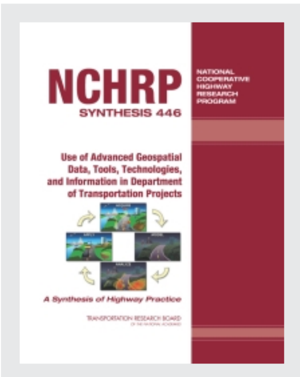

Use of Advance Geospatial Data, Tools, Technologies, and Information in Department of Transportation Projects

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 446

Use of Advanced Geospatial Data, Tools, Technologies, and Information in Department of Transportation Projects

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

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Cover figure: This image depicts the use of geospatial technology throughout various phases of transportation projects and operations. Artwork by Bradley C. Olsen (Fedora Productions) based on an original concept by Michael J. Olsen (Oregon State University), Gene V. Roe (MPN Components), and John D. Raugust (Oregon State University).

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice.*

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Tanya M. Zwahlen
Consultant
Transportation Research Board

This Synthesis report identifies the current state of the practice regarding the development, documentation, and introduction of advanced geospatial technologies within departments of transportation (DOTs). A primary objective of this study is to document practices and applications using advanced geospatial data tools. The report also provides a discussion of strengths and weaknesses of leading technologies, and how they are being used today.

Information used in this study was acquired through a review of the literature, a survey of DOT representatives in all states, and a survey of service providers.

Michael J. Olsen and John D. Raugust, Oregon State University, Corvallis, Oregon, and Gene V. Roe, MPN Components, Hampton, New Hampshire, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable with the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

APPENDIX D IS WEB-ONLY AND CAN BE FOUND AT WWW.TRB.ORG, SEARCH ON “NCHRP SYNTHESIS 446.”

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

USE OF ADVANCED GEOSPATIAL DATA, TOOLS, TECHNOLOGIES, AND INFORMATION IN DEPARTMENT OF TRANSPORTATION PROJECTS

SUMMARY

Transportation agencies in the United States are under increasing pressure to do more with less. From Maine to Hawaii, most transportation agencies are experiencing staff reductions; in some cases these have been significant. Simply to maintain their current level of service, transportation agencies may consider investing in advanced geospatial data tools and technologies, such as Mobile Light Detection and Ranging (LIDAR) and Automated Machine Guidance (AMG). During this three-dimensional (3D) decade, geospatial information may become the life blood of the transportation agency.

This Synthesis report identifies the current state of the practice regarding the development, documentation, and introduction of advanced geospatial technologies within the transportation agencies. It is intended to be a detailed, actively linked, and geographically searchable reference source to online publications, as well as a summary of the results of questionnaires that were distributed to the departments of transportation (DOTs) (96% of state DOTs responded, as did those of Puerto Rico, Washington, DC, and Alberta, Canada) and the service provider community (81% response rate) concerning their current and planned use of advanced geospatial technologies. In addition, there is a discussion of the strengths and weaknesses of a number of the leading technologies, along with how they are being used and applied today.

The service provider questionnaire helped to draw out some common inferences and determine themes and trends in current geospatial technology usage. It should be noted that the sample size of service provider responses was 13, compared with 97 DOT responses (including Puerto Rico, Washington, DC, and Alberta). As a result of potential service provider biases, however, their responses should not carry weight equal to the DOT responses in determining these themes and trends. Therefore, a direct correlation of responses is not to be inferred from this report.

Along with the shift to advanced geospatial technologies comes a significant requirement to effectively manage what, in some cases, are large data files. To get the maximum return on investment, multiple departments within a transportation agency should share data that are centrally managed. These concepts may require a change in culture in some transportation agencies.

Given the rapid pace of change that is occurring with some of these advanced technologies, quality management is a critical issue, particularly when tools are combined, such as with Global Navigation Satellite System (GNSS) and 3D laser scanning in a Mobile LIDAR mapping system. Unfortunately, there are limited standards of practice and guidelines in place that can be relied on to avoid "reinventing the wheel." Work is in progress on other NCHRP-funded projects, but there is a significant need for additional, documented research to enable effective implementation of these technologies into the workflows of transportation agencies. Some other examples of needed research include identifying and resolving barriers to adoption, learning from successes of other organizations, development of 3D digital workflows, and centralized data management.

Some of the key findings of this study include:

1. The most important change that is taking place is the transition from two-dimensional (2D) to 3D workflows. Transportation agencies that have transitioned or are transitioning to 3D workflows and software can reap the decision-making benefits of utilizing geo-referenced spatial information contained in 3D design, asset management, and Geographical Information System environments.
2. DOTs indicated relatively high levels of experience with advanced geospatial technologies.
3. The top three barriers to technology adoption, indicated by the DOTs, are cost, inertia, and technical expertise.
4. The three key drivers of success when it comes to the introduction of new geospatial technologies are an early adopter mindset, an internal champion, and an interest in safety.
5. The top three geospatial technology research needs identified by the DOTs were data management, data integration, and transition from 2D to 3D workflow. Most research reports are published internally only. Reports for pilot projects are generally not made available on the web. Failures and decisions not to use a technology are rarely documented and even more rarely made publicly available.
6. DOTs were split between a desire for national and state standards. Service providers favored national standards, when possible. They also preferred performance-based specifications and guidelines.
7. Using advanced geospatial data technologies can have many benefits for transportation agencies. Change can sometimes be a slow, difficult process, but given the economic conditions that exist today, most cannot afford the luxury of waiting for a complete set of best practices and guidelines to be developed for new technologies. By sharing the experiences and lessons learned among transportation (and other) agencies, the learning curve will be shortened and cost efficiencies will be achieved.
8. Geospatial service providers are early adopters of geospatial technologies, particularly 3D workflows. They indicated that the three key drivers of success when it comes to the introduction of new geospatial technologies are an early adopter mindset, an internal champion, and an interest in safety. Similar to the DOTs, service providers believed that focused research projects, documentation, and centralized information dissemination would help overcome many barriers.

CHAPTER ONE

INTRODUCTION AND SCOPE

INTRODUCTION

State transportation agencies are under increasing pressure to do more with less. From Maine to Hawaii, many agencies are experiencing significant staff reductions. To maintain their current level of service, these agencies are considering investing more in advanced geospatial data tools and technologies.

The good news is that highway administrators, engineers, surveyors, planners, designers, and contractors have access to an increasing variety of powerful geospatial data tools, technologies, and information. The challenge is that making full use of these new methodologies often requires significant organizational change.

Today, significant variability exists in the level of geospatial information provided with project results and the associated allocation of risk based on the procedures used. Some of these technologies do not have adopted standards or guidelines. For example, few well-defined standards exist for the use of Light Detection and Ranging (LIDAR) systems, and in many cases incorrect techniques are employed. There is also substantial variability regarding the scope of and data submittal requirements for geospatial information, the program of geospatial-related quality control and assurance during construction, and the contract provisions related to design and construction positioning requirements.

Simultaneously, the core information technology platforms upon which the transportation agencies operate are transitioning from two-dimensional (2D) to three-dimensional (3D), significantly disrupting the status quo. Design is moving from paper-based 2D plan and profile to digital 3D models; survey is beginning to use static and kinematic LIDAR; and contractors are adopting the use of Automated Machine Guidance (AMG). In addition, the pace of change is accelerating. As a result, the cost-effective use and management of geospatial information and emerging positioning/measurement technologies will be beneficial to successful operation. Transportation agencies embracing this rapid change, rather than seeing it as a threat, will be able to realize higher efficiencies because these technologies and information will enable divisions to work together and streamline their operations.

There are limitations to each of these tools and technologies; one size does not fit all. Many individual transportation agencies have performed research studies and pilot projects to understand the potential of these tools and technologies, as well as their limitations and risks. Case studies have been developed by these agencies to illustrate and address the issues cited earlier. Some of these agencies have established guidelines that describe which tools can be used to meet specific positioning requirements, including establishing survey control and coordinate systems for automated machine control and guidance, using LIDAR systems for the development of 3D data models, determining how to use satellite imagery effectively, using two-way data exchange formats between computer-aided design (CAD) and Geographical Information System (GIS), and developing tools for web-based data exchange and editing.

This information, however, is fragmented, scattered, and unevaluated at this time. Often, the information is transferred from person to person only at national conferences and meetings. As a result, transportation agencies are not benefiting from these costly research studies and pilot projects, and are unable to give proper consideration to recommended practices that meet their positioning requirements and manage their associated risk.

GEOSPATIAL–INFRASTRUCTURE LIFE CYCLE

Geospatial technologies and information provide core support across most transportation operations. These technologies can help integrate divisions by providing a framework to link and share each division's data into a unified geospatial transportation model. For example, an integrated model for a bridge can be queried by various divisions within a transportation agency, including structural engineers, geotechnical engineers, traffic engineers, and maintenance crews. As each organization documents an inspection or updates the bridge database in this central model, the other divisions can be informed immediately of these efforts and have that information to assist them in their future tasks.

These geospatial technologies are valuable at all phases of infrastructure projects, from new construction to routine maintenance. Figure 1 illustrates the concept of an infrastructure life cycle, where several cycles of decision making are aided by geospatial technologies during the acquisition, modeling, analysis, and application phases.

All projects, including maintenance, result in some form of data being collected, whether it is documented using a

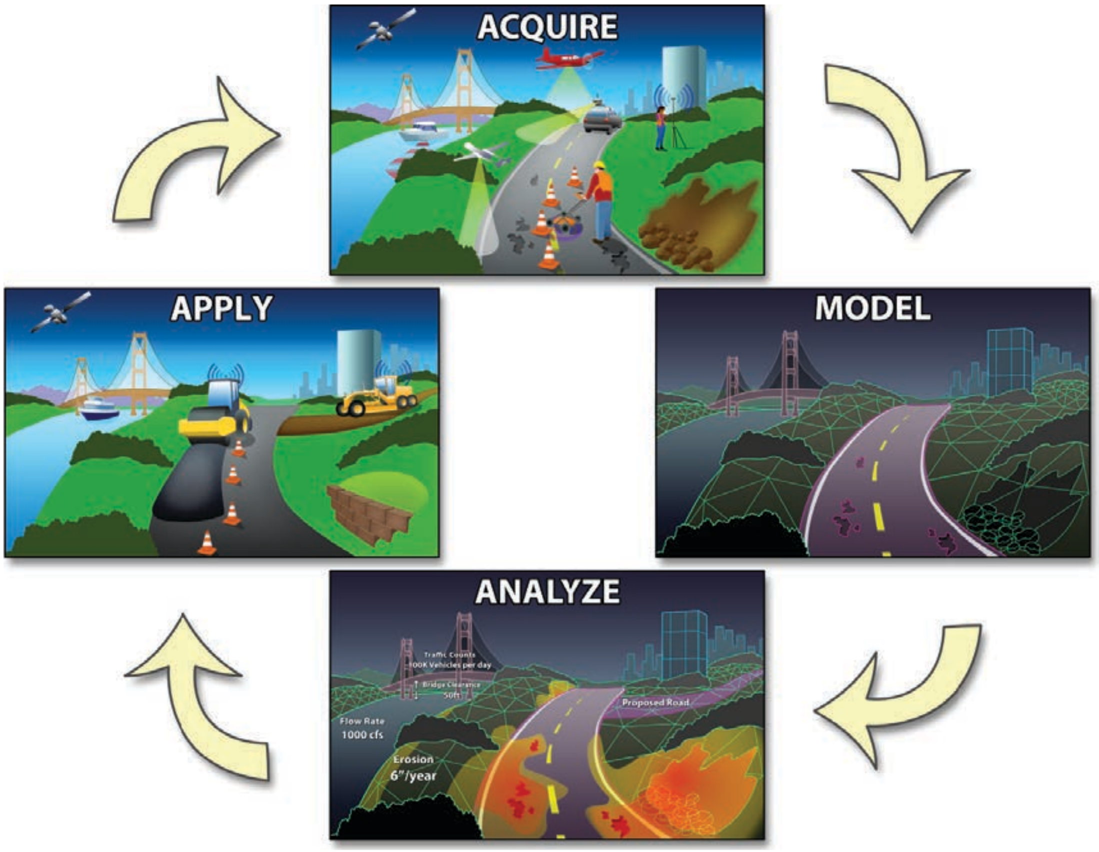

FIGURE 1 Geospatial tools applied across various phases of infrastructure life cycle.

technology or through human observations. With a centralized, geospatial information model that is updated by all departments, all historical data can be leveraged at any phase of a project. In many cases, these data will still be usable. In other cases, historical data can be instrumental in the planning of any additional data collection.

The acquired data are then converted into models to enable the data to be analyzed in design and planning processes. When construction or maintenance is required, these models can be used to support the project.

The geospatial life cycle should not end at the completion of a project. It should continue as data are collected before the start of a project and through all phases of maintenance and construction as part of the infrastructure life cycle (Singh 2008).

Updating this geospatial information database with routinely collected maintenance and other data enables analyses to be performed in context. Field crews can use that information to plan their schedules to perform all necessary work in an area, minimizing losses in time and money for travel.

Unfortunately, such a model rarely exists and requires substantial discipline to create. However, the sooner an organization starts to develop a model, the sooner it will have those resources available. Continual implementation of this life cycle will enable many of these benefits to be realized.

TECHNOLOGY BACKGROUND

The purpose of this report is to examine the state of the practice relating to the gathering, analyzing, storing, and use of geospatial data in transportation agencies. These are topics that are coming to the forefront of the workflows of transportation agencies with the advent of geospatial gathering tools and techniques, such as Global Navigation Satellite System (GNSS), LIDAR, 3D image reconstruction, and AMG. With these new collection tools, data are collected faster and in greater quantities than ever before. Thus, it is essential that these tools and data be integrated and used effectively for a variety of applications to minimize duplicate or unnecessary data collection and to enable the same data to be queried across disciplines, departments, and projects.

GIS platforms enable integrated, geospatial data management by combining spatial information with attributes. This versatility enables numerous informational tools to be created and visualized. GIS can help to show the public some of the magnitude of infrastructure projects by way of maps that tell stories. Previously, the cost associated with creating these types of maps was not warranted, so the work went undone. In addition to providing an efficient way to inform the public about these projects, GIS can provide decision makers more metrics with which to make important decisions. Furthermore, these tools can help expedite project design and quality management to ensure that completed projects more closely match final designs, ultimately reducing costs and improving quality.

Linear referencing systems (LRS) are used by some transportation agencies, many of which are integrated into a GIS. These systems define a known starting point and reference locations of objects at a linear distance from that point. This is an alternative to the geographic coordinates location method. Common uses of LRS are asset management and emergency response, where crews may not have a global positioning system (GPS) unit.

GNSS technology has become an indispensable tool for the completion of transportation projects ranging from survey (at the millimeter to centimeter level) to inexpensive hand-held (decimeter to meter level) grades. Continuously Operating Reference Stations (CORS 2012) are now located throughout the United States and enable improved data accuracy. With handheld units returning data well suited for asset management and accuracy levels in consumer grade systems increasing, a common trend toward GPS integration across the organization has been noted by transportation officials.

LIDAR data can be obtained from terrestrial, mobile, and airborne platforms, depending on project needs (typically resolution, accuracy, and extents) and budget. This technology enables the quick collection of high-resolution (millimeter to decimeter level) spatial data. With new mobile and airborne LIDAR systems using highly accurate GNSS and inertial measurement unit (IMU) systems, the spatial data are completely geo-referenced. Initial cost, processing time, and specialized training and software are the main drawbacks of this technology. However, as this technology becomes mainstream, the cost becomes more manageable for government agencies. The benefits created are quickly being shown to outweigh associated costs, especially when compared with traditional techniques. Further, new processing technologies are emerging to automate some of these processes, enabling more people to make use of the data.

Aerial photography is a useful tool for the visualization of current, past, and proposed projects. Photogrammetry uses stereo pairs of imagery to enable measurements with a data set containing *x, y,* and *z* coordinates. Because photogrammetry has been used for decades, it is well understood and can serve as a stand-alone product, a complementary aid, or a quality control measure for emerging LIDAR technology. As photographic resolution and quality have improved in the digital era, new advances of photogrammetric algorithms have enabled dense 3D point clouds to be reconstructed from a series of 2D images.

Despite these advances, it is important to realize that all of these technologies are tools and the end user selects the most appropriate combination of each for use in particular jobs. Although some traditional surveying tools can be replaced by more efficient means in some cases, many traditional tools are still needed. The traditional tools provide vital quality control as new technologies are developing. In addition, traditional surveying tools are tried, true, reliable, and understood well by people in the geospatial industry.

Additional technologies that will be addressed in this report include ground penetrating radar (GPR) and its use in roadway roughness analysis, video logging for traffic analyses and project progression, and the integration of tablets and smartphones into transportation workflows.

This report can serve as a reference source for understanding these emerging technologies. Creating a solid framework of these current geospatial data, tools, and technologies will serve as a foundation for the transition from 2D to 3D.

ORGANIZATION AND HUMAN FACTORS

In theory, a technology may be able to provide valuable information and dramatically reduce costs on a wide variety of projects; however, if it cannot be effectively implemented by an organization its value will not be realized. In addition, new technologies often require people to adapt to new workflows. Implementation of a new technology requires a transportation agency to examine all potential costs (e.g., equipment purchase, accessories, training, and maintenance) and benefits (e.g., ability of data to be used by multiple departments). Internally, transportation agencies are choosing what level of geospatial technology usage produces the optimal benefit-to-cost ratio for their organization. The following represents four possible levels of involvement with a new technology:

1. Transportation agency chooses to invest in a particular technology and acquire software, hardware, and training.
2. Transportation agency develops a working knowledge of the technology and is able to implement basic processing and data manipulation. However, the bulk of the acquisition and processing is completed by a consultant.
3. Transportation agency can use derivative products of the technology provided by a consultant but has limited knowledge of the technology.
4. Transportation agency decides not to use the technology (e.g., the technology has not been proven to provide acceptable results, the technology has a lower benefit-to-cost ratio compared with other technologies, and so forth).

SCOPE

Rather than each transportation agency allocating resources to perform its own research studies and pilot projects to investigate how best to adopt and manage advanced geospatial technologies, this study documents and summarizes the current state of the practice throughout the United States as of 2012, including emerging standards and guidelines. In addition, this study identifies gaps in the research needed to achieve the desired level of systems integration and assist transportation agencies in developing a systematic approach to adopting these technologies into standard operating procedure.

The key purposes of this study are to:

1. Document and summarize the current state of the practice related to advanced geospatial data tools, technologies, and information for highway projects, including procedures and proposed standards of practice that can be used to attain the information objectives when using these advanced geospatial technologies.
2. Identify how, when, and why these tools are used in combination to attain stated objectives.
3. Identify potential research needs, such as development of effective tools for assessment and management of risk.
4. Document practices and applications using advanced geospatial data tools, technologies, and information, and make the results available to the entire transportation community.
5. Produce a report that will help transportation agencies develop effective procedures in support of planning, design, and maintenance and operations functions.

This report serves as a synopsis of the recent developments related to advanced geospatial data, tools, and technologies. These include GNSS, automated machine control, LIDAR, photogrammetry, 3D visualization, robotic and manual total stations, leveling, satellite remote sensing, GIS, GPR, video logging, and tablets and smartphones. This report also shows the current usage trends for these technologies within transportation agencies.

The introduction of a new technology into any organization carries a certain amount of risk. This report intends to provide the most up-to-date information on the best practices and lessons learned to help minimize that risk. However, it is not likely that all risk can be eliminated. Thus, it is important to recognize and plan for short-term setbacks during the adoption phase. These should be expected and are the reason it is important to document both successes and failures. In the end, it is a matter of managing expectations and being realistic about managing change in a complex organization, such as a transportation agency.

Some key challenges faced by the transportation agencies in adopting these technologies are as follows:

1. Large data sets are the result of gathering geospatial data with high resolution. In some cases, these can be on the magnitude of millions or even billions of points. Storing and processing these data in a cost-effective manner requires analysis and planning.
2. New technologies consist of a wide variety of mechanical, electrical, and computer components. Technical expertise and special training often are required to process and use the data efficiently.
3. These emerging technologies are changing rapidly, making it difficult for any organization to stay current. Different techniques using these technologies emerge quickly, sometimes rendering "new" equipment obsolete.
4. New workflows and procedures are being developed without standardization or well-defined best practices. Transportation agencies are faced with creating these frameworks as advanced geospatial data, tools, and technologies are integrated into their workflows.
5. Significant resistance to change can occur when developing new geospatial workflows. Justifying the dedication of resources toward these efforts can prove difficult for transportation agencies.

Some key beneficial opportunities anticipated by the transportation agencies with the use of advanced geospatial technologies can include:

1. Transportation agencies are being asked to do more with less. Geospatial technologies offer transportation agencies the ability to increase productivity to at least maintain, if not improve, their current level of service.
2. New technologies can produce significant safety benefits for field personnel and the traveling public.
3. Significant cost savings can be realized by using these new technologies and maximizing the return on investment through the sharing of data between divisions.
4. Up-to-date geospatial data can lead to more informed decision making and better use of scarce resources. This can be especially important for rapid response to emergency situations.
5. The adoption of nationally recognized standards and methods offers transportation agencies the ability to share information across state lines and leverage investments made by other agencies.
6. The development of a reliable and actionable transportation data model can establish the transportation agency as a go-to source for accurate information by other state agencies and the legislature.

Ryerson and Aronoff (2010) outline the "GeoEconomy," an emerging concept of an economy driven by and dependent upon geospatial information. This forward-thinking book presents concepts that link geography-based data with future economic trends. Tying these two concepts together, the authors offer insights related to gaining the "Geo-advantage." This resource is not tailored to one audience; rather, it can be implemented by individuals and governmental organizations alike.

STUDY APPROACH: METHODS OF INFORMATION GATHERING AND DELIVERY

Questionnaires

A geospatial data technologies questionnaire (chapter two) was developed and distributed to relevant geospatial contacts from state and federal transportation agencies obtained through a questionnaire for project NCHRP 15-44, state TRB representatives, as well as AASHTO standing committee members from GIS-T (GIS for Transportation), Research, Planning, Design, and Asset Management. Because geospatial technology is implemented by a large range of personnel across the departments of transportation (DOTs), the questionnaire was sent to multiple lists, rather than just the GIS-T list. However, the goal was to obtain at least an 80% response rate from the GIS-T list. A total of 42 of the 52 GIS-T representatives completed the questionnaire.

