Objectives

The objective of this research is to investigate the applicability of 4D-CAD for constructing transportation projects. 4D-CAD has proved to be useful for other types of construction projects—it may provide significant benefits to the transportation sector for constructing or renewing our nation’s roads and bridges. A comprehensive literature review will be performed to better understand the usefulness of this approach. The 4D-CAD approach will be pilot tested and evaluated on at least one project. Benefits and costs of applying this proposed approach will be tracked and recommendations will be made concerning the applicability of 4D-CAD technology in the transportation sector.

VI. ESTIMATE OF PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding:
$250,000

Research Schedule:
2 years

VII. Urgency, Payoff Potential, And Implementation

Payoff Potential
As stated above, cost savings from application of 4D-CAD in construction planning is estimated to be 4 to 6 percent of the overall project cost. The anticipated reduced cost will eventually lead to lower bid prices and reduced construction costs for the public. Considering the total contract volume awarded by counties, cities and other public agencies nation wide, the overall economic benefits to public agencies from the proposed technology could be quite significant. In addition to the direct cost benefits, indirect benefits such as shorter construction duration and less interference to traffic, and improved public relations may also be achieved through improved development and communication of construction plans using this approach.

**Urgency**

Obtaining funding for transportation projects is becoming a greater issue today. The earlier the proposed technology is developed and applied, the earlier it can start generate savings for the government agencies, contractors, and the people of the United States.

**Implementation Strategy**

Previous research on 4D-CAD in construction planning will be investigated and commercial software packages will be evaluated for their applicability in roadway construction planning, design, and construction. Current construction planning practices for road and bridge contractors will be investigated. Based on this research, a proposed methodology for applying 4D-CAD to roadway and bridge construction will be investigated. It is envisioned to pilot test this concept on at least one project to thoroughly explore its benefits and challenges. At the conclusion of this project, recommendations will be made regarding the usefulness of this approach.

**VIII. Persons Developing The Problem**

Dr. Trefor P. Williams  
Dr. Edward J. Jaselskis  
Dr. Russell C. Walters

**IX. Problem Monitor**

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**X. Date and Submitted by**

February 28, 2005  
Richard Griffin, Research Coordination Engineer  
Colorado DOT – Research
IX. References


5. Fischer, M., Benefits of 4D Models for Facility Owners and AEC Service Providers, Construction Congress VI, 2000, p. 990, ASCE.


15. Williams, Mike (Bechtel Corp) Graphical simulation for project planning: 4D-Planner\textsuperscript{TM} Congress on Computing in Civil Engineering, Proceedings, 1996, p 404-409.


I. Problem 5: Application of Three-Dimensional Laser Scanning for the Identification, Evaluation, and Management of Unstable Highway Slopes

II. Problem Statement:

Rockfall threatens thousands of miles of highway in the United States bordered by rock slopes. In addition to older, increasingly unstable, highway cuts, expansion of transportation networks and populations into areas of rugged mountainous terrain has resulted in many additional rock cuts that expose highway users to rockfall hazards, and transportation agencies to economic and social liabilities. In order to ensure public safety, to make certain that rockfall maintenance is organized and cost efficient, and to address potential rockfall hazards proactively, many state agencies have adopted rock cut management systems. Implementation of these rockfall management and mitigation programs requires comprehensive geologic characterization of individual rock slopes in order to assess their stability and assign hazard ratings.

Despite the advantages of rockfall management systems, the identification, evaluation, and categorization of comparatively high risk slopes remains a labor-intensive task that is further complicated by the broad range of geologic conditions that influence rockfall hazards. Laser based, three-dimensional imaging, combined with advanced 3D image processing algorithms, can accelerate field data acquisition, reduce identification difficulties, eliminate safety constraints, and remove human bias and subjectivity.

III. Research Objective:

The proposed project focuses on the development and application of software that incorporates three-dimensional laser scanning technology for automated geologic characterization and stability assessment of highway rock cuts. Exposed rock surfaces can be scanned quickly and accurately using a laser scanner, resulting in a collection of millions of discrete points each having a 3D value relative to the scanner’s position. Preliminary algorithm development has lead to semi-automated processes capable of orienting the point cloud, creating a polygonal surface model from the point cloud, determining rock discontinuity information, and defining block size distributions. These procedures can provide accurate geologic information required by rockfall hazard rating systems and for planning mitigation measures.
This proposed research will address four major objectives:

1. **Develop a field procedure for the scanning and rescanning of highway rock cuts.** Efficient scanning procedures must adhere to guidelines for collecting, documenting, and reporting laser-scanned data, accuracy statements, digital photographs, and complete records of survey. This ensures that all required data are collected and preserved as a part of a digital record. A recommended method for geo-referencing the collected data will be included.