Ninety-seven responses were obtained from 48 of the 50 state DOTs, plus two from Puerto Rico, one from the District of Columbia, and one response from Alberta, Canada. Results of this questionnaire aided in the analysis of the current usage of advanced geospatial technologies within individual DOTs. Such analysis helped identify which DOTs have experience and expertise with key geospatial technologies. The questionnaire also determined which states have integrated geospatial standards and specifications into their workflows, particularly as they relate to performance-based accuracy requirements.

Another key aspect to this questionnaire was to determine where DOTs publish research reports related to geospatial technologies and what topics require additional research. Additionally, questions were asked to determine which DOTs typically published these findings so that the entire transportation community can benefit from them.

A second questionnaire targeted private sector service providers, including geospatial tools and software vendors, contractors, and consultants. Providers to be interviewed were selected by the following criteria: (1) providers who work frequently with DOTs, (2) providers who are active in disseminating experiences at national and international conferences, and (3) geographical distribution of selected providers across the country. This was included to provide an external, third-party perspective of current transportation agency data, tools, and technological products as viewed by industry service providers. Despite the small sample size (13 of 16 contacted) compared with that of the DOT respondents, the service provider questionnaire helps to draw some common inferences and determine themes and trends in current geospatial technology usage. A summary of the results regarding current practice is presented in chapter three.

Literature Review of Individual States, Foreign, and Private Practices

An overview of literature related to geospatial data tools, technologies, and information as they apply to transportation projects was compiled and summarized. This included a review of common sources, including magazines, conference proceedings, journals, reports, and online resources [e.g., the Transportation Research Information Database provided by TRB, state agency annual reports on Highway Engineering Exchange Program (HEEP)]. Several contacts in various agencies, including state DOTs, ASCE, American Society of Photogrammetry and Remote Sensing (ASPRS), American Congress on Surveying and Mapping (ACSM), National Geodetic Survey (NGS), TRB (particularly committee AFB80), and ASTM, provided input on both needs and available knowledge on advanced geospatial topics. The procedures and results for this literature search are described in more detail in chapters four through seven.

GIS Research Database

Accompanying this report is a searchable GIS (Figure 2), Google Earth (Figure 3), and spreadsheet database containing layers specific to current and past geospatial research, specific state-of-the-practice geospatial guidelines and specifications, and concurrent projects using prototypical geospatial technology.

This searchable matrix also includes relevant agencies that publish reports, journal papers, conference papers, and white papers related to geospatial technology, with hyperlinks to sources of information such as DOT research office web pages where reports are published. This provides a solid background for transportation agencies to study current geospatial technologies.

The list of resources for this synthesis was compiled by the study team into an MS Excel spreadsheet. This spreadsheet serves as the common link to the GIS database provided in Appendix C. In addition to the study title and associated state or organization, fields such as issuing and performing organizations, key words and concepts, hosting address, and main technology type are represented. These fields were added for enhanced querying, filtering, and sorting capabilities.

Potential expansion to this database identified by the study team could include continued work with transportation agencies and private organizations for the inclusion of relevant research, an author field, and development of a web-based, graphical user interface for simple user navigation without the need for GIS software.

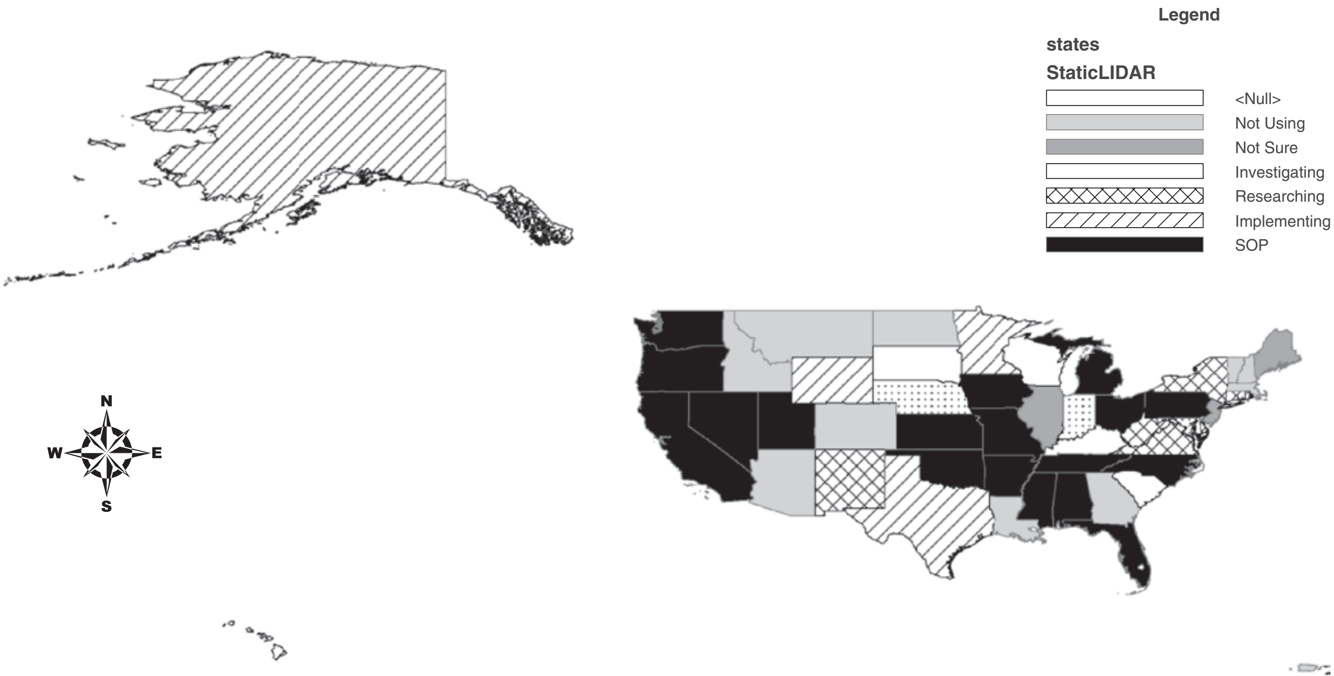

FIGURE 2 Example of GIS database showing static LIDAR usage by state DOTs.

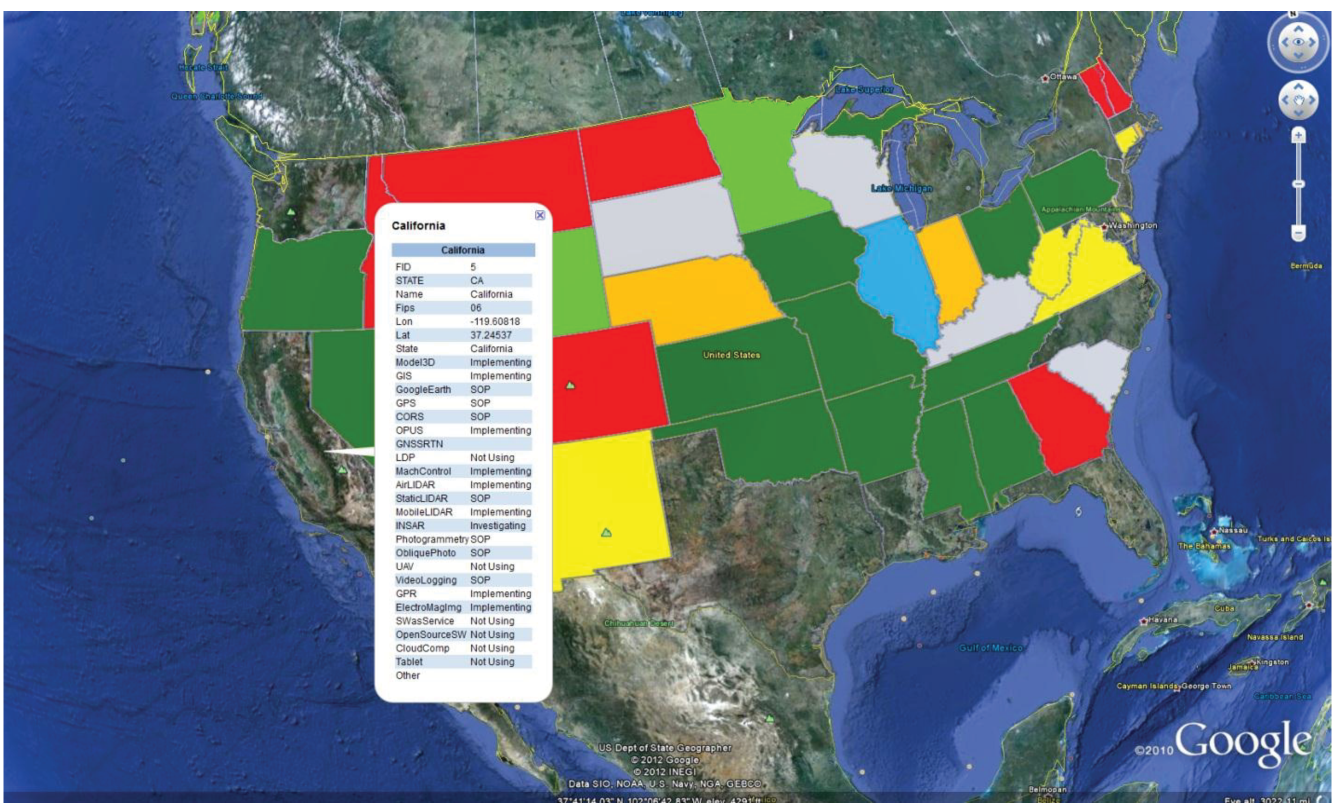

FIGURE 3 Example of Google Earth database showing static LIDAR usage by transportation agencies.

CHAPTER TWO

DEPARTMENT OF TRANSPORTATION QUESTIONNAIRE RESULTS

This chapter provides an overview of the key topics and results addressed with the distribution of a DOT questionnaire. The questionnaire results show trends of states having expertise in certain technologies, along with an analysis of where the current state of the practice is heading. This information provides the foundation for concepts and terminology in subsequent chapters.

The objectives of this questionnaire were to:

1. Determine the current usage of advanced geospatial technologies within the DOTs.
2. Identify which DOTs have expertise and experience with key geospatial technologies and determine how best to systematically make this knowledge available to the entire transportation community.
3. Determine where DOTs publish research reports related to geospatial technologies and what topics require additional research.
4. Determine whether geospatial standards and specifications are available, particularly as they relate to performance-based accuracy requirements.
5. Gain a sense of the potential impact of national standards on the growth in acceptance of these technologies.
6. Identify key geospatial personnel within the DOTs.

QUESTIONNAIRE DISTRIBUTION

A DOT questionnaire was developed by the study team with a target completion time of 30 minutes. The project panel reviewed the questionnaire and subsequent revisions. TRB representatives and the panel also tested the questionnaire once it was uploaded. The questionnaire was distributed in March 2012 to AASHTO standing committee members (through mailing lists provided by NCHRP), including GIS-T, Research (many of whom were serving as state TRB representatives), Planning, Design, and Asset Management. Additionally, the questionnaire was sent to DOT geospatial and other relevant contacts assembled by the study team. These contacts were identified as the primary geospatial contact by DOT respondents through a relevant questionnaire distributed for the NCHRP 15-44 Mobile LIDAR Guidelines project, which is currently under way.

Because the questionnaire was sent to a large group (e.g., several AASHTO Committee mailing lists) in comparison to typical synthesis projects, a target response rate of 80% of only the GIS-T members was requested and achieved. A total of 42 GIS-T representatives (40 of 50 state DOTs plus Washington, DC, and Puerto Rico) completed the questionnaire. A total of 97 individuals responded from 48 of the 50 states, Washington, DC, Puerto Rico, and Alberta, Canada.

To track response rates, each group was given a unique link to the questionnaire. However, many DOTs combined answers into a single response. Thus, many GIS-T candidates actually responded through a different link than the GIS-T link. We confirmed these responses through follow-up phone calls. In addition to state responses, we received one response from the transportation department for Alberta, Canada; however, we did not use this response in the analysis because there were no other non-U.S. sources. Figure 4 shows the division indicated by each of the respondents. Other categories indicated by the respondents included photogrammetry, information technology, and GIS/cartography.

It can be noted that problems were experienced during the distribution of this questionnaire. In addition, many respondents from the GIS-T list indicated that they had received several questionnaires recently and felt overwhelmed with trying to respond to the frequent requests.

ANALYSIS METHODOLOGY

Data were exported from the survey into a Microsoft Excel file. Because a separate link was given to each key mailing list, the results from all questionnaires were compiled and integrated. Depending on the question, results were analyzed either by respondent or DOT. For example, questions related to usage of geospatial technology within a DOT were analyzed as a single, maximum-level-of-interest response for each DOT rather than by individual, because some individuals may not be aware of usage by other divisions.

Table A1 in Appendix A explains the analysis method for each question and how conflicts were handled. For example, regarding the technology usages, if one person in a DOT indicated that it was the standard operating procedure (SOP) and another indicated that the DOT was researching the technology, the ranking for the DOT was recorded as SOP because it was assumed that the person who gave the lower ranking might not be aware of how often another division was using the technology.

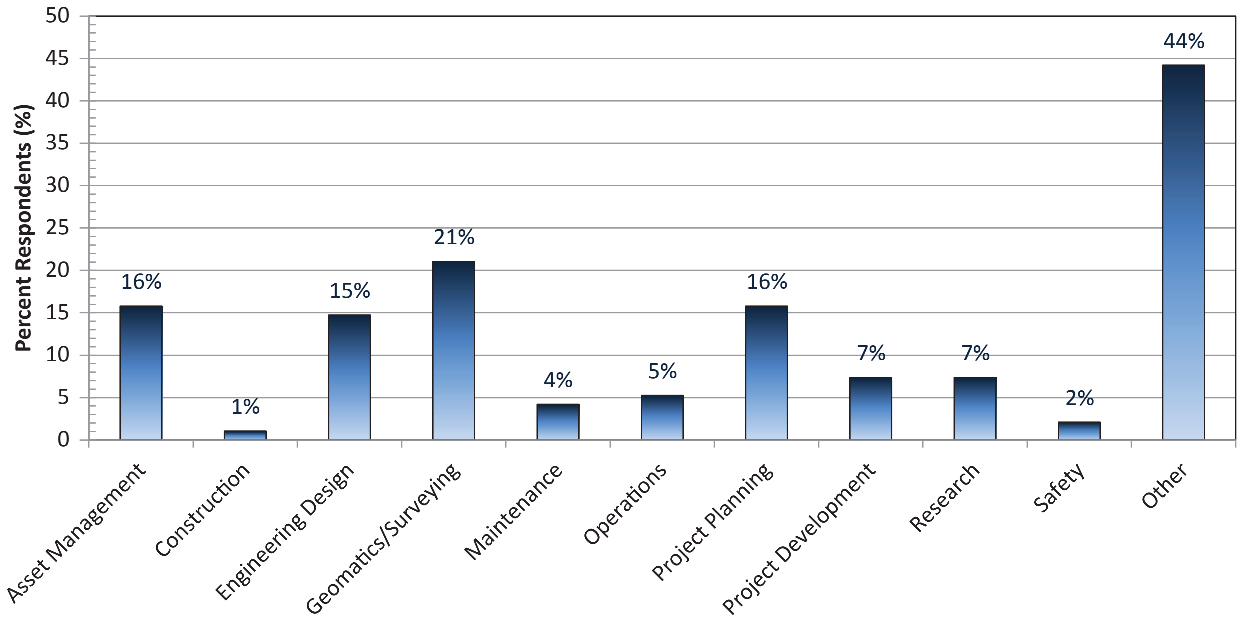

FIGURE 4 Division of DOT respondents. (Note that some respondents selected multiple options.)

Note that owing to rounding error, some results may not add to exactly 100% but will be within ±1%.

GEOSPATIAL TECHNOLOGY USAGE

The vast majority (84%) of respondents regularly use geospatial technologies (Figure 5). This was expected because most people who do not use the technology would be less motivated to respond to the invitation or complete the questionnaire. It is also important to keep this in mind because the respondents are the most actively involved with geospatial technology compared with average personnel in the DOT, who probably would not be as well versed in geospatial technology use. Those who responded "Rarely" or "Never" did not complete the rest of the questionnaire. In terms of technology adoption (Figure 6), almost 90% are involved proactively with the introduction of new technology to modify their SOP.

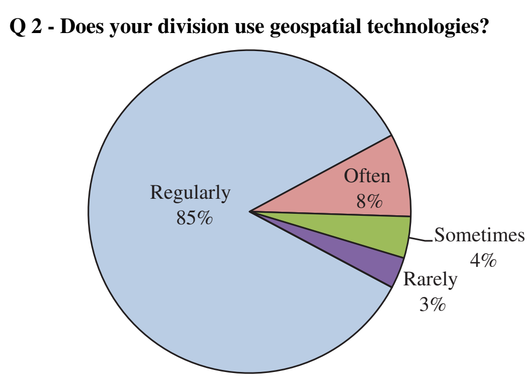

FIGURE 5 Geospatial technology use by respondent for the respondent's division.

The top three factors holding back adoption of new technologies for DOTs (Figure 7) are cost, inertia, and technical expertise.

DEPARTMENT OF TRANSPORTATION EXPERTISE

Table 1 ranks the level of familiarity with each advanced geospatial technology. Given the relative maturity of photogrammetry, video logging, and GPS and GIS technologies, they top the list. Cloud computing, 3D-model-based design, Mobile LIDAR, and machine control are standard operating procedure in approximately 25% of the DOTs.

In Table 2, the applications in which the technology is most likely being used are identified. The more familiar the DOT is with the technology, the more widespread it is used, in general.

Table 3 contains a set of questions whose results indicate that essentially all of the DOTs are collecting geospatial data internally and using external sources. Only one-third of the states are involved with the 50 States spatial data initiative plans. Approximately two-thirds of the DOTs are tracking local government data initiatives. Similarly, approximately two-thirds are also tracking the cost-effectiveness of implementing advanced geospatial data tools, technologies, and information.

When asked how new geospatial technologies were being investigated (Figure 8), respondents split evenly among the four choices—by department, centrally, individually, and by multiple groups. This split in responses probably is the result of difficulties in data management and integration into workflows because each data source has its own unique challenges.

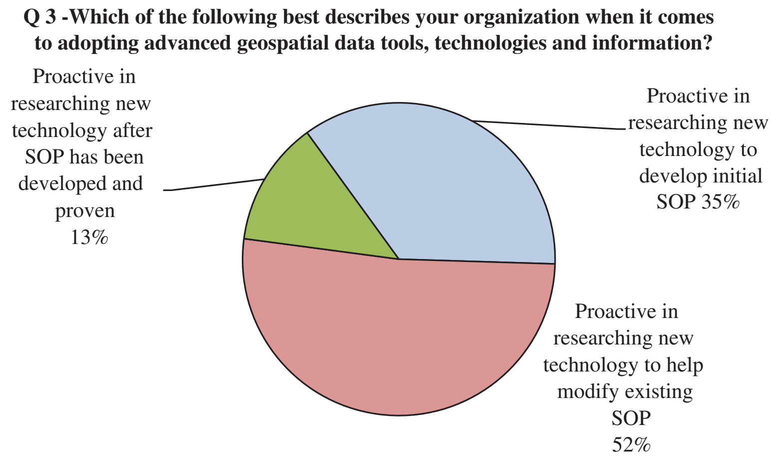

FIGURE 6 Geospatial technology adoption approach indicated by respondent for the respondent's organization. SOP, standard operating procedure.

For example, GIS data are easy to store centrally and share through a network among a variety of departments. However, LIDAR data sets are large and difficult for information technology staff to maintain in an efficient manner to store, back up, and share across a network.

In terms of their overall level of expertise with advanced geospatial technologies (Figure 9), most of the DOTs indicated they were experienced, but not quite expert. This correlates with the results shown in Figure 6, which shows most DOTs are active in adopting new technologies. However, given the diversity and evolving nature of these technologies, few people in industry would consider themselves experts.

Given this level of expertise, almost two-thirds of the DOTs stated that most divisions had integrated advanced geospatial technologies into their daily workflows (Figure 10).

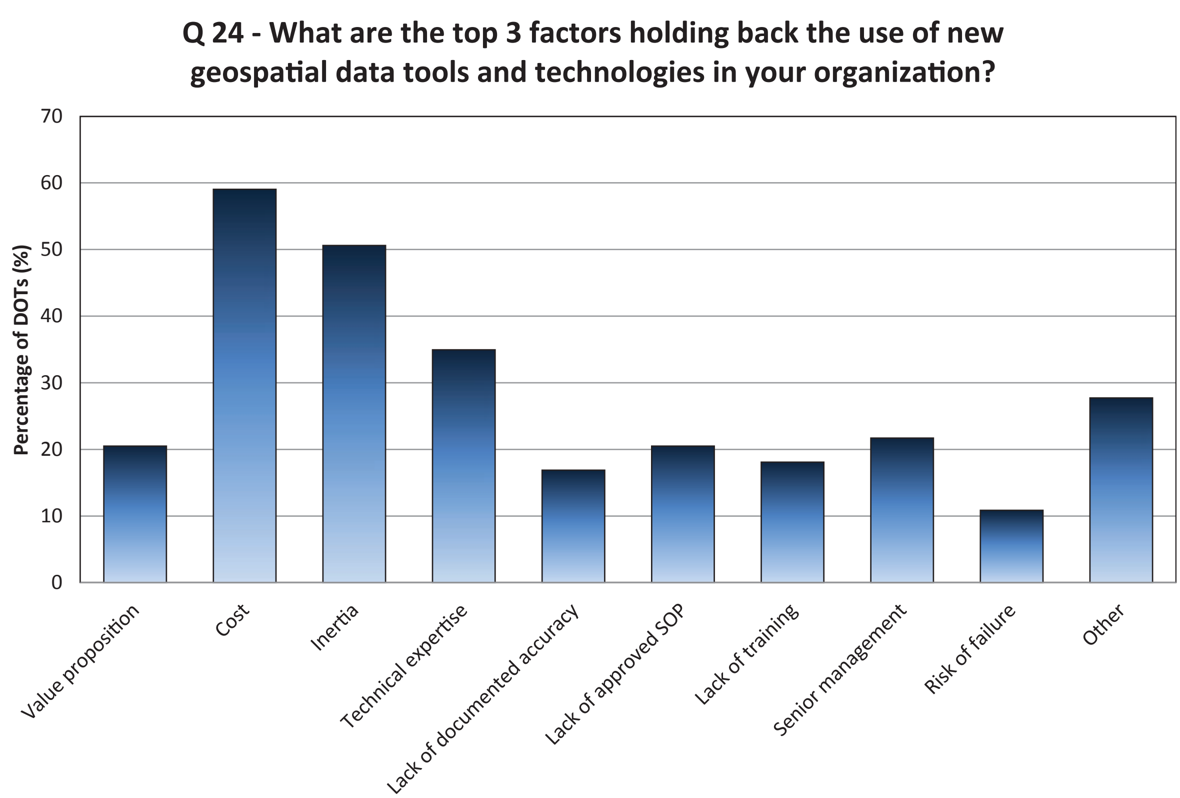

FIGURE 7 Top factors holding back the use of geospatial data tools and technologies.

TABLE 1
PERCENTAGE OF DOTs USING TECHNOLOGIES, SORTED FROM MOST COMMON TO LEAST COMMON

Technology	Standard Operating Procedure	Implementing	Investigating	Researching	Not Using	No Interest	Not Sure
Photogrammetry	90%	6%	2%	0%	0%	0%	2%
Video logging	90%	6%	0%	0%	4%	0%	0%
GPS	88%	10%	0%	2%	0%	0%	0%
GIS	88%	8%	0%	2%	2%	0%	0%
Statewide CORS network	67%	8%	2%	4%	12%	0%	6%
Online Mapping Services	65%	16%	2%	4%	12%	0%	0%
Statewide GNSS real time networks	56%	13%	8%	2%	13%	2%	6%
Oblique Photography	47%	8%	16%	2%	18%	2%	6%
OPUS (Online Positioning User Service)	45%	8%	6%	2%	20%	2%	16%
Software as a Service	43%	14%	10%	8%	16%	2%	6%
Tablet computers/smartphones	39%	31%	16%	4%	8%	0%	2%
Static 3D laser scanning	38%	10%	8%	13%	25%	0%	6%
Airborne LIDAR	35%	33%	14%	4%	10%	0%	4%
Open Source Software	34%	14%	16%	8%	22%	4%	2%
Ground Penetrating Radar	33%	8%	10%	14%	22%	0%	12%
3D model-based design	29%	23%	19%	10%	15%	2%	2%
Low distortion coordinate systems	28%	14%	8%	4%	26%	2%	18%
Mobile LIDAR	22%	20%	22%	18%	14%	0%	2%
Cloud Computing	22%	20%	24%	14%	18%	0%	2%
Machine Control	20%	24%	6%	18%	14%	0%	16%
Electromagnetic imaging	6%	4%	8%	8%	45%	0%	29%
Unmanned Airborne Vehicle (UAV)	2%	4%	6%	18%	63%	2%	4%
InSAR/IFSAR (Interferometric Synthetic Aperture Radar)	2%	2%	6%	10%	51%	2%	27%

TABLE 2
PERCENTAGE OF DOTs IDENTIFYING APPLICATIONS FOR TECHNOLOGIES

Technology	Planning	Right of Way	Design	Construction	Operations	Other	Not Using	Not Sure
Photogrammetry	82%	64%	86%	62%	58%	42%	4%	2%
Video logging	88%	56%	66%	54%	68%	46%	4%	2%
GIS	88%	74%	74%	50%	84%	52%	2%	2%
GPS	80%	68%	84%	82%	78%	50%	0%	2%
Statewide CORS network	40%	48%	60%	60%	38%	24%	16%	14%
Online Mapping Services	74%	52%	54%	40%	54%	42%	14%	8%
Statewide GNSS real time networks	28%	34%	54%	50%	28%	20%	20%	10%
Oblique Photography	42%	20%	38%	18%	22%	18%	32%	16%
OPUS (Online Positioning User Servic	16%	22%	38%	18%	8%	10%	16%	22%
Software as a Service	44%	26%	36%	30%	34%	38%	24%	14%
Tablet computers/smartphones	46%	30%	34%	40%	54%	34%	20%	6%
Static 3D laser scanning	14%	10%	44%	18%	18%	12%	28%	16%
Airborne LIDAR	54%	14%	64%	18%	24%	22%	18%	12%
Open Source Software	42%	16%	28%	22%	32%	34%	28%	8%
Ground Penetrating Radar	8%	4%	38%	24%	16%	20%	24%	22%
3D model-based design	28%	14%	72%	38%	14%	12%	16%	8%
Low distortion coordinate systems	18%	14%	32%	30%	10%	10%	24%	30%
Mobile LIDAR	32%	12%	48%	16%	22%	12%	32%	8%
Cloud Computing	22%	14%	26%	12%	20%	24%	42%	10%
Machine Control	6%	2%	20%	56%	4%	6%	18%	20%
Electromagnetic imaging	6%	0%	6%	2%	4%	0%	58%	24%
InSAR/IFSAR (Interferometric Synthet	6%	0%	4%	2%	4%	0%	58%	28%
Unmanned Airborne Vehicle (UAV)	4%	0%	4%	2%	2%	6%	76%	8%

TABLE 3
DOT GEOSPATIAL TECHNOLOGY USAGE AND INTEREST

Question	Yes	No	Not Sure
Is your organization collecting geospatial data internally?	96%	0%	4%
Is your organization interfacing with external geospatial data sources?	92%	2%	6%
Is your organization involved with the 50 States initiative to develop Spatial Data Infrastructure (SDI) plans?	33%	35%	31%
Are you tracking local government’s geospatial data initiatives?	69%	27%	4%
Are you tracking the cost-effectiveness of implementing advanced geospatial data tools, technologies, and information?	63%	31%	6%

Implementation

Managing the introduction of advanced geospatial technologies was evenly divided among the choices of centrally, by department, and multiple groups (Figure 11). Note that “multiple” indicates that each of the respondents within a single DOT indicated a different response. Thus, there probably is some flexibility in how the introduction is performed, depending on the technology and staff needs.

Training

Ninety-eight percent of DOTs responded that their organization provides training in the use of advanced geospatial data tools and technologies (Figure 12); 2% were unsure. A number of training options were used, with hands-on and peer-to-peer training being the most common. In terms of the effectiveness of the training offered, most DOTs reported it was reasonably effective (Figure 13) but there was room for improvement.

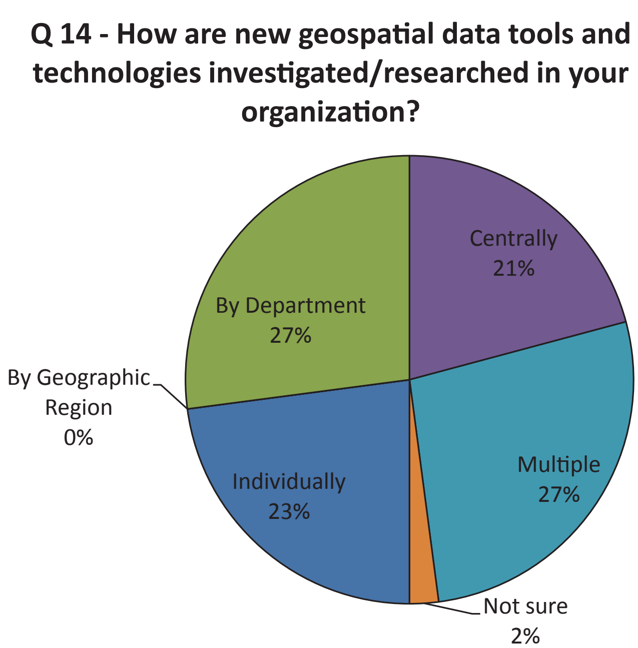

FIGURE 8 Investigation strategies for new geospatial data technologies.

Data Management and Workflows

On the critical issue of geospatial data management (Figure 14), 50% indicated data were managed centrally, 29% said by department, and 19% by multiple methods and groups. Comments by respondents indicated that there is significant variability within a DOT on how data are managed. This often varies by project and the data type.

INFORMATION RESOURCES

Several questions were asked to determine the extent to which the DOTs have been willing to share the results of their research into advanced geospatial technologies.

When asked where the results of their research are published (Figure 15), the DOTs indicated that most often the results are available only internally, followed by almost 50% indicating that results are made available on a public website; 40% publish certain results behind a DOT firewall; and 30% also use print.

Eighty-five percent of the DOTs conduct pilot projects to investigate new geospatial technologies (Table 4), but the results are not typically made public. Rarely does an agency document failures or make such results public.

Most DOTs favored the use of a public website to disseminate research and lessons learned about advanced geospatial technologies, followed by more federal support and then more visibility at the annual TRB meeting (Figure 16).

FIGURE 9 DOT experience levels with advanced geospatial technologies based on average and maximum responses within a DOT.

To reduce the risk associated with the adoption of advanced geospatial technologies, the DOTs identified the ability to obtain the results of pilot projects from other DOTs as their top response, followed closely by the desire to cost share the research with other groups, including service providers. In the next group was the need for additional research funding and the use of public/private partnerships (Figure 17).

The top two research needs (Figure 18) were both data related—better data management and integration. In third place was the transition from 2D to 3D.

The DOTs were somewhat interested in the idea of supporting the concept of an online central clearinghouse to disseminate research information and even more interested in contributing information (Figure 19).

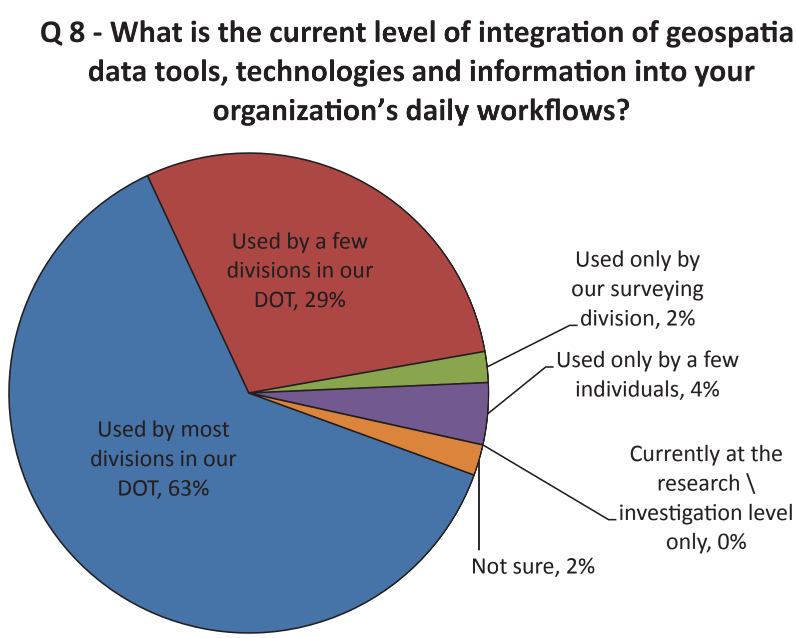

FIGURE 10 Integration of geospatial data tools, technologies, and information within DOTs.

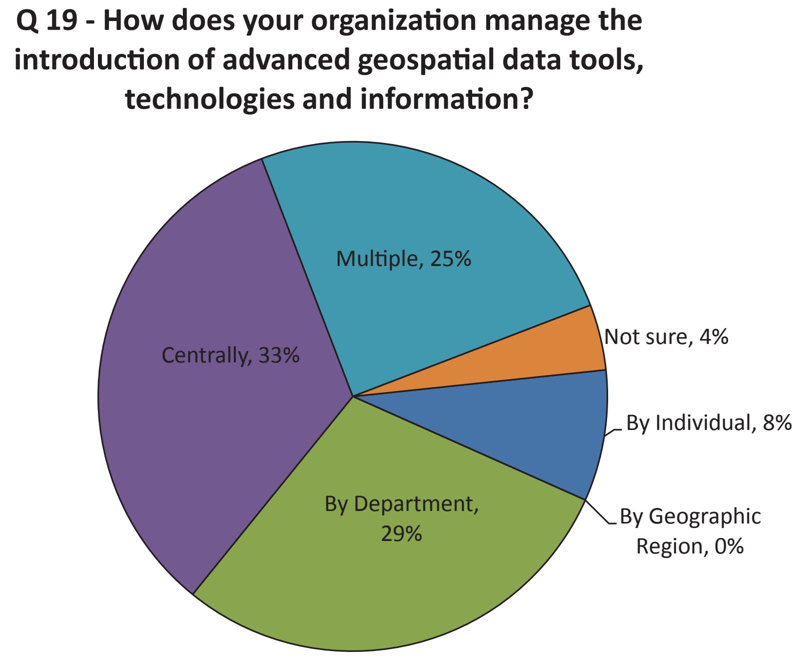

FIGURE 11 Management of geospatial data tools, technologies, and information introduction.

FIGURE 12 Methods of geospatial training indicated by DOTs.

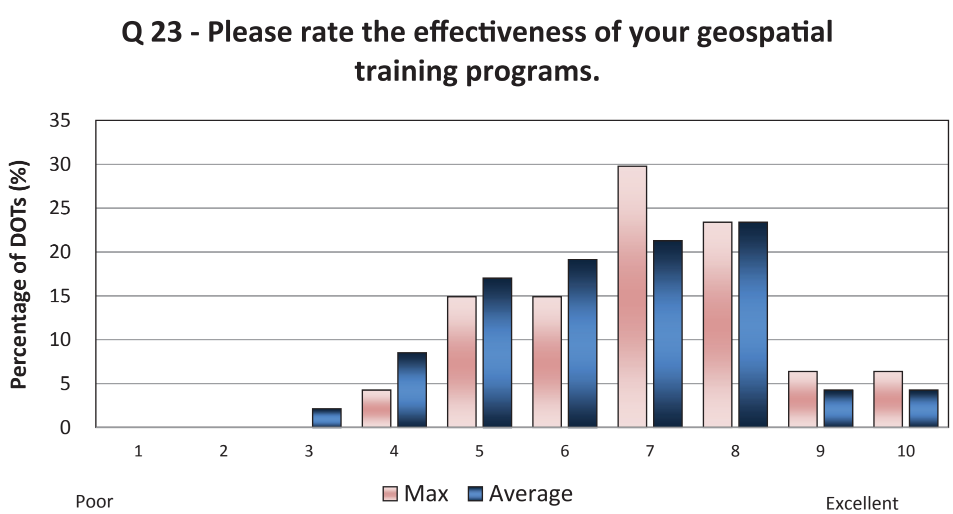

FIGURE 13 Evaluation of effectiveness of geospatial training.

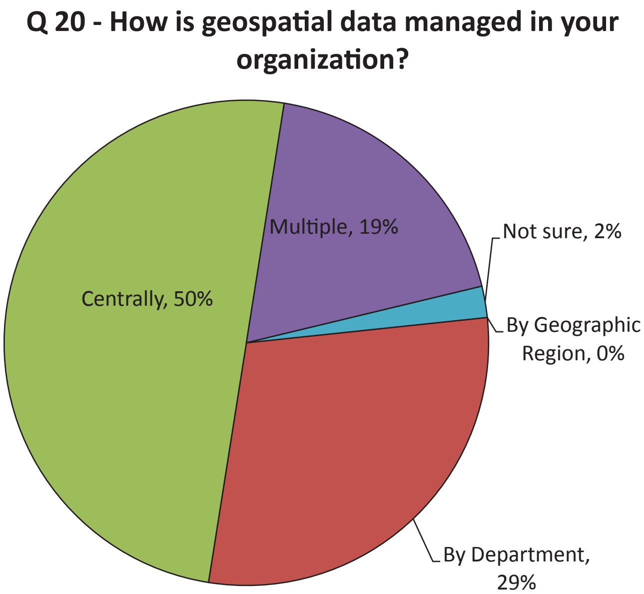

FIGURE 14 Management of geospatial data within DOTs.

Most DOTs look to a wide variety of sources for information on advanced geospatial technologies, including internal champions, consultants, other DOTs, and service providers (Figure 20).

STANDARDS

Most DOTs reported it is important for them to be investigating new geospatial technologies as well as the use of related standards (Figure 21) for some of those technologies. Concerning the development of standards, the DOTs were evenly split as to whether to adopt national standards or develop them in-house (Figure 22), with one-third not sure which is better. (Note that because this question was analyzed by DOTs, rather than respondents, when there were conflicting answers within a DOT, the DOT response was "not sure.") Similar trends are observed when analyzed by respondent rather than DOT.

More than 75% of the DOTs reported having developed their own standards, specifications, best practices, and/or quality management procedures (Figure 23). Concerning validating the geometric accuracy of data (Figure 24), 50% of the DOTs reported having a quality management program in place and the other 50% do not for at least one of these technologies for certain applications.

KEY GEOSPATIAL PERSONNEL

Key geospatial personnel were identified for each DOT. A compilation of their names and contact information is included in Appendix D, a web-only appendix of this report.

CONCLUSIONS

In summary, analysis from the DOT questionnaire found the following information related to geospatial technology usage within the DOTs:

- Most DOTs show significant interest in geospatial technology, and many show that they are proactively involved with introducing new technologies into their organization and developing standard operating procedures.
- DOTs indicated relatively high levels of experience with advanced geospatial technologies.

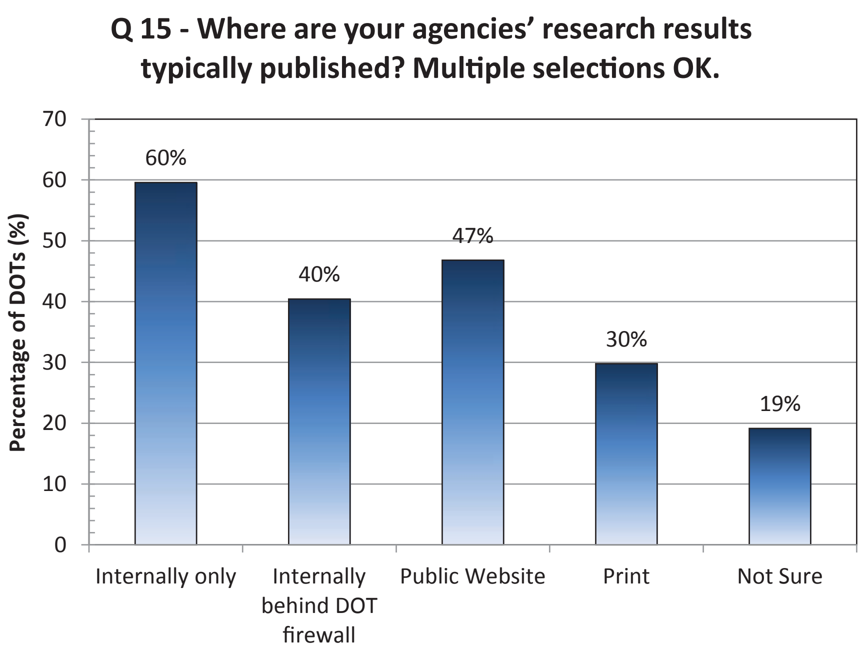

FIGURE 15 Publication locations for agency research results.

TABLE 4
RESEARCH AND DOCUMENTATION FOR DOTs

Question	Yes	Sometimes*	No	Not Sure
Does your organization conduct pilot projects to investigate new geospatial data tools and technologies?	85%	—	10%	4%
Are these results made publicly available on the web?	21%	—	67%	13%
Does your organization document failures and decisions not to use a new technology?	17%	54%	8%	21%
If yes, are these reports made public?	15%	—	37%	49%

"Sometimes" was only an option for the third question in this table.

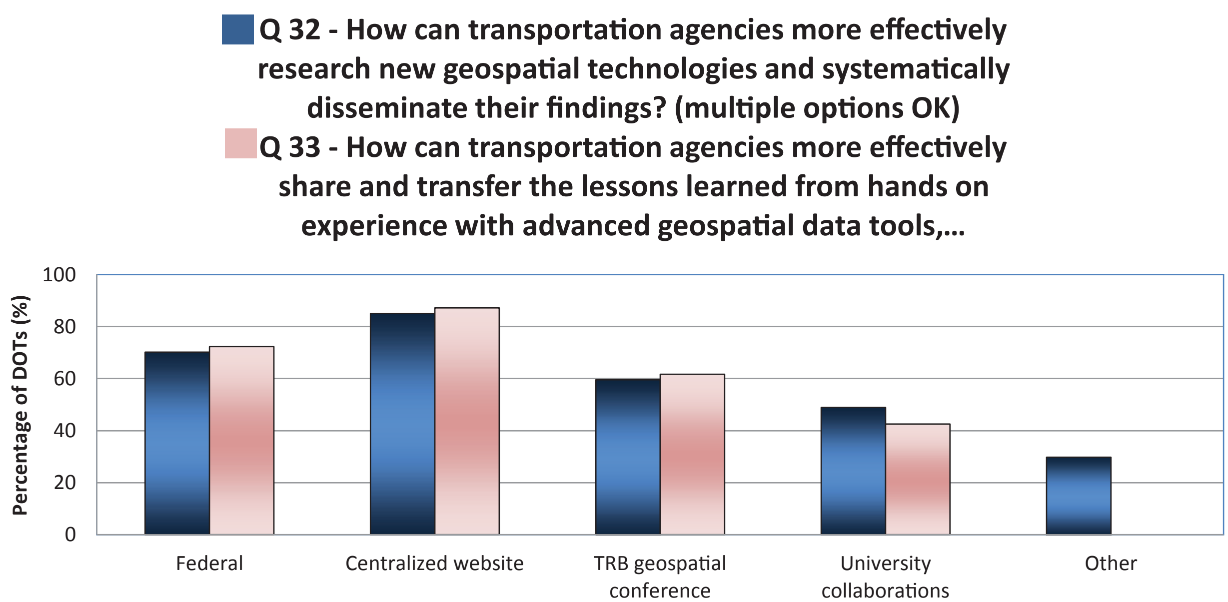

FIGURE 16 Mechanism to share and transfer knowledge among DOTs.