2. **Field-test previously developed algorithms for the processing of laser scan data (point clouds).** Algorithm testing will involve three aspects:
   a. **Processing, transforming, and managing the laser-scan “point cloud” data.** This includes geo-referencing, stitching adjacent scans together, aligning multiple scans of the same slope, and creating a three-dimensional surface model.
   b. **Implementation of texture mapping to combine point cloud data and photographic imagery.** Texture mapping produces a photorealistic 3D model that allows hazard raters to gather qualitative information such as amount of erosion, the presence of water, clay infilling, etc.
   c. **Refine algorithms for automatic extraction of rock discontinuity data.** Existing algorithms will be validated and refined in terms of the specific needs of rockfall hazard ratings. These algorithms are capable of:
      - Automatically identifying discontinuity surfaces and determining their orientation (strike and dip)
      - Calculating the roughness of a discontinuity surface
      - Identifying joint sets and determining spacing.
      - Determining the block size distribution of potential rockfalls

3. **Evaluate the Integration of Laser-scanned Data into Rockfall Hazard Rating Systems.** This objective includes two aspects:
   a. **Develop a process for utilizing multiple scans, taken over time, of the same rock cut.** Comparisons of two or more scans accurately registered to a common coordinate base allow for determination of the amount of deformation, and calculation of volumes of anticipated rockfall. In addition to quantitative results, graphical representation of relative movements of points and surfaces allow non-technical personnel to rapidly identify areas of moderate to high risk of rockfall.
   b. **Investigate the feasibility of automatically extracting other data relevant to rockfall hazard ratings.** Laser scan data can potentially identify and measure roadway width, ditch/catchment width, and line-of-sight, in addition to slope height. These geometric quantities are all necessary when computing rockfall hazard ratings.

4. **Facilitate Widespread Systematic Use of Laser-scanned Data by State transportation Agencies.** This objective has two components:
   a. **Develop standard visual and graphical methods for data display and analysis.** A sequence of standard color codes, related to rockfall
hazard ratings, will ensure the new assessment products can be readily interpreted and used throughout the state transportation agencies.

b. Ensure that the data products merge seamlessly with design tools and information standards of state transportation agencies. The large data volumes produced by laser scans represent a challenge to many applications within state transportation agencies. Data storage and output standards will be evaluated to ensure compatibility with traditional procedures and design tools used by state transportation agencies.

IV. Key Words:

LIDAR, laser scanning, rockfall hazard, rockfall mitigation

V. Related work:

Laser scanning has been used to evaluate rock slopes for mining and transportation-related applications in many parts of the world. Reports describe test cases within the USA by Pennsylvania DOT, Missouri DOT, and several others. The U.S. Bureau of Reclamation has undertaken some tests for evaluating dam abutments. A multi-year National Science Foundation grant entitled “Characterization of Three Dimensional Discontinuity Properties from Digital Images of Rock Masses” is concluding in March 2005. It can provide much valuable information, as can several published papers based on research conducted in Europe. These include a paper presented at the TRB 2005 Annual Meeting by Slob and others.

VI. Urgency, Payoff, and Implementation:

Ultimately, protection of the traveling public is the major issue. Economic benefits, resulting from improved efficiencies provided by the new technologies, and also personnel safety and better program management planning, make the development, testing, and adoption of LIDAR technologies and 3D analysis tools for evaluating potentially unstable rock slopes an urgent matter for state departments of transportation and others concerned with the maintenance and safe operation of transportation facilities.

Cost: The estimated costs are $175,000. And the anticipated duration of this research is 1 year.

User Community: Geotechnical engineers and geologists, state departments of transportation, railroads, public utility companies, and construction industry. Potential partners in this research are:

- Transportation Research Board Committees and NCHRP-IDEA Program
- U.S. Department of Transportation
  - Federal Highway Administration
  - Federal Railroad Administration
- State departments of transportation
• Public Utility Companies
• LIDAR equipment manufacturers

**Implementation:** Implementation will be through partnerships among several interested state departments of transportation that will provide access to suitable rock slopes and assess the viability of the resulting procedures and recommendations. Academic or private sector research personnel will perform the actual research tasks with funds provided by appropriate grants and contracts.

**Effectiveness:** The proposed research offers a coherent and systematic approach to the development of appropriate standards and procedures for using the comparatively new LIDAR technology that is lacking in these related projects. It builds on the earlier experiences.

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