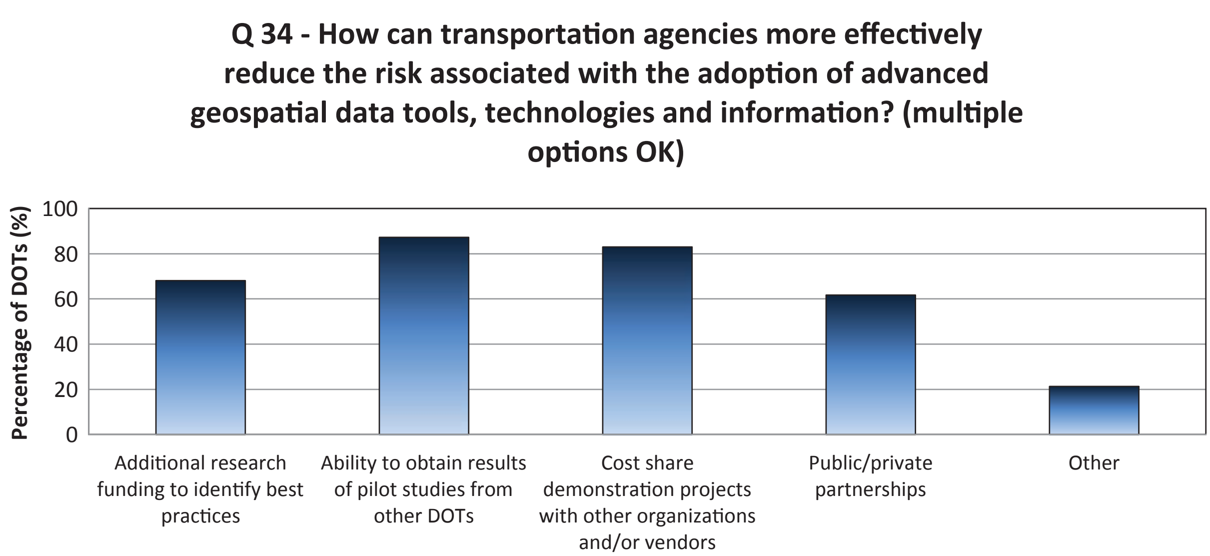

FIGURE 17 Methods to reduce risk in adopting advanced geospatial technologies.

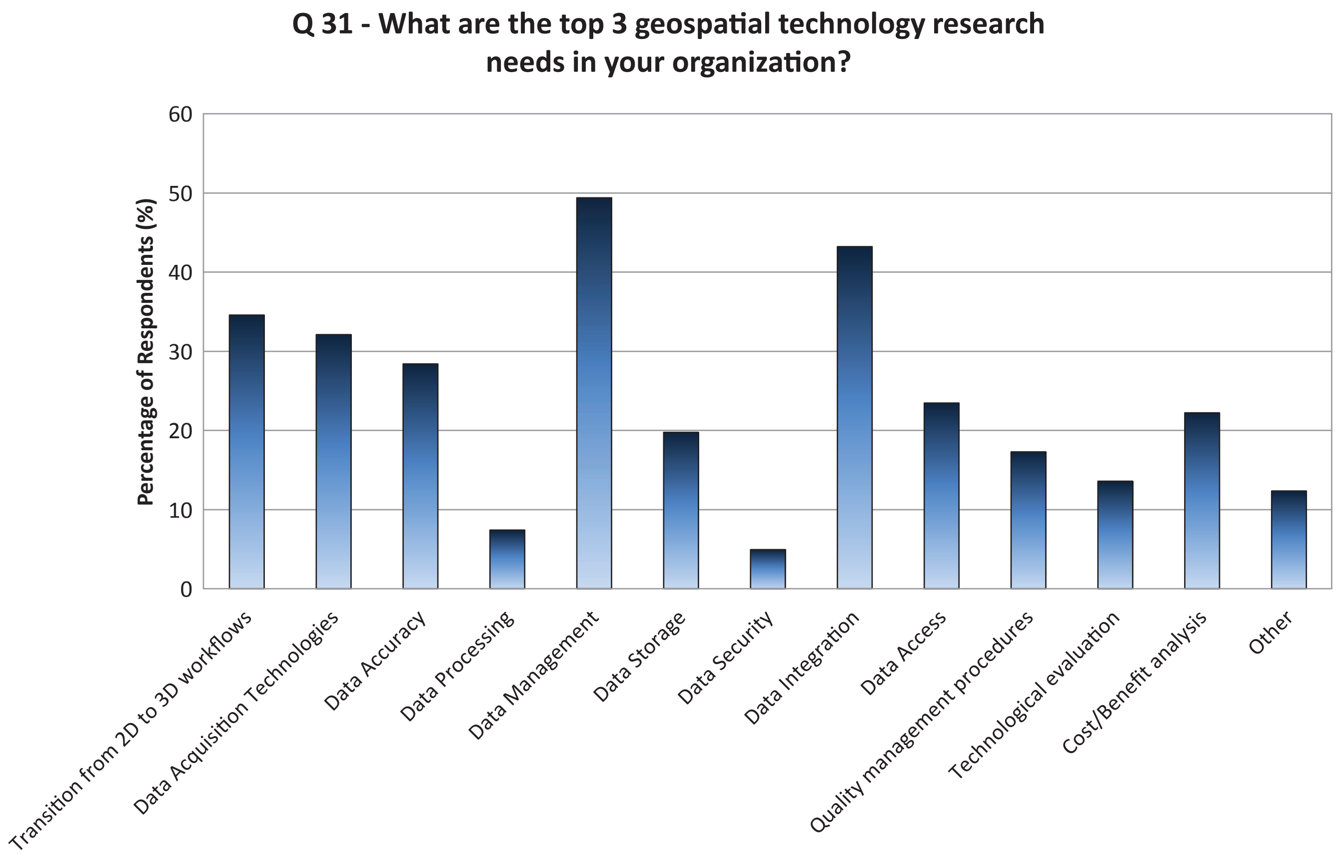

FIGURE 18 Top research needs related to geospatial technologies, by respondent. Respondents could select their top three choices.

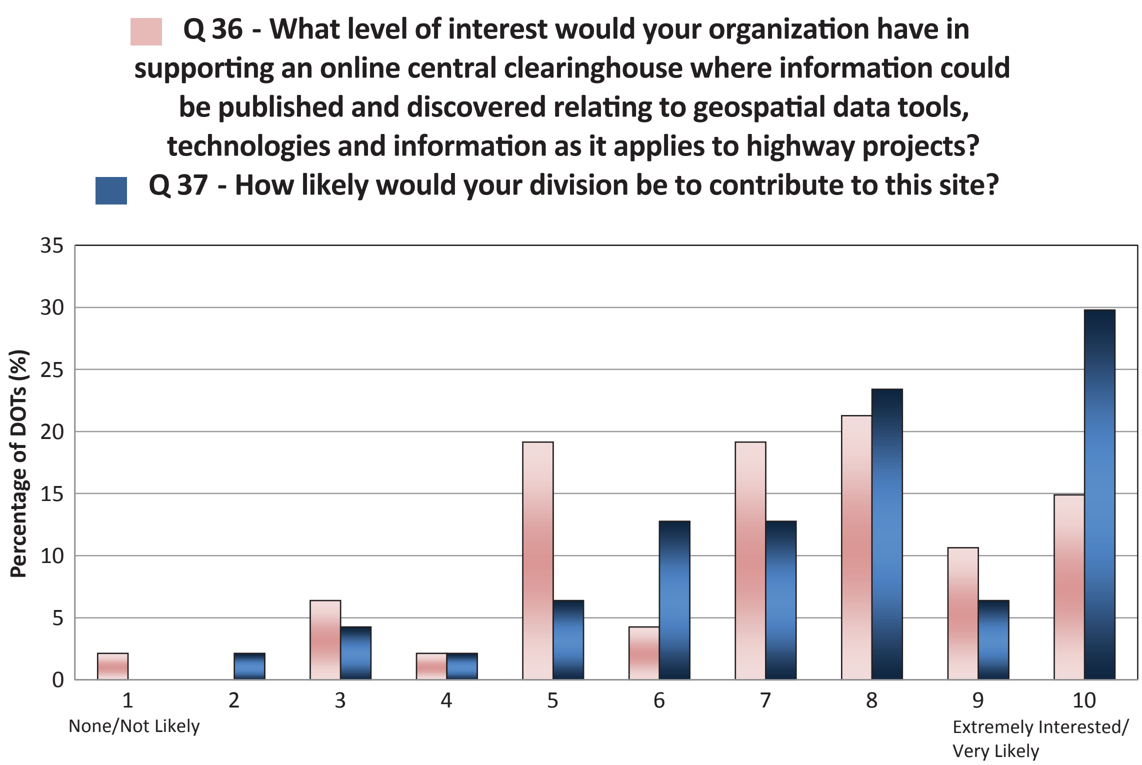

FIGURE 19 Level of interest in an online central clearinghouse.

FIGURE 20 Common sources of information and advice for DOTs.

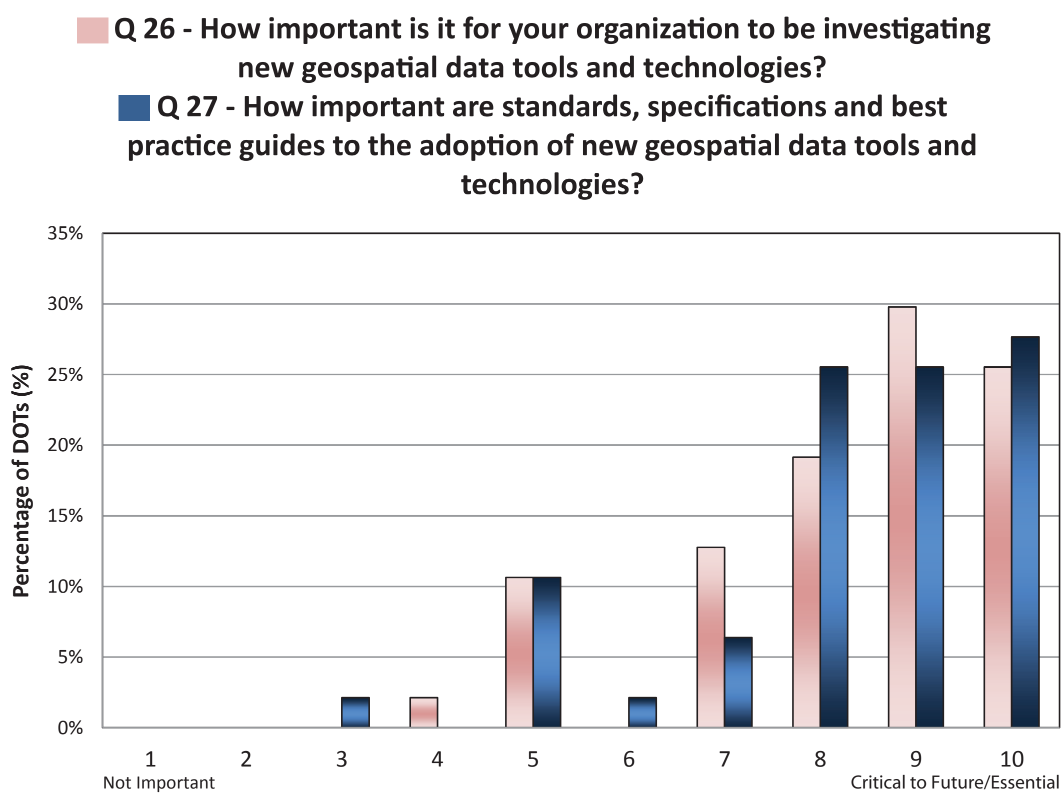

FIGURE 21 Importance of geospatial technology and development of standards, specifications, and best practice guides for adoption.

- The top three barriers to technology adoption are cost, inertia, and technical expertise.
- DOTs are comfortable with technologies such as photogrammetry, video logging, GPS, GIS, and statewide CORS networks and have integrated those into their operations. These technologies are relatively mature and have a wide support base. These common technologies also appear to be widely used across several applications [planning, right of way (ROW), design, construction, operations, and other]. However, newer technologies such as cloud computing, machine control, electromagnetic imaging, unmanned airborne vehicles (UAVs), and interferometric synthetic aperture radar (inSAR/ifSAR) are not yet well integrated. Many states are transitioning to using LIDAR technology; however, any form of LIDAR is not a standard operating procedure for the majority of the states.
- Technology investigation is conducted at the individual level, by department, centrally, and by multiple groups.
- Several methods of training are being implemented by the DOTs, and they were deemed to be somewhat effective.
- Most research reports are published internally only. Reports for pilot projects generally are not made available on the web. Failures and decisions not to use a technology are rarely documented and even more rarely made publicly available.
- Most DOTs favored the use of a publicly accessible website to disseminate research and lessons learned about advanced geospatial technologies, followed by more federal support and then more visibility at the annual TRB meeting.
- The top three geospatial technology research needs identified were data management, data integration, and transition from 2D to 3D.
- Most DOTs indicated that they would contribute information to an integrated, online site, and many indicated that they would support it.
- DOTs are split regarding development of national standards or guidelines compared with state versions. However, many believed that national guidelines that can be adapted by states would be helpful.

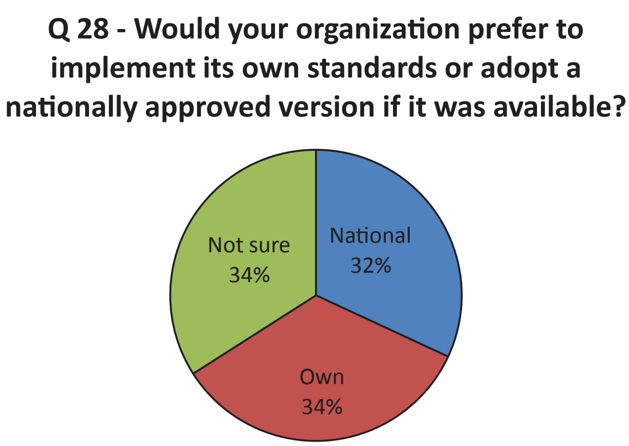

FIGURE 22 Interest in state versus national DOT geospatial standards, by DOT.

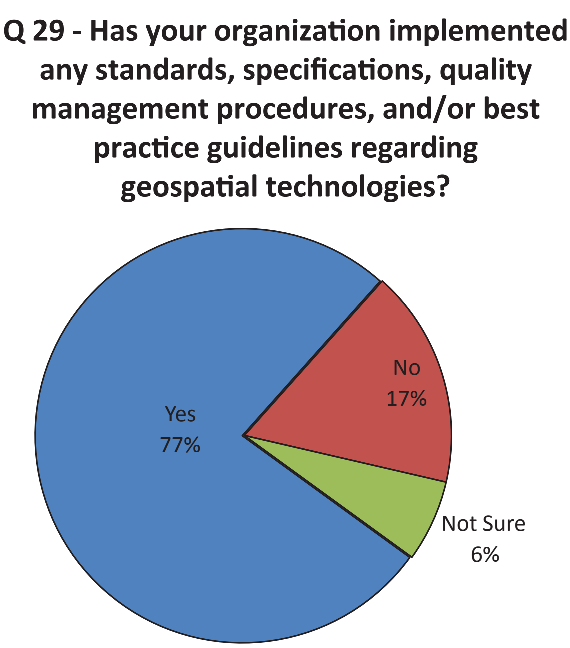

FIGURE 23 DOTs with standards, specifications, quality management procedures, and/or best practice guidelines regarding geospatial technologies.

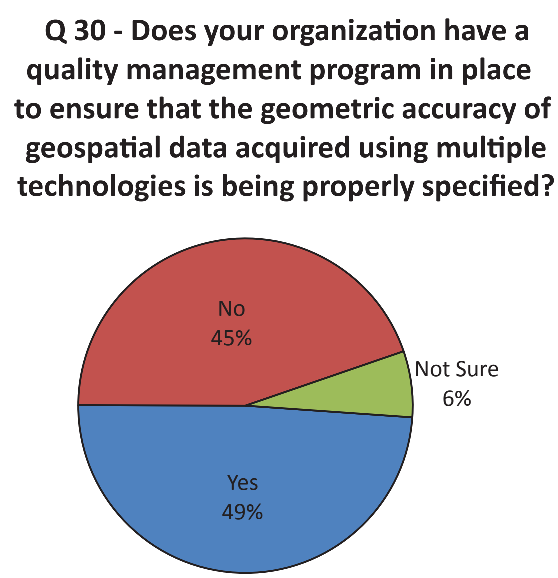

FIGURE 24 Organizations with a quality management program.

CHAPTER THREE

SERVICE PROVIDER QUESTIONNAIRE RESULTS

This chapter provides an overview of the key topics and findings from the distribution of a service provider questionnaire, similar to the DOT questionnaire discussed in the previous chapter. The service provider questionnaire results provide the service providers' perceptions of trends regarding the use of advanced geospatial technologies by the transportation agencies. The objectives for this questionnaire were the same as those listed in chapter two.

Providers to be interviewed were selected by the following criteria: (1) providers who work frequently with DOTs, (2) providers who are active in disseminating experiences at national or international conferences, and (3) geographical distribution of selected providers across the country. It can be noted that the sample size of service provider responses was 13 (of 16 contacted) compared with 97 DOT responses, roughly one-tenth. However, because of potential service provider biases, these responses should not carry equal weight with the DOT responses and a direct correlation of responses should not be inferred from this report. For example, service providers likely will be aware of technology usage only among transportation agencies with which they are working.

DEMOGRAPHICS

Thirteen service providers were interviewed by telephone. These service providers varied from software and hardware developers to companies providing geospatial services, including acquisition, processing, and analysis. As shown in Figure 25, most service providers had at least 10 years of experience with geospatial technologies, indicating that largely experienced companies were interviewed.

The service providers are making extensive use of 3D geospatial technologies (Table 5), including 3D-model-based design, laser scanning, machine control, and even cloud computing. This contrasts with the DOTs, who have not been as quick to adopt 3D-model-based design. However, as seen in the DOT list, GIS and GPS technology are at the top. DOTs indicated video logging is one of the top technologies used; however, only 54% of the service providers provide this service.

Only 24% of these service providers derive more than 40% of their business from the DOTs, indicating that the service providers have significant experience working with organizations other than DOTs (see Figure 26).

ANALYSIS METHODOLOGY

During the phone interviews, the responses were input. The results were then exported as a Microsoft Excel file for analysis. All questions were analyzed using the 13 respondents that were interviewed.

Note that as a result of rounding error, some results may not add to exactly 100% but will be within ±1%.

GEOSPATIAL TECHNOLOGY USAGE

The service providers identified that the technologies being used extensively by advanced DOTs include GPS, GIS, laser scanning, 3D-model-based design, video logging, and machine control. The DOT responses did not indicate this level of adoption. This difference can be explained by these service providers tending to work with the DOTs that are making use of these technologies, rather than those that are not.

One service provider noted that its experience indicates 90% of mobile laser scanning is being used for mapping and 10% for design.

The service providers reported the three key drivers of success when it comes to the introduction of new geospatial technologies in an organization are an early adopter mindset, an internal champion, and an interest in safety. However, the service providers identified several challenges to geospatial adoption. The most common were management, technical expertise, and lack of approved standards. The majority of the service providers reported that the use of focused research projects would help overcome some of these challenges. Some service providers indicated they spend a lot of time educating DOTs about the multiple uses of data. One service provider recommended that a DOT consider establishing a cross-functional technology innovation team that would be responsible for collecting the needs of each group and evaluating available technologies to meet those needs. California, Nevada, Georgia, Kentucky, and Texas were identified as having experience with this approach.

Deliverables

The majority of service providers stated that it was necessary for a geospatial technology service provider to report on its

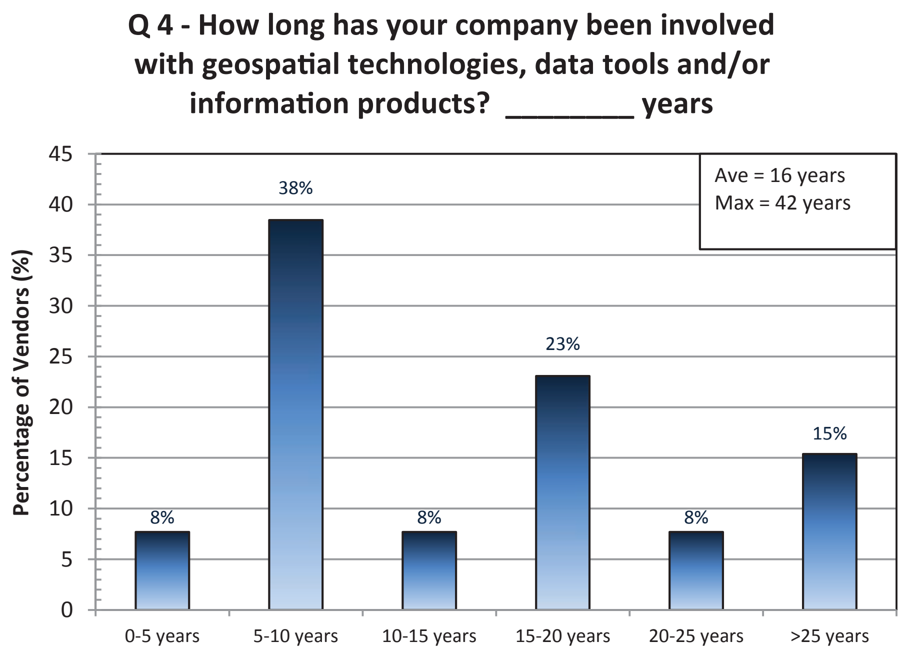

FIGURE 25 Years of experience for service providers with geospatial technologies.

TABLE 5
TYPES OF GEOSPATIAL SERVICES OR PRODUCTS USED BY SERVICE PROVIDERS, SORTED BY MOST PREVALENT TO LEAST PREVALENT

Technology	Yes	No	In the Near Future	No Interest	Not Sure
GIS	100%	0%	0%	0%	0%
3D-model-based design	92%	8%	0%	0%	0%
GPS	85%	15%	0%	0%	0%
Mobile LIDAR	85%	15%	0%	0%	0%
Static 3D laser scanning	69%	31%	0%	0%	0%
Photogrammetry	69%	31%	0%	0%	0%
Cloud computing	62%	23%	15%	0%	0%
Statewide GNSS real-time networks	62%	31%	8%	0%	0%
Tablet computers/smartphones	62%	31%	8%	0%	0%
Online mapping services	62%	39%	0%	0%	0%
Statewide CORS network	62%	39%	0%	0%	0%
Machine Control	62%	39%	0%	0%	0%
Video Logging	54%	39%	8%	0%	0%
OPUS	54%	46%	0%	0%	0%
Oblique Photography	54%	46%	0%	0%	0%
Airborne LIDAR	46%	54%	0%	0%	0%
Software as a Service	46%	54%	0%	0%	0%
Low Distortion Coordinate Systems	39%	46%	8%	0%	8%
Unmanned Airborne Vehicle (UAV)	39%	54%	8%	0%	0%
Open Source Software	39%	62%	0%	0%	0%
Ground Penetrating Radar	31%	69%	0%	0%	0%
InSAR/IFSAR	15%	77%	0%	0%	8%
Electromagnetic Imaging	15%	85%	0%	0%	0%

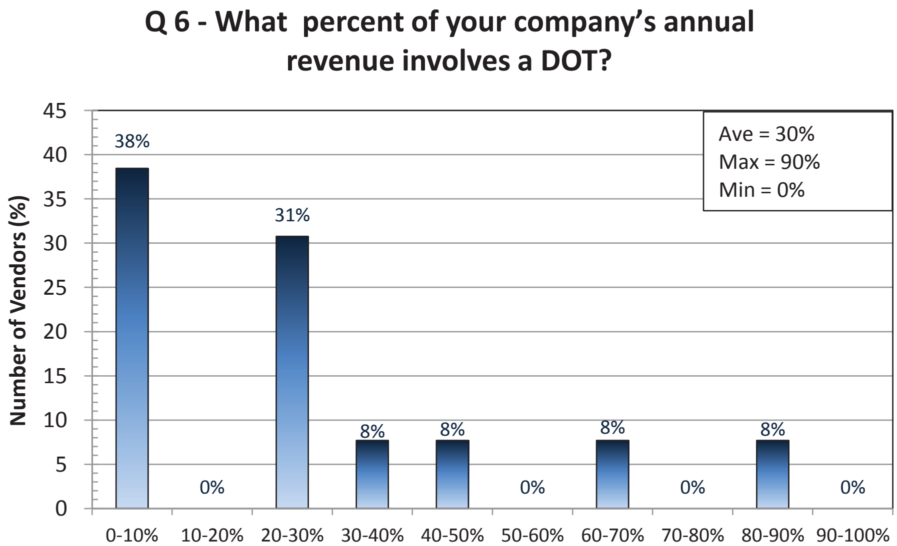

FIGURE 26 Annual revenue for companies from DOTs.

methodology as part of the project deliverable rather than merely certifying the final accuracy.

INFORMATION RESOURCES

Similar to the DOTs, the service providers supported a central website (Figure 27) as a way to disseminate best practice information more systematically, followed by more federal support and coordination. The service providers reported that for nearly 70% of projects the results are "sometimes" or "often" documented (Figure 28). The service providers stated that for slightly more than 50% of the projects, the results are "sometimes" or "often" made public (Figure 29). The service providers reported that results, when published, were published on a public website or in print. The service providers cited liability as the primary reason results are not published. The service providers reported that the top three geospatial technology research needs are the transition from 2D to 3D, data management, and data integration. One service provider indicated that a new technologies group that can do evaluations and pilot projects would be beneficial.

One service provider recommended a workshop before TRB conferences to disseminate report findings and highlight best practices at advanced DOTs. This service provider also suggested compiling an executive version of this report (no more than six or seven pages) emphasizing how the DOTs can

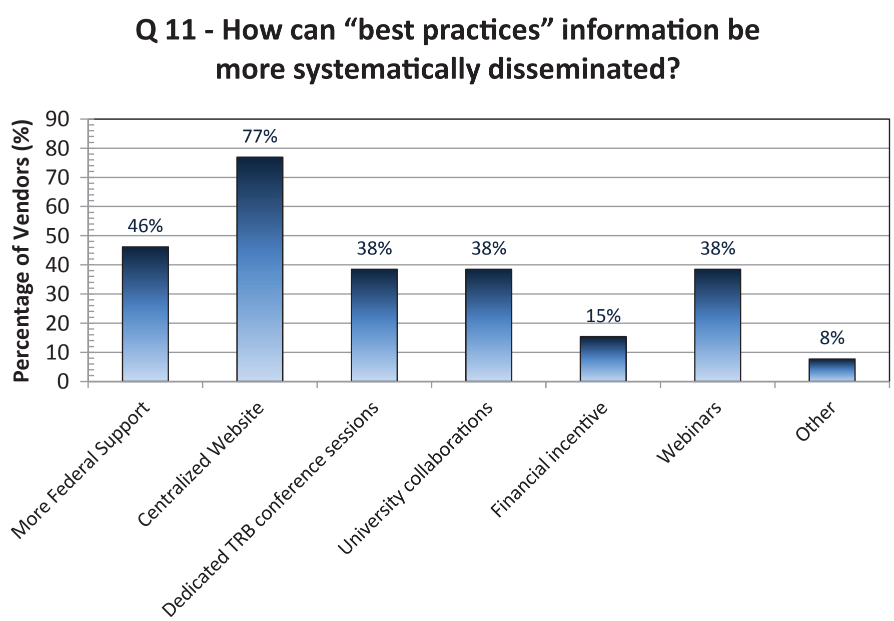

FIGURE 27 Methods for systematically disseminating best practices.

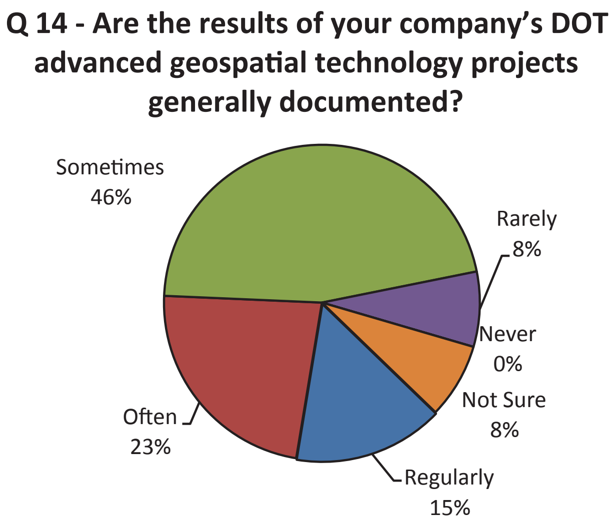

FIGURE 28 Level of documentation by service providers.

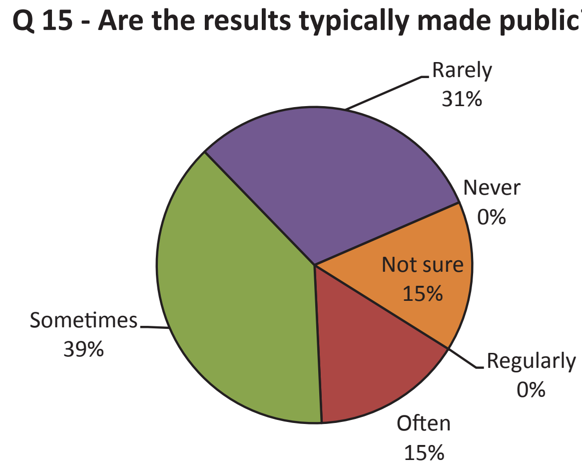

FIGURE 29 Public availability of documentation by service providers.

become successful using a new technology and what is the return on investment (ROI). This service provider indicated that service providers have not done a good job of documenting and explaining the value proposition.

STANDARDS

The service providers reported that slightly more than 50% of the DOTs that they work with have written geospatial standards and specifications. To improve the effectiveness of these standards (Figure 30) the service providers recommended that the DOTs make use of national standards, emphasize performance rather than procedure, and involve an industry panel in the process. One service provider noted that standards are too complex.

Procurements

To streamline procurement for advanced geospatial technologies, the service providers recommended that bidders be prequalified and that indefinite delivery indefinite quantity (IDIQ) contracts be established (Figure 31). One service provider suggested that DOTs qualify firms for data acquisition, similar to what has been done for photogrammetry.

KEY GEOSPATIAL PERSONNEL

Additional geospatial personnel were identified by the service providers and are included in the table in Appendix D. Many of these also were identified in the DOT questionnaire.

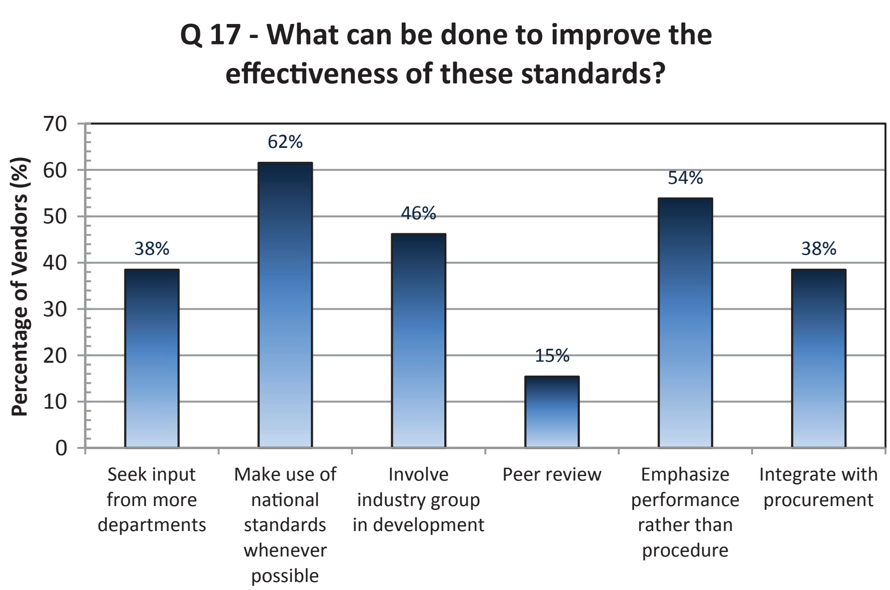

FIGURE 30 Methods to improve standard effectiveness, as perceived by service providers.

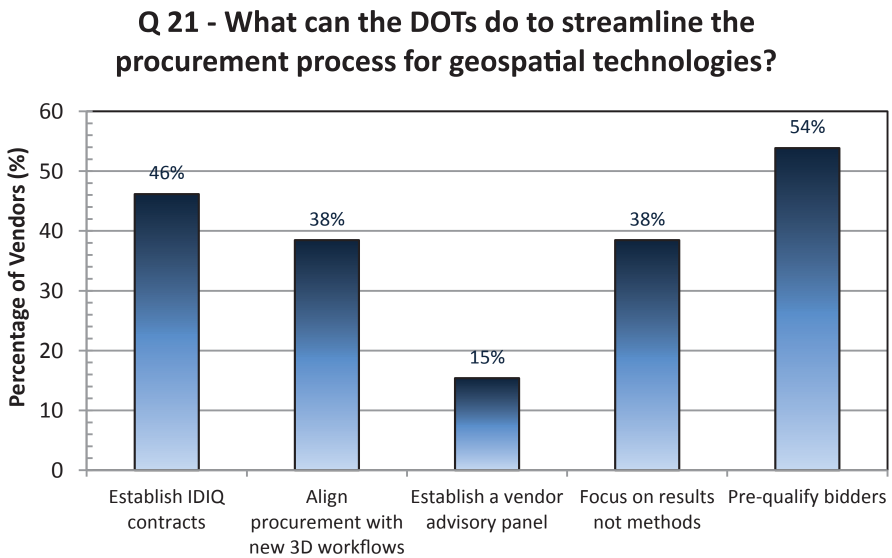

FIGURE 31 Possible methods to improve the procurement process for geospatial technologies, as perceived by service providers.

ADDITIONAL COMMENTS

One service provider commented on the Highway Performance Monitoring System FHWA mandate and indicated that integrated systems can collect as much as 70% (the rest is not geospatial) of the required data with such systems. Another service provider commented on the importance of focusing on the end result, rather than the actual data or technology used to obtain that data.

CONCLUSIONS

The service provider questionnaire uncovered several key points of information related to geospatial technology usage within the DOTs:

- Service providers are early adopters of geospatial technologies, particularly 3D workflows.
- The three key drivers of success when it comes to the introduction of new geospatial technologies are an early adopter mindset, an internal champion, and an interest in safety.
- Similar to the DOTs, service providers reported that focused research projects would help overcome barriers.
- Service providers were also in support of a centralized website for disseminating best practices.
- Service providers, however, indicated that projects are only sometimes documented and only sometimes made public once documented. Liability was a significant concern in determining whether or not to publish the results.
- Service providers indicated that data management, data integration, and transition from 2D to 3D were the top three geospatial technology research needs.
- Service providers favored national standards, when possible. They also preferred performance-based specifications.
- Service providers also believed that the prequalification of contractors is important for streamlining the procurement process for data acquired using geospatial technologies. Other factors indicated include IDIQ contracts, alignment with 3D workflows, and focusing on results rather than methods.

CHAPTER FOUR

LITERATURE REVIEW APPROACH

APPROACH

Geospatial research for transportation exists in pilot studies, individual technology analyses, and in-depth comparison projects. However, these results are scattered and reside in archives of research committees, university collaborations, or in-state organizations—often behind firewalls. This chapter reports the key findings and documented resources related to geospatial data, tools, and technologies.

First, the data, tools, and technologies to be examined were chosen or excluded according to relevance to transportation agencies. Relevant data were then compiled and analyzed for common conclusions or contradictions. Lastly, these data were integrated into a structured, searchable, "live" database of available online resources.

This Synthesis documents a variety of sources that may be of value to transportation agencies to support their cost-effective implementation of geospatial data, tools, technology, and information. With the vast quantity and types of geospatial research that currently exist, it would be impossible to include every source in a single, readable document. However, every effort was made to ensure key representative reports, studies, and collaborations were included in the body of the report. Links to additional documents that are not discussed in this report can be found in Appendix C, the database of sources.

Internet hyperlinks are used throughout the text of this document to provide the reader with quick access to reference materials available online. These source links were verified in August 2012.

INFORMATION SOURCES

Initially, researchers used the Internet to search for publicly available information and data from each state DOT. The relevant publications found and associated hyperlinks are listed in a database sorted by state and technology in Appendix C.

In addition to specific DOT analysis, several other sources were valuable resources for investigating geospatial technology use in transportation agencies. These data have strengths and weaknesses specific to each source. For example, industry conferences can offer quick and specific information from several service providers; however, this information can be biased and often has not been peer reviewed. Conversely, journal publications typically have a lengthy review process, which improves the professional credibility of the findings, but the lag in publication can prove to be an issue with rapidly evolving technologies. A list of typical advantages and disadvantages of the relevant information sources examined is presented in Table 6.

Relevancy level definitions used in Tables 7 through 10 are as follows: I = focused directly on both transportation and geospatial technology; II = focused on either transportation or geospatial technology; III = broader focus, some of which has relevance to transportation, geospatial technology, or both.

Agencies providing geospatial information are listed in Table 7, along with their corresponding relevance level to geospatial projects. These agencies can offer a starting point for research by transportation agency. Further, the information retrieved typically is current and presented for professionals associated with these specific industries. This requires a certain amount of peer and editorial review for verification. Many times the most current guidelines and specifications can be found at the websites of these agencies. Because these are agency-specific, they tend to present material in a manner that is beneficial to their particular agency, similar to a service provider workshop or conference presentation.

Continuing education through training sessions, workshops, webinars, and conferences helps many transportation agency employees become technological leaders in their organizations. Many organizations discussed previously conduct continuing education courses or have training at their regular meetings.

Conference proceedings are valuable resources for learning about or expanding knowledge of a certain technology or workflow. This can be a more cost-effective method of education than pilot studies or dedicated research projects. Organizations often find the cost and time associated with traveling to these conferences to be a limiting factor. In addition, conference presentations often are not peer reviewed before presentation.

Once at a conference, however, attendees may converse directly with a significant number of industry experts, attend

TABLE 6
DATA SOURCE TYPE ADVANTAGES AND DISADVANTAGES

Data Source Type	Advantages	Disadvantages
Federal/State Agency	• Generally substantial internal (and sometimes external) review in development of published results	• Due to long review process, reports are under development for a long time • Specific to the goals of the agency, limiting applicability
State DOTs	• High relevance • Needs-based undertakings • Specific conclusions • Can utilize pooled fund efforts for funding	• Some reports are not made publicly available • Funding needs can limit scope and completion of work
Conferences	• Ability to network and talk directly • Quick dissemination • Large number of experts with multiple views	• Can be costly to attend • Travel restrictions • May or may not be peer-reviewed • Proceedings can sometimes be difficult to find
Archival Journals	• Rigorous peer review process provides a check on the work and its quality • Minimal bias toward a specific service provider • Scientific methods of evaluation • Generally requires rigorous statistical evaluations	• Significant lag in publication from research completion; however, many journals are publishing accepted manuscripts online before print versions are made available • Difficult to keep up with the large number of journals
E-magazines / Websites	• Quick information related to a variety of subjects • Work presented by a variety of service providers • Current information	• Generally not a lot of detail in how and how well work was performed • Articles can contain service provider bias • Not necessarily professionally reviewed
White Papers	• Useful supplemental information • Allows clarification on specific, sometimes recurring technical problems • Quick publication	• Often not reviewed by an external audience • Can be too general and may not include proprietary information • Not archived

specific presentations on a tool or technique, and disseminate information quickly. Table 8 lists specific conferences relevant to geospatial proceedings and their associated relevancy level. In addition, several vendors have user meetings, which can be helpful to those wanting to learn about geospatial workflows and emerging technologies.

Peer-reviewed technical journals usually contain some of the most in-depth documented findings of any research information source. These journals require thorough peer review of all research they publish. Most journals do not allow endorsement of or bias toward a particular vendor or service provider. They require the results of studies published in journals to be documented sufficiently to be repeatable by someone else. Many journals also now promote data sharing.

There tends to be a significant lag time between when a study is performed and its publication in a journal. In certain instances, manuscripts are accepted and published online before print versions are available. Certain journals have been selected and listed in Table 9 with their associated relevancy level.

E-magazines, blogs, and open forum websites (Table 10) can be beneficial to a transportation agency entering into or evaluating current geospatial tools in use. These data sources tend to provide current information presented by a variety of

TABLE 7
AGENCIES WITH TRANSPORTATION AND/OR GEOSPATIAL TECHNOLOGY EXPERIENCE, CATEGORIZED BY RELEVANCE (STATE DOTs ARE LISTED SEPARATELY)

Agency / Organization	Website Address	Category
American Association of State Highway Officials (AASHTO)	http://www.transportation.org/	I
American Congress on Surveying and Mapping (ACSM) (currently merging with NSPS)	http://www.acsm.net/	III
American Society for Testing and Materials (ASTM)	http://www.astm.org/	III
American Society of Civil Engineers (ASCE) Geomatics Division	http://www.asce.org/Content.aspx?id=2147488648	II
American Society of Civil Engineers (ASCE) Journal of Surveying Engineering	http://ascelibrary.org/suo/	II
American Society for Photogrammetry and Remote Sensing (ASPRS)	http://www.asprs.org/	II
Coalition of Geospatial Organizations (COGO)	http://www.urisa.org/cogo	II
Federal Emergency Management Agency (FEMA)	http://fema.gov	II
Federal Geographic Data Committee (FGDC)	http://www.fgdc.gov	I
Federal Highway Administration (FHWA)	http://www.fhwa.dot.gov	I
International Federation of Surveyors (FIG)	http://www.fig.net/	II
Highway Engineering Exchange Program (HEEP)	http://www.heepweb.org	I
International Society for Photogrammetry and Remote Sensing (ISPRS)	http://www.isprs.org/	II
Joint Board of Geospatial Information Societies	http://www.fig.net/jbgis	II
National Association of Counties (NACO)	http://www.naco.org/Pages/default.aspx	II
National Geodetic Survey (NGS)	http://www.ngs.noaa.gov/	II
National Oceanic and Atmospheric Administration (NOAA)	http://www.noaa.gov/	I
Transportation Research Board (TRB)	http://www.trb.org/Main/Home.aspx	I
United States Army Corps of Engineers (USACE)	http://www.usace.army.mil/	II
United States Department of Transportation (U.S.DOT)	http://www.dot.gov/	I
United States Geological Survey (USGS)	http://www.usgs.gov/	I
Surveyors and Geomatics Educators (SaGES)	http://www.geoscholar.com/Sages/	III
US Geospatial Transportation Mapping Association	http://www.usgtma.org/	I

State DOTs are listed separately.

service providers and other industry leaders. However, these sources tend to be less formal and not peer reviewed, as are conference and journal sources. In addition, this information may contain service provider biases and often omits how information was obtained or evaluated (e.g., “trade secrets”). Vendors and service providers often have helpful documents on their websites regarding examples of technology implementation.

A number of agencies and organizations are collecting geospatial data. It can be seen from the DOT questionnaire that DOTs are generally in support of a central clearinghouse to store and retrieve geospatial information (see Figure 19). Table 11 lists some of these clearinghouses and their website addresses.

Additional information can be available through universities or agencies funding or conducting research. In some cases, investigations for transportation agencies were performed by geospatial faculty and students in universities and have been incorporated into masters or doctorate theses, which are not easily obtainable through general search methods. In many others, the research was funded by the university, governmental organizations, or one of the many other sources mentioned in this section.

TABLE 8
CONFERENCES WITH TRANSPORTATION AND/OR GEOSPATIAL TECHNOLOGY EXPERIENCE, CATEGORIZED BY RELEVANCE

Conferences	Website Address	Category
AASHTO GIS for Transportation Symposium	http://www.gis-t.org/	I
ASPRS	http://www.asprs.org/	II
ACSM Survey Summit (ESRI)	http://www.surveysummit.com/index.html	I
European LIDAR Mapping Forum (ELMF)	http://www.LIDARmap.org/ELMF/	III
FIG	http://www.fig.net/	II
Highway Engineering Exchange Forum	http://www.heepweb.org/	II
Institute of Electrical and Electronics Engineers	http://www.ieee.org/conferences_events/index.html	III
International LIDAR Mapping Forum (ILMF)	http://www.LIDARmap.org/ILMF.aspx	II
ISPRS	http://www.isprs.org/	II
Institute of Transportation Engineers	http://www.ite.org/conference/	II
Photogrammetry Week Conference, University of Stuttgart, Germany	http://www.ifp.uni-stuttgart.de/publications/phowo.en.html	II
SPAR	http://www.sparpointgroup.com/	I
TRB	http://www.trb.org/Main/Home.aspx	I

TABLE 9
JOURNALS WITH TRANSPORTATION AND/OR GEOSPATIAL TECHNOLOGY EXPERIENCE, CATEGORIZED BY RELEVANCE

Publication	Publishing Agency	Website Address	Category
Annals of GIS	Taylor and Francis	www.tandf.co.uk/journals/tagi	II
ASTM Testing Journal	ASTM	http://www.astm.org/	II
GeoCarto International	Taylor and Francis	www.tandf.co.uk/journals/tgei	II
International Journal of Photogrammetry and Remote Sensing (ISPRS)	ISPRS	http://www.isprs.org/	II
Journal of Computing in Civil Engineering	ASCE	http://ascelibrary.org/journal/jccee5	I
Journal of Spatial Science	Taylor and Francis	www.tandf.co.uk/journals/tjss	II
Journal of Surveying Engineering	ASCE	http://ascelibrary.org/suo/	I
Journal of Transportation Engineering	ASCE	http://ascelibrary.org/journal/jtpedi	II
Lasers in Engineering	Old City Publishing	http://www.oldcitypublishing.com/LIE/LIE.html	II
Photogrammetry Engineering and Remote Sensing	ASPRS	http://www.asprs.org/	II
Remote Sensing	MDPI	http://www.mdpi.com/journal/remotesensing	II
Survey and Land Information Sciences (SALIS)	ACMS (NSPS)	http://www.acsm.net/	II
Transactions on Geoscience and Remote Sensing	IEEE	http://www.grss-ieee.org/publications/transactions/	II
Transportation Research Record (TRR)	TRB	http://www.trb.org/Main/Home.aspx	I

TABLE 10
E-MAGAZINES/WEBSITES WITH TRANSPORTATION AND/OR GEOSPATIAL TECHNOLOGY EXPERIENCE, CATEGORIZED BY RELEVANCE

E-magazines\Websites	Website Address	Category
American Surveyor	www.amerisurv.com/	I
Geomatics World	www.pvpubs.com/	II
GIM International	www.gim-international.com/	I
GPS World	www.gpsworld.com/	II
Laser Scanning Forum	www.laserscanning.org.uk/forum/	II
LIDAR news	www.LIDARnews.com	I
Linked In—Location Intelligence and Geospatial BI	http://www.linkedin.com/groups?gid=51019&trk=group-name	I
Machine Control Online	http://www.machinecontrolonline.com/	II
Open Geospatial Consortium	http://www.opengeospatial.org/	I
Point of Beginning	www.pobonline.com/	I
Professional Surveyor	www.profsurv.com/	I
Site Prep Magazine	www.siteprepmag.com	III

State DOTs (Publications, Manuals, GIS Databases, Research Studies, and Reports)

Most, if not all, state DOTs have a protocol for use of one or more geospatial technologies; whether field or office procedures, some type of standard is usually followed. Many times there are printed guidelines and specifications to which employees can refer to help them achieve standardized results. For example, in the case of traditional surveying, 34 states have readily accessible survey manuals publicly available on their websites (see chapter seven, Table 25). Most likely, several others have this information available internally.

However, the level of detail of these documents varies significantly. Some of these manuals just scratch the surface as to what is required when conducting location, geodetic, right of way, and property surveys, providing only a base of the requirements for performing certain survey work in their state. Others, such as those of California, Wisconsin, Pennsylvania, New York, and New Mexico, are more detailed. Some go as far as specifying strict requirements for horizontal and vertical closure limits, instrument calibration requirements, and monumentation guidelines, to name a few.

Other manuals available, in addition to traditional surveying, may include the following advanced geospatial

TABLE 11
GEOSPATIAL DATA CLEARINGHOUSES

Name	Website
LIDAR Links for Mappers	http://www.LIDARbasemaps.org/
Wikipedia	http://blog.LIDARnews.com/national-LIDAR-datasets-on-wikipedia
	http://en.wikipedia.org/wiki/National_LIDAR_Dataset_%E2%80%93_USA
	http://en.wikipedia.org/wiki/National_LIDAR_Dataset
Open Topography	http://www.opentopography.org/
Cyark—cultural heritage LIDAR datasets	http://archive.cyark.org/
NOAA Digital Coast: LIDAR, ifSAR of the coast	http://www.csc.noaa.gov/digitalcoast/
USGS Click	http://LIDAR.cr.usgs.gov/
USGS National Map Seamless Server	http://seamless.usgs.gov/index.php
USGS National Elevation Dataset	http://ned.usgs.gov/
Puget Sound LIDAR Consortium	http://pugetsoundLIDAR.ess.washington.edu/LIDARdata/index.html
DOGAMI LIDAR for Oregon	http://www.oregongeology.org/sub/projects/olc/default.htm
USDA Forest Service Remote Sensing Applications Center (RSAC)	http://www.fs.fed.us/eng/rsac/
ESRI	http://www.esri.com/software/arcgis/arcgisonline/map-services.html
LIDAR Online	http://www.LIDAR-online.com/

technologies: aerial mapping and photogrammetry, LIDAR specifications, guidelines and best practices, and ROW manuals. These can exist as stand-alone documents, such as those for New York, Connecticut, and Massachusetts. Other states (Indiana and Missouri) prefer to have a large manual divided into sections with each technology generally discussed in a dedicated chapter or two. Several states (including Montana, North Dakota, and Florida) have a manuals page that contains hyperlinks to many manuals, with topics ranging from erosion and sediment control, to traffic control devices, to photogrammetric standards. Often these manuals and standards exist in specific departmental locations and on a general manuals page, so a person can navigate to these documents through multiple paths. Having these documents accessible rather than hidden provides more freedom to employees, consultants, other DOTs, and the general public to obtain information such as accuracy standards and best practices quickly and easily for quality assurance/quality control (QA/QC) checks.

State databases utilizing numerous GIS platforms are becoming standard practice for providing geospatial data to the public. These platforms allow states to display their data with satellite imagery and topographic backgrounds to create relevant, interactive, online tools. These tools provide end users with answers to geospatial-related queries in a matter of seconds. End users may be the general public, DOT employees, other state and federal agency employees, or private businesses. Some of the numerous examples of GIS integration by transportation agencies include land boundaries; crash statistics; current, planned, and completed building projects; weather; traffic; utilities; topography; railroads; and zoning. This information can exist as separate applications or in collective data clearinghouses in some cases. Examples of states with GIS clearinghouses are Georgia, Illinois, South Carolina, Oregon, and Maine. Several states also include advanced data, such as LIDAR, orthorectified photography, and aerial imagery along with these GIS layers.

Research studies for the advancement of geospatial technologies have been undertaken by several states. In addition, studies are performed by some transportation agencies to analyze technologies in use to seek enhancement techniques and evaluate the ROI. Sometimes these research studies are collaborative efforts with pooled funding from multiple transportation agencies, enabling states to share resources and accomplish a common or similar analytical goal that can be provided by dedicated research. Collaborations also have the luxury of bringing in outside consultants to aid with their expertise. No matter how funding is gained, synthesizing these data will be a great benefit to all who look to enter new technology platforms or analyze their current use of advanced geospatial technologies.

CURRENT INITIATIVES

Fortunately, geospatial technologies recently have received more national attention. MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), was recently signed into law to fund surface transportation programs at a cost of more than $105 billion for fiscal years (FY) 2013 and 2014.

This legislation is quite forward looking. In addition to an emphasis on the use of performance-based versus prescriptive specifications, MAP-21 includes financial incentives for the use of 3D technology.

In particular, Section 1304 of the legislation authorizes as much as 100% federal financing for projects that contain innovative technologies such as "digital 3-dimensional modeling."

In addition, the FHWA is also promoting the use of 3D through its Every Day Counts (EDC)—DC initiative. This program is "designed to identify and deploy innovation aimed at shortening project delivery, enhancing the safety of our roadways, and protecting the environment." In the recently announced second round of initiatives, 3D modeling, geospatial data collaboration, and GPS-based intelligent compaction are highlighted.

As evidence of the connection, the Utah DOT's use of mobile mapping to create what they are calling "uPlan" has been identified as one of the second round of EDC initiatives. The database for this 3D asset management system was collected using a variety of sensors, including Mobile LIDAR. This program has the potential to become a model for transportation agencies here in the United States and around the world.

CHAPTER FIVE

TECHNOLOGY

Public safety aspects related to geospatial data, tools, and techniques deserve the highest concern. Virtually all systems evaluated in this work are able to obtain parameters important to increased safety on roadways (e.g., sign placement, bridge clearances, and lane and shoulder widths). These parameters are presented in the AASHTO *Highway Safety Manual* (HSM) and are benchmarks for state DOTs to achieve. Further, safety parameters are almost always desired and typically a part of any research and development for geospatial tools. For example, collecting geospatial data by means of remote sensing techniques offers safety benefits to surveyors owing to the reduced roadway exposure it affords. In many cases, multiple parameters can be obtained from a single platform.

The technological background in this chapter is organized by technology type. The discussion of each technology is further divided into sections discussing strengths and weaknesses of the technology (compiled based on information found in the reviewed literature and questionnaire comments) and current uses by transportation agencies that have been documented.

With the migration of geospatial data from 2D to 3D, and the further integration of attributes such as time and cost, a clear vision of where transportation agencies are headed is needed. Strategic plans have been published by the Oregon and Kansas DOTs. These are documents that aim to give employees, managers, and the public a technology roadmap for the future of the transportation agency.

The Oregon DOT report, *Engineering Automation* (Singh 2008), is discussed in the Machine Control and Automation section of this chapter, whereas the Kansas report, "Geospatial Enablement Strategy," is covered in chapter six. GIS is a significant, advanced geospatial tool presented in chapter six.

A key to the use of these technologies is that many can be integrated into a single data collection for efficiency and cost-effectiveness. For example, a single mobile platform can have multiple sensors (LIDAR, cameras, inertial profilers, reflectometers, and so forth) to enable data to be linked geospatially and collected in a single pass. DOTs are responsible for complying with the *Manual on Uniform Traffic Control Devices* (*MUTCD*) and FHWA regulations. By linking these various data geospatially, DOTs can determine more efficiently their level of compliance and where they need to improve. Much of the data necessary to collect are geometric and can be obtained from an integrated system.

These technologies can present tremendous benefits compared with costs. For example, Dewberry (2012) analyzed benefit-to-cost ratios for federal, state, and nongovernmental users of the availability of high-quality elevation data. The combined benefit-to-cost ratio was 4.7, indicating the tremendous value of all of these data acquisition technologies.

PHOTOGRAPHY

Photography is a mature technology that has been used in transportation agency workflows for several decades. These still images can be used to support workflows such as mapping, change detection, surveillance, and digital terrain models. Photographic information traditionally has been collected from film-based cameras. However, digital sensors such as a charge-coupled device (CCD) have enabled faster processing workflows and improved data preservation.

Photography can be implemented from a variety of platforms, including satellite, airplane, helicopter, automobile, floating, stationary, or handheld. Aerial photography is typically performed nadir (looking directly at the ground), which is optimal for horizontal feature layout. However, oblique photography is conducted at a nonorthogonal angle to the ground, which provides information on vertical features. Several companies provide both of these forms of imagery, as well as street view imagery, free of charge.

Additional processes enable this photographic information to be used for surveying and mapping purposes. These processes include photogrammetry, orthorectification, and photo-mosaicking.

Photogrammetry is a specialized practice for determining geometric information from photographs. Typically, photogrammetry uses stereoscopic cameras to take images that overlap one another to model terrain and map planimetrics. These images are referred to as stereo pairs. By knowing certain parameters, such as the flight altitude and camera focal length, elevation measurements can be determined. These measurements can then be resolved into a digital terrain model (DTM). Current photogrammetric techniques are extending into a "street view" type rectification as well. This allows 3D environments to be extracted, analyzed, and navigated. Further workflows incorporating photogrammetric methods can be found in this chapter in the section Three-Dimensional Model-Based Design.

Orthorectification is the process of geometrically correcting an image to remove topographic relief, lens distortion, and camera tilt so that the scale is uniform (i.e., each pixel size is a constant distance). The resulting image is called an orthophoto, orthophotograph, or orthoimage. These images can then be digitized in GIS or CAD to create features and objects through manual, semi-automatic, and fully automatic processes. They often are used as base maps.

Photo-mosaicking is the process of combining several photographs into a single, seamless image. This process is helpful for projects that cover large extents that cannot be captured in a single image. Orthorectification and photo-mosaicking can be used in conjunction to create maps that span long transportation corridors.

Recent advances in computing technology have enabled advanced 3D models to be created through 3D reconstruction from a series of 2D images. For example, Microsoft hosts a program, "Photosynth" (http://photosynth.net) that enables users to upload photographs taken from arbitrary locations and link the photographs in 3D.

Strengths/Weaknesses

Photographic techniques can be nonintrusive, remote sensing methods with significant visualization benefits. Products created from single, time-series, and multiple photographs include DTMs, virtual reality systems, 3D line work, and other geometric models. These data can be both project-specific and traffic-metric oriented. This is well-understood technology that has undergone significant research and development efforts by several transportation agencies. Several state guidelines, specifications, and best practices have been incorporated into transportation workflows in such states as Michigan, Indiana, Colorado, Minnesota, Mississippi, and California.

Fixed-wing and mobile platforms may require moderate to considerable mobilization time. Terrestrial photography, alternatively, can be mobilized quickly for a small area. Although several software suites have been in use for several years, photo interpretation typically is validated by a professional to ensure the accuracy of the results. Deng and Faig (Aguilar et al. 2010) performed an evaluation of commercial off-the-shelf (COTS) software packages for close-range photogrammetry. Currently, feature extraction algorithms are being developed to enhance and automate this process.

This technology can be applied to images pointing in any direction; likewise, differing scales of resolution can be used. A summary of these strengths and weaknesses can be found in Table 12.

Current Uses of Photography Techniques in Transportation

Photography techniques are a beneficial supplement to nearly all geospatial-related tools and techniques, as discussed in other sections of this document. However, these techniques have the ability to create specific, stand-alone products.

Aerial Orthophotography Specifications

The California DOT (Caltrans) compiled specifications to use GPS and aerial block photos for large-scale mapping projects. Caltrans examined whether these block photos could be integrated into their existing strip photorectification standards. Furthermore, it was determined that using CORS stations and postprocessing eliminates the need for ground base stations. The end products are standards and specifications that are integrated into the Caltrans manual. They are discussed further in chapter seven (Munjy and Hussain 2010).

The state of Maryland uses a detailed outline of service provider requirements for orthophotography. The outlines describe the imagery deliverables of items such as data density, accuracy, precision, county buy-up options, QA/QC, coordinate systems, ground control, coverage, and validation. All data will be orthorectified and meet ASPRS standards (Maryland 2010).

TABLE 12
STRENGTHS AND WEAKNESSES OF PHOTOGRAPHY TECHNIQUES

	Strengths	Weaknesses	Common Transportation Applications
Photography Techniques	• Non-intrusive • Tried and true • Decreases safety risk for surveyors • Aerial or terrestrial • Can cover large areas • Easy to interpret	• Mobilization may be difficult (aerial) • Line-of-sight creates occlusions • Technical staff may be required	• Aerial mapping • Existing condition evaluation • Virtual reality environments • Asset management • DTM creation

Close-Range Photogrammetry

The New Mexico DOT found beneficial results in a pilot study involving close-range digital photogrammetry for remote bridge inspections and 3D modeling of historic bridges. The cost for this work typically is competitive with that of other methods (Jáuregui et al. 2006b).

Traffic accident reconstruction and investigation using photogrammetry was researched by the Virginia DOT. It is estimated that every minute an accident blocks a roadway can be equated to five minutes of total delay for motorists. For this reason, it is useful to clear the roadway of traffic incidents as quickly as possible. Key findings were that purchasing photogrammetric units is less costly and alleviates the burden of getting total station units to crash scenes in a timely manner. However, some transportation agencies have already invested in total station units and training. In that case, the benefits of photogrammetry are reduced. This report does not find photogrammetric techniques to be a clear recommendation over current total station methods. Further research was recommended for both methods in either mock or real crash scenes (Arnold 2007).

Bridge gusset plate connections were modeled using photogrammetric techniques and checked for validity in a study done for the Oregon DOT. This was done for the geometric makeup of gusset plates, rather than distress values. Reasons for this validation were mostly to increase the potential of photographic inspections, decreasing the field exposure for inspectors (Higgens and Nguyen 2009). Further work has gone into developing bridge gusset plate modeling. When obstructions exist between the photographer and the gusset plate, fisheye lenses are used to see the entire connection. This further work includes step-by-step instructions to convert fisheye images to perspective ones. In addition, this report provides instructions for stitching these photos together and then rectifying them as described in the aforementioned study. This work is completed by an interactive computer program (Turan and Higgens 2011).

REMOTE SENSING/SATELLITE IMAGERY

In remote sensing, data or information about an object are obtained without physical contact. Both passive (detect natural radiation) and active (emit energy) sensors are used. This section focuses on satellite imagery, which is the form of remote sensing most commonly used by transportation agencies. However, it is important to recognize that the tools in remote sensing are much broader than just imagery. For example, technologies such as hyperspectral imaging enable information to be obtained throughout the electromagnetic spectrum in addition to the visible. Others, such as LIDAR, GNSS, and GPR, will be discussed in other sections.

Examples of passive remote sensing technologies include:

- Photography
- Infrared
- Radiometers.

Examples of active remote sensing technologies include:

- RADAR (radio detection and ranging)
- InSAR, IfSAR
- LIDAR
- Radiometers.

Some systems, such as sound navigation and ranging (SONAR), are available as both active and passive sensors.

Satellite imagery is a common geospatial technology and is available to the general public. This technology uses sensors mounted on satellites that are capable of recording calibrated images with spatial, spectral, temporal, and/or radiometric attributes. Satellite orbits commonly used are:

- Polar, or near-polar orbits, which pass over both north and south poles in roughly a 90-minute orbit, so short-term change detection can be monitored.
- Sun-synchronized orbits, positioned so that the amount of sunlight needed for the satellite imaging is optimized (e.g., earth images need light, whereas radiation level imaging works best in darkness).
- Geo-synchronous orbits, which rotate at the same rate as the earth while maintaining their fixed position above it (Khorram et al. 2012).

Sources of imagery include governmental agencies as well as commercial service providers. Some of these images can be found online from National Oceanic and Atmospheric Administration (NOAA) Satellite and Information Service, U.S. Geological Survey (USGS) National Map Viewer, USGS Earth Explorer, NASA Landsat, Spot, GeoEye, TerraServer, National Geospatial-Intelligence Agency (NGA), and NASA World Wind.

Strengths/Weaknesses

Remote sensing using satellite imagery allows nonintrusive, geospatial data collection. These data sets are widely available to the public at resolutions ranging from 30 meters from NASA Landsat, which is free, to proprietary image sets with decimeter resolution (e.g., GeoEye). High-resolution images, such as those available from GeoEye, can be expensive to acquire and mosiac for a large project site (e.g., transportation corridor). Satellite imagery is used in numerous transportation projects as an underlayment.

Strengths and weaknesses of this technology are summarized in Table 13.

TABLE 13
STRENGTHS AND WEAKNESSES OF REMOTE SENSING AND SATELLITE IMAGERY

	Strengths	Weaknesses	Common Transportation Applications
Remote Sensing / Satellite Imagery	• Non-intrusive • Widely available • Numerous publicly available data sources • Large coverage area • Different resolutions available (spatial, temporal, spectral, and radiometric)	• Typically only low resolution data available for no-cost • High resolution images expensive • Difficult to task the satellite to a specific area from its orbit • Issues with cloud cover	• Traffic visualization • Weather monitoring • Disaster monitoring • Large-scale project analysis • Visualization underlay

Current Uses of Satellite Imagery in Transportation

Currently, satellite imagery provides the background for numerous map applications. Several states provide general or state-specific satellite image links, connecting the viewer directly to these websites. A few examples are Colorado, Texas, Washington, and Maine. Online mapping services were cited in the DOT questionnaire (chapter two) as integrated into more than 60% of state DOT information sharing. This technology allows transportation agencies to combine Earth image backgrounds with interactive GIS environments. These GIS layers quickly answer queries from state officials and the general public alike. Some examples include land boundaries; crash statistics; current, planned, and completed building projects; weather; traffic; utilities; topography; railroads; and zoning.

Background Imagery

Caltrans took advantage of federal tax incentives through the Clean Renewable Energy Bonds (CREB) by constructing photovoltaic (PV) panels on several of their existing facilities. Satellite imagery helped expedite the process of determining which of these sites would produce the maximum benefit for this technology. Caltrans learned of this federal tax incentive only a few weeks before the application deadline, but with the aid of satellite imagery and as-built construction plans, the DOT was able to complete the application and obtain funding. Current with the date of this publication, 54 of the 70 sites have been constructed and are delivering power into the energy grid (Caltrans 2011).

Caltrans cites satellite imagery in Chapter 13, Photogrammetric Surveys, of their survey manual as the base map for planning photogrammetric surveys, as well as being acceptable for public displays and nonengineering applications. The Indiana DOT also uses satellite images as a base map for use in terrestrial LIDAR mapping (Bethel et al. 2005).

Direct Analysis Studies

The Virginia DOT used satellite images to aid in the investigation of land development adjacent to the commonwealth's 5,700-mile Statewide Mobility System, specifically multimodal transportation facilities. Combining more than 40 GIS layers and numerous expert opinions, this study aimed to determine the most significant needs of risk management. Satellite imagery helped with the macro-scale analysis of large corridors, especially historical land use and multimodal access points. Researchers cited poor image quality (30-meter resolution) and difficulties providing seamless interaction of their developed software with satellite images that did not follow these corridors, as difficulties of using this remote sensing technology (Lambert et al. 2011).

The Washington DOT evaluated several satellite imagery databases to determine roadway and total impervious surface areas for the state's infrastructure. To determine the road impervious surface area (RISA) and the total impervious surface area (TISA), researchers at the University of Washington used satellite imagery databases from Landsat and Système Pour l'Observation de la Terre (SPOT). They concluded that the free Landsat imagery (30-meter spatial resolution) performed as well or better than the higher-resolution (10-meter), for-purchase SPOT imagery. The largest amount of time in this process was spent in on-screen digitizing of these images for accurate feature extraction. Alternatively, proprietary feature extraction software was explored, with promising results. A completely autonomous extraction was not attainable at the time of publication of this Washington DOT report. One noteworthy conclusion was that the increased spatial resolution provided by the SPOT imagery was deemed not worth the monetary investment owing to the large overall scale needed for the total project area as well as the relatively small regional scale needed for accurate feature extraction (Alberti et al. 2006).

Monitoring traffic counts using satellite imagery has been an area investigated in Ohio. In 1998, Ohio started a research project to incorporate satellite imagery into traffic monitoring analysis. It was determined that 1-meter spatial resolution was needed to accurately detect all sizes of vehicles (McCord et al. 1998). This research was followed with a report to assess the feasibility of conducting annual average daily traffic (AADT) traffic counts using satellite imagery. Empirically based methods were compared from satellite, air-based, and ground traffic counts. It was determined that satellite or air-based images of the necessary spatial resolution would give accurate results but not be cost-effective at the time of print of this report (McCord et al. 2003).

Since the Ohio reports, automatic vehicle detection algorithms have been developed to further this area of analysis. It has been determined that satellite-imaging–based methods can offer a beneficial supplement to ground traffic counts. The researchers noted several limitations to this developed software, including time resolution limitations caused by the use of a single snapshot image, shadow effects, erroneously classified vehicles caused by poor lighting contrast or vegetation cover, noisy images, and a general underestimate of vehicle counts. They have deemed this work as an area worthy of expansion and offer several resources to the already completed reference materials. However, several of these resources are fixed-wing–based approaches (Larsen et al. 2009).

Another use of a satellite imagery data set was presented by the Nevada DOT, which used satellite images for mapping and planning of ecosystems adjacent to the state's highways. The goal of this research was to develop specifications for vegetation remediation. This report shows a specific benefit of mashing together GIS layers with satellite imagery to create analysis tools for planning and remediation (Tueller et al. 2002).

LIGHT DETECTION AND RANGING

LIDAR is quickly becoming an important tool for collecting geospatial data for transportation projects. LIDAR units send out a swath of light pulses (typically near-infrared) and measure the time of flight and intensity level of those beams as they are returned to the unit, creating a dense, 3D spatial data set called a point cloud. There are several methods of data collection included in this report: static terrestrial laser scanning (STLS), airborne laser scanning (ALS), helicopter laser scanning (HLS), and mobile laser scanning (MLS). The recently published ASPRS Manual of Airborne topographic LIDAR provides a detailed overview of airborne LIDAR technology and applications.

STLS systems are nonmoving, tripod-mounted scanners, similar to traditional total stations. ALS refers to fixed-wing aircraft platforms, whereas MLS systems are mounted to vehicles that travel our nation's roadways, off road, rail systems, or in boats. Many of these systems have integrated cameras and other components. The main difference between these systems is that STLS does not use an IMU, whereas any moving platform typically will include an IMU and GNSS receiver to obtain the vehicle's positioning and trajectory information.

Photographic and video recording obtained simultaneously with laser scanning provides greater detail than does laser scanning alone (Toth 2009). The primary purpose of

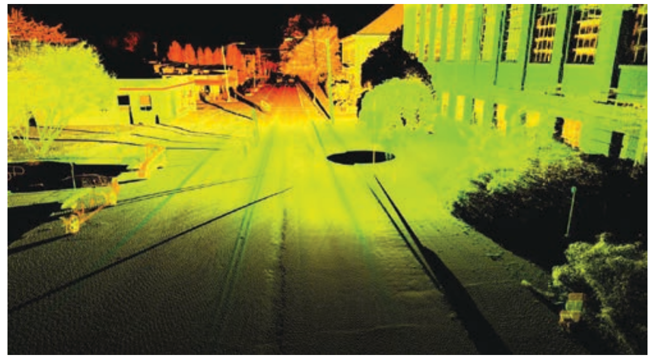

FIGURE 32 Terrestrial laser scan point cloud colored by intensity values.

this equipment is to color individual scan points in the point cloud to the representative real world color. This is done by mapping red, green, and blue (RGB) color values to the geo-referenced point location. This point coloring can make a highly dense point cloud appear as if it were a photograph (see Figure 32). In addition, a visual record provided by this equipment can assist users in determining abnormalities in the scan data. This imagery can be used by itself as a video log without the scan data, if needed. McCarthy et al. (2008) discuss advantages to using combined LIDAR and photographic information for transportation applications, including improved measurements, classifications, workflows, quality control checks, and usefulness. The scan data was particularly important for measurements on large objects such as bridges and embankments, whereas the photographs were most helpful for smaller objects.

LIDAR provides a measurement of the return signal strength, intensity. This measurement can be useful in distinguishing between material types (e.g., distinguishing painted stripes from pavement, damaged sections). Exploitation of intensity information as well as RGB values mapped to point clouds is still at its infancy and is used in conjunction with geometric information for development of automatic and semi-automatic feature extraction processes. Toth et al. (2008) used intensity values to distinguish pavement markings for QA/QC of LIDAR data. Recent advances in GNSS and IMU components enable centimeter-level accuracies in both horizontal and vertical dimensions for the higher-end systems. Lower-grade systems are available with submeter accuracies. With geo-referenced data maintaining high accuracies over large spatial extents, LIDAR can be a robust alternative to traditional survey methods. In addition, combining LIDAR with technologies such as high-resolution photography, GPR, machine control and guidance, and UAVs provides significant efficiency improvements for transportation applications. For example, the use of digital images adds a significant visualization benefit by mapping colors to point clouds.

Although LIDAR data can be developed into traditional DTM, CAD, or GIS deliverables, more packages are supporting point clouds. Two major formats exist for data exchange between packages. ASPRS has developed the LAS format (current version 1.4), which is the most commonly used format for airborne laser scanning. This format has been integrated into several software packages. The ASTM E57 subcommittee recently developed an additional format E57 for 3D imaging systems. This format has additional benefits, including advanced, integrated image support and internal data structure support (Huber 2011). Integration for the E57 format in software is limited; however, support is growing rapidly.

The "LIDAR manual" released by ASPRS in fall 2012 provides a valuable resource discussing details of LIDAR systems and a variety of applications.

Strengths/Weaknesses

LIDAR has shown promise as a leading surveying and mapping technology. As a new technology, several challenges remain, but these are active areas of research and development. Table 14 summarizes strengths and weaknesses of LIDAR.

Data Sharing

LIDAR data can be used to support many applications, including planning, design, asset management, construction, maintenance, and inspection. Thus, significant cost savings have been achieved by sharing data between divisions within an organization, reducing the need for multiple data collection efforts.

LIDAR data can also be acquired and shared between agencies. For example, the Oregon LIDAR consortium (http://www.oregongeology.org/sub/projects/olc/default.htm) coordinates LIDAR acquisition among several state and federal agencies pooling resources to reduce acquisition costs. This also helps ensure that experts within the consortium can perform quality control on the data, rather than each agency needing its own LIDAR expert. Other states and regions with LIDAR consortiums include Idaho, Alaska, South Carolina, and the Puget Sound.

Similar LIDAR pooled resource projects have been undertaken by several county agencies in Washington state (e.g., Trojak 2011) for transportation corridors in the Northeast and Puget Sound (e.g., Lidar 2012; Puget 2012), and in a geotechnical analysis by Kemeney et al. (n.d.) that is discussed in the ensuing chapter. Projects such as these employ either front-end pooled resource methods or buy up/in options after the data have been collected.

Data Resolution

LIDAR has the capability to gather large quantities of 3D geospatial information quickly, which can be seen as both a strength and a weakness. The volume of data produced in one acquisition run reduces the need for return visits. In addition, compared with sparse cross sections acquired through traditional techniques, LIDAR provides a 3D virtual world of the site of interest, which can document variations across the site with detail. The high data density provides personnel in the transportation agency with a much better understanding of the field conditions.

Managing and storing the extremely large data sets that result for laser scanning can be a challenge. The software industry has not been able to keep pace with the rapid developments in laser scanner data collection rates. This is a major issue holding back the true integration of this technology into transportation workflows. Processing often requires use of multiple software packages. It should be noted that knowledgeable technical staff, increased processing time, and new software may all be required to integrate LIDAR data into transportation workflows.

Data Coverage

One drawback to LIDAR and all line-of-sight techniques is the occlusions (data gaps) that are created when the laser beam is blocked by traffic or other obstacles. However, this can be minimized with good planning.

TABLE 14
SUMMARY OF LIDAR STRENGTHS AND WEAKNESSES

	Strengths	Weaknesses	Common Transportation Applications
LIDAR	• Survey grade measurements • High resolution capabilities • Intensity measurements • Multiple end uses and opportunities to share data • Increased safety for surveyors • Reduced number of field visits (collect once, use many times)	• Expensive up-front cost • Data can be cumbersome • Technical staff may be required • Mobilization may be difficult • Line-of-sight creates occlusions • Points require processing to be classified, which is generally a semi-automatic process.	• Asset management • Pavement analysis • Bridge analysis • Geotechnical analysis • Construction applications • Design aid

Sampling intervals for LIDAR are also not uniform. The resolution will degrade with distance from the scanner. However, processing techniques can enable the data to be filtered to produce a model with uniform sampling (e.g., a grid), if desired.

One advantage of LIDAR data over other techniques is the ability to "penetrate" vegetation cover through multiple returns of a single laser pulse. Portions of the laser beam can find their way to the ground. However, there are limitations, including degraded accuracy and resolution in comparison to results in open terrain.

Data Quality

The precision and accuracy of LIDAR point clouds can be comparable to traditional surveying methods. Although a traditional survey instrument can obtain higher accuracy (±2 mm) for a single point, static LIDAR obtains several orders of magnitude more points at slightly lower accuracies (3 to 6 mm). The additional information enables topography and other features to be modeled with improved accuracy over traditional techniques. However, many postprocessing techniques are employed for these accuracy levels, particularly in mobile systems.

Quantifying comparisons of the different LIDAR systems [ALS, STLS, mobile terrestrial laser scanning (MTLS)] with photogrammetry and traditional survey methods was the main objective for the Missouri DOT in a 2010 study. Table 15 summarizes the results of that study and expands them to include additional observations in this synthesis. Recommendations include integrating LIDAR in Missouri DOT projects, developing in-house leaders in associated fields, developing standards and specifications for the use of LIDAR survey data sets, staying current with associated LIDAR software and hardware, and determining when it is appropriate to use each technology type. Currently, two static LIDAR units have been purchased by the Missouri DOT, and their effectiveness will continue to be analyzed. In addition, 85.2 miles of roadway were slated to be mapped with ALS in 2011 with the aid of aerial photography as a quality control measure. These efforts are further explored in chapter seven (Vincent 2010).

Safety and Field Benefits

Acquiring LIDAR data often significantly reduces field time, resulting in safety benefits. Often, terrestrial units can be located on the sides of roads or sidewalks, out of the way of traffic movement. Mobile systems can acquire data at traffic speeds.

Cost Considerations

One issue associated with purchasing a LIDAR system is the high up-front cost ($50,000 to $200,000 for STLS, $300,000 to $1 million for MLS, and more than $1,000,000 for ALS). Thus, it is important that a detailed benefit-to-cost ratio analysis be performed before purchase. Fortunately, the cost of these units is rapidly declining as the demand for this technology increases. In addition, the time savings, improved data quality, and reduced site visits often quickly offset these initial costs.

TABLE 15
LIDAR SYSTEM BENEFITS/LIMITATIONS/BEST USES (MODIFIED FROM VINCENT 2010)

	ALS	MTLS	STLS	Traditional Survey	Aerial Mapping
Benefits	• Day or night data collection • Can cover large area with limited occlusions • High point density • Lower safety risks associated • Reduced field time	• Day or night data collection • Lower safety risks associated • Very high point density • Fast collection rates • Additional sensors can be linked • Reduced field time	• Day or night data collection • Lowered data collection time than traditional surveys • Very high point density • Reduced field time	• Tried and true technology • Traditional standards are based off of typical survey technologies • Less office processing required	• Proven technology
Limitations	• Specialized and costly software required • Lowest density LIDAR point clouds • Difficult to capture steep features	• Specialized and costly software required • Ground perspective limits visualization	• Specialized and costly software required • Ground perspective limits visualization	• Higher cost associated with gathering the same data • Lower point density	• Difficulty capturing steep, vertical features • Lower resolution • Cannot penetrate canopy
Best uses	• Cost-effective for large projects	• Corridor, urban, and tunnel mapping	• High detail "local" surveys	• Engineering surveys for project sites	

The Washington DOT evaluated the integration and efficiency achievable in transportation workflows with LIDAR data. This report started with a pilot study aimed at determining the benefits of LIDAR in transportation workflows, specifically in feature extraction. The next portion reports on the results of seven separate cost-benefit analyses performed on the contracting, renting, or purchasing of Mobile LIDAR systems for mapping or surveying grade data output. This report has several implications, such as QA/QC benefits, roadside asset management investigation, bridge clearance quantification, and ADA feature inventory. It was determined that the purchasing option of a Mobile LIDAR system created the highest cost benefit of these options. Alternatively, if the data collection period for the Washington DOT was increased to four years rather than two and utilization of the scanner was low, renting and operating a mobile scanning system would be considered. Items such as intangible benefits and the limited availability of mobile scanning systems for rent would be considered in that instance (Yen et al. 2011).

Current Uses of LIDAR in Transportation

Currently, as shown in chapter two, LIDAR has been or is being integrated into several transportation agencies' workflows. Many other agencies are interested in these results to aid in their geospatial decisions. Care should be taken that the proper approach be used for each project. The precision, usefulness, and cost of LIDAR have been areas of interest in virtually all the studies examined in this report.

A subchapter of the recently published ASPRS Manual of Airborne Topographic LIDAR provides an overview of a variety of applications for the use of LIDAR technology for transportation applications from highway survey and bridge clearances to construction and pavement management. In addition, a discussion of considerations for use of LIDAR technology in transportation operations is provided, including traffic, environmental conditions, scanning geometry, minimal guidelines, and varying accuracy and resolution needs.

Williams (2012) provides a detailed description of MLS components, workflows, current and emerging applications of Mobile LIDAR for transportation, data quality control, current challenges, guidelines, and best practices. Applications discussed in the literature review of this thesis include project planning, development, construction, operations, maintenance, safety, research, tourism, and asset management.

Wisconsin DOT previously funded a synthesis on LIDAR applications in transportation agencies, which can be a helpful starting point. The synthesis contains abstracts or short descriptions of more than 20 different technical reports, presentations, state surveys, and upcoming transportation projects. In most cases, hyperlinks direct the reader to these works (CTC & Associates 2010).

Feature Extraction

Effective extracting of LIDAR feature data currently requires highly trained technicians. This has proved to be a limitation of LIDAR use. Soni et al. (2011) have evaluated several software packages (e.g., Innovmetric PolyWorks, Leica Cyclone, MicroSurvey PointCloud CAD, Trimble Realworks Survey, and VG4D) for integration into Caltrans LIDAR workflows. They determined that VG4D was the most robust software, and a step-by-step workflow, including importing, viewing, and extracting LIDAR data, is the main deliverable of this research.

McQuat (2011) discusses several different structures (signs, facades, bays, automobiles, curbs, and so forth) and how they can be automatically detected within a point cloud. McQuat also provides insight on how these structures can be converted to useful shapes for use in a GIS.

Asset management using extracted features from a MLS system for the Washington State DOT is an important topic and is covered in chapter six (Trojak 2011).

Ground Control for LIDAR

Establishing ground control is essential for accurate data extraction. Historically, accurate elevations were the most important QC measure of ALS. However, with the need for engineering grade transportation corridor mapping, it has become increasingly important to have horizontal accuracies that can meet tight tolerances. This is a topic that has been heavily researched by the Ohio DOT for airborne LIDAR. Csanyi and Toth (2007) explored the ideal size, shape, and placement of moveable ground targets. It was determined that rotation invariant (circular) targets, located off the ground to distinguish elevation, obtained the most accurate results. Further, painting targets with reflective coating optimized the target extraction.

Using these large, moveable reflective targets to gain ground control is neither feasible nor cost-effective for transportation projects. Therefore, an alternative method of feature extraction using pavement striping was explored by Toth et al. (2008). This report outlines the general process of using a combination of intensity-based data extraction, piecewise weighted least-squares curve fitting for each GNSS and LIDAR point obtained along a stripe, and an iterative closest point (ICP) method to match and compare the GNSS and LIDAR curves. The results from this study showed an encouraging method to extract spatial components with horizontal and vertical accuracies on the same order. Particularly, the ICP algorithm showed noteworthy curve-matching results.

The authors followed up this research concept with another report for using reflective ground markings not only for horizontal accuracy QC, but also for splicing ALS strips. Results from this ongoing study determined that with a combination of careful flight planning, adequate processing, and QA/QC methods, results could be obtained with 1–2 cm and 5 cm accuracies in the vertical and horizontal, respectively (Toth and Brzezinska 2009).

Previous to these Ohio DOT reports, a study performed by researchers at Purdue University evaluated ALS for transportation corridor mapping. Results showed that ALS gave accurate mapping grade results. It was determined that ground control techniques would be needed to obtain engineering grade surveys (Bethel et al. 2006). This is consistent with results from the Ohio DOT, and the research has further confirmed these accurate feature extraction needs.

Construction Quality Control

In Alaska, STLS is being used for QC monitoring for the construction of the Trans America Pipeline System (TAPS), an 800-mile pipeline carrying oil from northern Alaska to Valdez. Although this project has always been privately funded, it has similar QC aspects that may be common to transportation projects. A private company implemented a plan to migrate the current traditional surveying and optical monitoring techniques in place for TAPS to a STLS- and GNSS-based system. This monitoring of TAPS is done once a year, mainly on the above-ground portion, which makes up about half of the pipeline's length. These efforts are in place to analyze pipe structural integrity, vertical support member's orientation, and geotechnical conditions, and to compare newly acquired data with historical records (Carber 2006).

Pavement Analysis

The South Carolina DOT discusses operational consideration for static LIDAR for highway construction, including comparisons of asphalt and concrete surfaces. The DOT also compares static scan results to GPS and total station measurements. Finally, this study evaluated the various configurations of target placement on accuracy (Hong Johnson and Johnson 2012).

The use of MLS to produce digital terrain models of pavement surfaces was evaluated by Yen et al. (2010) for Caltrans. Although this study was directed at determining the feasibility of a specific use of mobile mapping, several concurrent uses were noted. The determination was that Mobile LIDAR had difficulty achieving the Caltrans-specified, 10-mm vertical accuracy at a 95% confidence level (Caltrans 2011).

Bridge Analysis

The effective modeling of bridges can be a useful tool for transportation agencies to analyze the structural elements, assess settlement, check for deterioration, and verify dimensions. These can aid in emergency efforts or periodic bridge inspections. The Utah DOT employed private consultants to provide an accurate, 3D, as-built model with a series of LIDAR point clouds. They used a combination of terrestrial laser scanning (TLS) and high-resolution camera for the data collection (DeMann 2010). The Indiana DOT went a similar route with LIDAR to model two different bridges on I-70. Geo-referencing techniques with GPS and IMU systems were explored, as well as integration of point cloud data into a GIS (Bethel et al. 2005).

The South Carolina DOT undertook a study to determine the accuracy of bridge under clearance measurements. They evaluated two variables: temperature variation and traffic flow over the bridge in question. Determinations were that TLS is a precise method of gathering bridge under clearance measurements and temperature, and live traffic had little impact on these measurements (Watson et al. 2011).

Geotechnical Investigations

A pooled fund study conducted recently evaluated the use of LIDAR to map geotechnical conditions of unstable slopes, including rock mass characterization, surficial slope stability, rockfall analyses, and displacement monitoring. The report (soon to be released) provides an overview of ground-based LIDAR and processing software, discusses how LIDAR can be integrated into geotechnical studies, and includes case studies in the states of Arizona, California, Colorado (two sites), New Hampshire, New York, Pennsylvania, Tennessee, and Texas. The authors also discuss best practices and procedures for acquiring data that are reliable for geotechnical analyses (Kemeny et al. unpublished).

Before the results of this pooled study, preliminary investigations were completed, often individually by state. Turner (2006) discusses processing procedures to use TLS to evaluate the stability of rocky slopes and how scan data can be integrated into geotechnical and geologic investigations. Kemeny and Turner (2008) evaluated the use of laser scanning for highway rock slope stability analysis and found that ground-based LIDAR offered several advantages, including safety, accuracy, access, and analysis speed, compared with traditional techniques. Kemeny et al. (2008) used LIDAR to evaluate several rockfall sites near highways in Utah and Colorado. Lato et al. (2009) demonstrate how rock fall hazards along transportation corridors can be monitored using MLS on both railway- and roadway-based systems. In both situations, MLS provided increased efficiency, safety, and the ability to investigate hazards. Olsen et al. (2012) developed an in situ change analysis algorithm using static LIDAR for the Oregon DOT, enabling one to process and analyze data directly in the field to determine if movements have occurred on slopes or structures.

A study of early sinkhole detection using ALS was conducted for the Florida DOT. This study did not show ALS was a feasible option for this task. A different conclusion may be reached currently because advances in ALS technology have occurred since the publication date of that report (Bloomquist et al. 2005).

Construction

The Illinois DOT evaluated the accuracy of LIDAR measurements for earthwork removal, pavement surface analysis, evaluation of damaged bridges, and as an as-built design aid. It was determined that LIDAR was more efficient and provided accurate earth volume calculations compared with traditional survey techniques. The results of this study and resulting software are being integrated into the Illinois DOT workflows (Slattery and Slattery 2010).

LIDARgrammetry

LIDARgrammetry is the process of creating stereo pairs from LIDAR intensity images for input into photogrammetric analysis for mapping. Resulting digital elevation (DEM) and other models are light weight compared with LIDAR data, but retain the same accuracy level as the LIDAR data sets. Benefits of LIDARgrammetry are the ability to use well-developed photogrammetric software, night collection capabilities, and the improved ability to discern ground points (particularly in vegetated areas) and breaklines compared with traditional photogrammetry (Ward 2006). Details for this process can be found in the ASPRS DEM user's manual, 2nd Edition (Maune 2007).

GLOBAL NAVIGATION SATELLITE SYSTEM

A GNSS consists of a constellation of navigation satellites capable of producing precise geospatial positioning. There are currently four GNSS platforms in use or in planning phases. These systems and their host nations, in order of becoming operational, are: United States (GPS), Russia (GLONASS), China (Compass), and the European Union (Galileo). The system components are listed in Table 16.

First developed in the late 1970s by the U.S. military, GPS (and now expanded to GNSS) has progressed from single to dual frequency, and from postprocessing to real-time kinematic (RTK). The Receiver Independent Exchange (RINEX) format enables transfer of GNSS data between any receiver and software package.

Varying grades of accuracy levels can be achieved with GNSS, depending on the hardware, the use and location of base (reference) stations, and time and duration of occupation. Hand-held units are prevalent for rapid mapping and navigation. These systems can be beneficial for obtaining a quick location for tasks such as asset management, where precise positioning is not required. Mapping grade GNSS systems typically have meter level accuracy, suitable for lower level resolution maps. However, newer systems can be post-processed to obtain decimeter level accuracies.

The highest GNSS accuracy comes with surveying grade specifications through static, rapid static, or RTK techniques. These systems are capable of returning measurements with centimeter or even millimeter precision. These are used in construction projects, height modernization, and in situ monitoring. Static and rapid static GNSS systems are similar, with the only difference being the time of occupation (15 min to 2 hours for rapid static, more than 4 hours for static). Static and rapid static observations are postprocessed against simultaneously collected data at CORS.

In the United States, the Online Positioning User Service (OPUS) is an automated service offered by NOAA to process static and rapid static observations. Soler et al. (2011) outlines the OPUS suite of services in specific, detailed chapters. These chapters define such items as applications, CORS criteria, numerous satellite technicalities, obtaining solutions, constraints, accuracy assessments, reliability, and best methods, among other specifics. Recently, the NGS developed OPUS projects, which now perform GNSS baseline processing and control network adjustments from static and rapid static GNSS data.

TABLE 16
GNSS SYSTEM COMPONENTS (MODIFIED FROM SATELLITE NAVIGATION 2012)

System	GPS	GLONASS	Compass	Galileo
Political Entity	United States	Russia	China	European Union
Number of Satellites	At least 24	30	30	24
Operational Status	Fully operational	24 satellites operational	10 satellites operational	2 test bed satellites in orbit
		6 in preparation	25 additional satellites planned	22 operational satellites planned

Conversely, RTK systems use a base station and one or more rovers. Base receivers obtain signals from the satellites carrier signal, rectify these signals to gain geospatial position, then broadcast the corrections to the rovers through ultrahigh frequency, or some other type of frequency. This reduces occupation times to seconds for centimeter-level data. However, RTK GNSS is more susceptible to multipath and positional dilution of precision problems resulting from poor satellite geometry. In cases where a radio link cannot be maintained, but a base station is located nearby, postprocessed kinematic GPS data can be obtained.

Many state DOTs are involved with the creation, maintenance, and use of real-time networks or virtual reference stations. With these networks, a user does not need to establish a base station. A user can obtain corrections from the network using an Internet connection on a cell phone. States that have dedicated networks are California, Oregon, Ohio, Iowa, Florida, Maine, New York, Missouri, Minnesota, Illinois, Indiana, Colorado, and possibly others. In some cases (e.g., California), these networks are run by private entities. In other cases, DOTs manage these networks (e.g., Oregon). Other states currently developing GNSS tools such as real-time networks and height modernization systems are Wisconsin, Ohio (see current uses of GNSS in DOTs later in this chapter), New Jersey, and Alabama. These real-time systems give states more flexibility by limiting the amount of direct interaction with satellite constellations; cutting down on the amount of hardware, setup, and completion time; and providing overall ease of surveys using GNSS.

Some applications of GNSS that currently benefit or may benefit DOTs in the future include, but are not limited to, asset management, GIS data layer integrations, video logging, site design, and construction applications, such as machine control and automation. GNSS measurements are often integrated with other technologies and are discussed in several sections throughout this report. For example, RTK GNSS is the primary positioning technology at work in machine control and automation; the topic is covered in the following section.

In an effort to create the most informed users of the National Spatial Reference System, NOAA's NGS offers a center providing a variety of training needs. This facility is available to host training workshops, lectures, and discussion groups and offers classes related to RTK, OPUS, digital leveling, vertical datums, and more (Corbin Training Center 2012).

ASCE published a book on GNSS technology in 2011 to inform civil engineering project managers about general principles, accuracy, and low-cost versus high-precision systems. The book also presents implementation considerations as well as specific civil engineering application examples, including machine control and construction automation (Ogaja 2011).

Strengths/Weaknesses

GPS has become a mainstream geospatial technology with new receivers enabling use of GNSS. Significant research and development has enabled GNSS measurements to produce survey grade results. Achieving accurate positioning in real time or through quick, simple, postprocessed methods is a strength of this technology, enabling surveys to be completed with speed. GNSS surveys are particularly important for surveys over large extents (several miles) where error propagation would be significant for most traditional techniques.

GNSS is limited by the quality and quantity of the satellite constellation. There are moderate, up-front investments required to acquire GNSS systems. An upside to this cost is that this system, similar to LIDAR data, can have multiple end uses, typically involving a GIS.

Table 17 summarizes various strengths and weaknesses associated with GNSS technology. As this technology continues to develop, the benefit-to-cost ratio is improving. GNSS receivers have varying degrees of accuracy (and costs), enabling transportation agencies to have different systems in place for varying uses. However, in such a case, one needs to document the receiver used and observation quality to ensure that future users of the data understand its limitations. New GNSS technological advancements continually occur. Table 18 presents error sources for GNSS. It is important to note that GNSS requires a clear view of the

TABLE 17
GNSS STRENGTHS AND WEAKNESSES

	Strengths	Weaknesses	Common Transportation Applications
GNSS	• Survey grade measurements • Real-time systems • Multiple end uses • Wide range of systems and accuracy for varying uses and budgets • Data are linked into global networks	• Limited by satellite constellation and configuration • Moderately expensive cost • Static systems require post-processing • Real-time systems may require extra personnel to watch base station	• Provides the input data link for GIS data • Survey control • Asset management • Emergency relief aid • Machine control

TABLE 18
COMMON GNSS ERROR SOURCES, CATEGORIZED BY SOURCE

Spatially Correctable	Satellite	Propagation	Receiver	Location	Operator
Yes	Clock Selective availability Ephemeris	Ionosphere Troposphere			
No			Antenna phase center Noise	Multipath Cycle slips	Setup (e.g., centering, level) Antenna height Operational

Spatially related errors can be corrected through differential GPS techniques (modified from Ron Singh, Oregon DOT).

sky, and quality degrades when trees, buildings, and such obstruct this view.

Current Uses of GNSS in Transportation

NCHRP Synthesis 301 discusses the integration of GPS into GIS, including common problems and solutions. The synthesis provides background on mapping standards and how to minimize map-matching problems from GPS usage. A background on GPS technology is provided, including mobile GPS.

The New York State DOT developed a real-time trafficking integration system involving GPS. This system employs smart highway cones (Sheckler 2010) equipped with GPS, cameras, and speed sensors as the main geo-referencing tool. The end users of this spatial data work through an interactive, on-screen program termed a graphical user interface (GUI) to view this in a GIS environment. Vehicle data are broadcast from trucks, the owners of which are paid to participate in this program. Traffic metrics and real-time data are distributed as the end products of this project (Sheckler 2009).

GNSS data provide heights above an ellipsoid model of the earth. However, often sea level elevations are needed. A geoid model obtained through precise leveling, satellite, and land-based gravimetric measurements enables a method to convert between ellipsoid heights and orthometric heights (elevation above a datum, typically sea level). The Ohio DOT studied local accuracies of the Geoid 09 version in place currently by the NGS. Their three main concerns with the Geoid 09 system were as follows: performance of NGS hybrid geoids in Ohio, gravimetric geoid development, and random error influence on gravimetric geoid solution. The conclusions were that Geoid 09 performed better than the 03 version, but a vertical error of ±5 cm was still observed throughout. Ohio will work to relevel current benchmarks to develop a hybrid geoid model and communicate this effort to the NGS (Grejner-Brzezinska and Edwards 2010). The NGS is currently in the process of developing a full gravimetric geoid model for release in 2022. The most current model available to convert geoid heights is Geoid 12, which became available in July 2012 ("National Geodetic Survey" 2012).

Current research is under way at Purdue University for the Indiana coordinate reference system (INCORS). Scale distortion errors associated with the current INCORS system have been identified, and this project is aimed at investigating the feasibility of reducing those errors. The distribution of scale distortion of this system varies by area, making an applied scale reduction factor (ground-to-grid distance) vary along with it. The two proposed solutions to alleviate this that will be analyzed in this research, are a reduction in the size of the grid area and integrating a more accurate mapping surface. This project began in early 2011, and the results have not been publicly published at this time (Van Gelder and Bethel unpublished).

The Louisiana Department of Transportation and Development (DOTD) recently (2012) developed a GPS technology management plan for operations involving recreational and professional grade GPS equipment. These two technologies lie between survey grade and hand-held devices. Hand-held device standard practices at DOTD were outlined and implemented in a system done by Agile Assets in 2010. In its literature review, DOTD found the most applicable references for them were from the Texas Commission on Environmental Quality. The functions of GPS evaluated in this study include latitude and longitude values for billboard signs, borrow pits, and wells for recreation devices. In terms of professional grade devices, determining roadway assets, levee inspections, and archaeological sites were some of the key functions analyzed. Findings from this study showed that the recreational grade units are not precise enough to be used in geospatial analysis, and mapping grade units could replace these. When upgrading these units, work should be done to develop a well-laid-out data management plan, organizational approach, and training and maintenance that will ensure that the devices are being used to the fullest extent of their capabilities (Barnett et al. 2012).

THREE-DIMENSIONAL MODEL-BASED DESIGN

Historically, highway design has been done in a 2D drawing environment, first manual and then digital, or CAD. This 2D approach involved a number of sequential steps that resulted in plan/profile drawings and cross sections typically at 50-foot intervals. These drawings were the design. The only way to visualize the actual highway or related improvements was for an individual to learn how to "see in 3D." That was part of the training for engineers, surveyors, and contractors.

If the geometric design was modified, all of the drawings had to be updated. This was time consuming and prone to human error. When problems with the plans are identified during construction, it can lead to costly project delays, cost overruns, and litigation.

More recently, through advances in CAD software and desktop computing technology, 3D model-based design has begun to emerge as a powerful alternative to the traditional 2D design process. In this new paradigm, a mathematical data model is defined by the design engineer. This is the source of the design—everything flows from this model, including the output model. This 3D data model is intelligent. It is not just a means of producing 2D plans.

By developing a mathematical data model in 3D, the designer no longer has to imagine what the highway will look like; he or she can see it on the computer screen. This ability to visualize the design generally leads to increases in efficiency, increased flexibility, improved accuracy, and construction cost savings through the ability to optimize the design.

With a mathematical data model, a number of alternative designs can be quickly analyzed by simply adjusting the design parameters. These changes are dynamically made to the model by the software, allowing the engineer to identify problems and optimize the design (Fuls 2005).

With a 3D model, the designer can use clash detection software to check for interference with utilities and structures. Designers can check site distances more accurately and even perform noise studies, but perhaps one of the most important benefits is for public presentations. The 3D model can be used to clearly demonstrate to the public what the proposed project will look like when completed.

In the construction phase, the data model is used to produce the output model. Because this is an automated process, there is little chance for human error to be introduced. If the contractor is using AMG, it is possible to avoid the printing of paper plans entirely. The 3D model can be directly transferred to the earth moving equipment.

On some larger scale projects, the concept of virtual design and construction (VDC) is being introduced to simulate the staging of the construction process over time. Some are referring to this as 4D, where time is added into the analysis. A fifth dimension, cost, can also be included.

The final emerging technology related to 3D model-based design is building information modeling (BIM). The idea is to take the concepts of BIM and apply them to infrastructure projects such as highways. This basically involves attaching a database link to each object in the design model so that it can carry additional intelligence, such as manufacturer, material properties, service date, and the like. With the use of a database, the information is more easily integrated with a GIS.

Strengths/Weaknesses

The use of 3D model-based design offers transportation agencies many advantages, including improved accuracy, the ability to optimize the design, reduced chance of error, and in general the ability to visualize the design. It also provides the opportunity to provide the public with an easy-to-understand concept of the proposed project. On the construction side, the use of 3D models is a perfect fit with AMG, offering the possibility of a "paperless" project.

An accurate 3D data model, when integrated with VDC, 4D/5D, BIM, GIS, and a project life cycle management approach, can become the foundation of an integrated, next-generation asset management system.

One key challenge with this technology is the change in standard operating procedures that occurs. This may prove difficult to achieve with time-proven design workflows already in place. Additionally, this design methodology uses specialized software packages that can be costly. These software packages are continually being improved, requiring ongoing education and training to take advantage of the new functionality.

A summary of these strengths and weaknesses is presented in Table 19.

Current Uses of 3D Model-Based Design in Transportation

Researchers at the University of Arkansas, funded by the U.S.DOT, have developed a 3D environment to analyze pavement roughness, cracking, and rutting. This system incorporates high-resolution sequential images, photogrammetry techniques, and feature extracting algorithms to create a 3D model of the pavement surface. Outputs of this system are the 3D surface model and images for QA/QC (Wang 2011).

The New Mexico DOT has been using a virtual reality workspace to aid in bridge inspections across the state.

TABLE 19
3D MODEL-BASED DESIGN STRENGTHS AND WEAKNESSES AND CURRENT USES

	Strengths	Weaknesses	Common Transportation Applications
3D Model-Based Design	• Accuracy • Efficiency • 3D Visualization • 3D Clash detection • Allows for all team members to develop one integrated model • Analyze in 3D • Support for AMG • VDC • Integrate with 3D laser scanning	• Significant modeling time • Knowledgeable designer required • Expensive software • Software may not support true 3D • Ongoing training	• Design • Existing condition evaluation • Clash detection • Public hearings • Marketing tool • Volumetrics • Safety analysis • AMG • Bridge clearance • Working drawings

They are utilizing high-resolution photography and proprietary software to create this workspace. This has allowed them to conduct routine bridge inspection remotely and help inspectors get familiar with sites before visiting. Hindrances found in this study were mostly view oriented, such as with traffic flow, underneath foliage, and other obstructions (Jáuregui 2006).

MACHINE CONTROL AND AUTOMATION

Machine control and automation can be considered using a machine to fully accomplish or aid in the accomplishment of task completion. Typically, this is accomplished with the aid of RTK GNSS to accurately geo-locate the earth-moving equipment on a site. This technology is a prime example of the transition from 2D to 3D that is taking place in the industry. Incorporating machine control and automation into transportation workflows likely will prove to be a necessity in the next 3 to 5 years. Guidelines and specifications for this technology are being developed through the NCHRP Project 10-77 (White 2013). Some of the leaders pioneering this effort include the California, Kansas, and Oregon DOTs.

Strengths/Weaknesses

Some strengths, weaknesses, and current uses of machine control and automation are presented in Table 20.

Current Uses of Machine Control and Automation in Transportation

The Oregon DOT has developed a forward-looking engineering automation document that outlines a strategy for developing purely digital workflows that do not require paper printing. Oregon recognizes the relevance of automating their engineering efforts in general. A significant portion of this concept is applied to machine control and automation; it is a broad vision that the DOT has applied to the entire organization (Singh 2008).

An analysis of GPS-based AMG on construction projects was conducted by the Mississippi DOT and the University of Southern Mississippi. A final report was issued in September 2010 that outlines a suggested workflow incorporating this technology into Mississippi DOT construction projects. Researchers found literature relevant to machine control and automation at the TRB Annual Conference. This literature consisted of agency specification from the states of California, Colorado, Iowa, New York, and Wisconsin. The Mississippi DOT recognizes the importance of providing workshops for employees to help utilize GPS data in workflows (Hannon 2010).

Rybka (2011) discusses a "design to dozer" demonstration of construction automation, hosted by the Oregon DOT and the PPI Group, depicting how MLS data can be used to create a DTM for machine control and construction automation to

TABLE 20
MACHINE CONTROL AND AUTOMATION STRENGTHS AND WEAKNESSES

	Strengths	Weaknesses	Common Transportation Applications
Machine Control and Automation	• Reduced field time • Reduced field crew • Reduced human-induced errors • Possible seamless integration with design	• High upfront costs • Few experts available • Technology not fully developed • Rapidly changing platforms • Data interoperability • Designers are not familiar with the needs of contractors	• Excavation operations • Snow removal • Grading • Paving

grade a site without ever having to drive stakes. All grading is done entirely through equipment guided by GPS and a base model created from the 3D point cloud. This presents cost savings and time savings, and improves site safety. The entire sample project was done digitally (including the digitally signed plans).

Caltrans developed GPS software that uses a GIS base map to find the centers of roads buried under snow. This software is used on a portable unit that utilizes an in-cab display to help drivers guide their rotary plows through snow-covered mountain passes (Yen et al. 2006). Further work has been done to develop this technology into three differing snowplow systems: rotary machines for springtime road openings, winter snowplow operations, and large rotary-plow machines. Each machine has separate best uses; therefore they were investigated slightly differently in each case. These systems have been integrated into Caltrans workflows along with QA/QC techniques to monitor and enhance workflows (Yen et al. 2009).

A system similar to that of Caltrans' is in place at the Alaska DOT. This technology utilizes RTK GPS, radar, and a GIS infrastructure, complete with road alignment and obstructions, such as guardrails. The interface is mounted inside the cab, with visual, auditory, and touch warnings when obstruction encounters are detected. This project and the previously mentioned Caltrans project are driven by the need to deal with extreme snowfall (Iways 2012; Pittman 2012).

The Iowa DOT is developing a tracking and asset monitoring system for snow removal and salt deicing. This system enables implementation of QA/QC techniques to most effectively utilize the DOT's snow removal and deicing efforts (Abrams 2012). This is part of an ongoing effort by many transportation agencies for increasingly detailed asset management. For more on these topics, see chapter six.

GROUND PENETRATING RADAR

GPR is a technique that enables the user to map subsurface conditions. This technique uses an antenna to record the time of reflection from emitted electromagnetic pulses. The return signals are then analyzed by trained professionals to determine specific layers and underground anomalies. Current work in GPR is automating this processing workflow. Emitted waves are in the UHF/VHF wavelength. GPR is becoming a common technology in the analysis of asphalt degradation analysis and subsequent reclamation projects.

These electromagnetic signals do not travel well through highly electromagnetic strata. Thus, GPR works best in sandy, dry soils and materials such as concrete, granite, limestone, sand, and ice. GPR also has difficulty determining more than two layers of strata. This technology typically is used in contact with or near the surface to be analyzed, but it can be deployed in airborne platforms. GPR can return values in areas with low levels of standing water but does best in areas with less than 3 feet of water depth. GPR can be used to map subsurface conditions in any orientation, so vertical items such as concrete columns can be analyzed for deterioration. This provides the opportunity for transportation agencies to use GPR for structural inspection and analysis. Newer mobile GPR systems allow the collection of road surface data at or near highways speeds.

When used in conjunction with LIDAR and photographic technologies, highly accurate 3D models of subsurface, pavement, and adjacent roadway conditions (signs, barriers, hazards, and so forth) can be gathered and analyzed. In addition, including GNSS and IMU sensors assures these models will be fully geo-referenced.

GPR can be considered a geophysical analysis technique. These types of methods use indirect measurements and physical properties to correlate relationships of subsurface conditions. Two organizations in place to advance this science are the Environmental and Engineering Geophysical Society (EEGS) and The American Society for Nondestructive Testing (NDT). The FHWA has a manual for the "Application of Geophysical Methods to Highway Related Problems" (Wightman et al. 2003). A comprehensive synthesis (*NCHRP Synthesis 357*) was published in 2006, which, in a manner similar to that of this synthesis, uses state-of-practice analysis to indicate if and where transportation agencies are using these types of technologies, with a following documentation of future needs and forward thinking regarding the potentials of geophysical analyses (Sirles 2006). A similar study was published 8 years earlier (Morey 1998).

Strengths/Weaknesses

GPR can be a relatively fast, nonintrusive, easy-access method to gather subsurface data. Some limitations of accuracy with this technology can be standing water, freezing conditions, clay soils, highly permeable surfaces, and salt. Cell phones have also been cited as interfering with the returning waves, thus degrading results. In addition, emission levels from the GPR unit need to be at levels low enough to satisfy current regulations for out-of-band electromagnetic frequencies.

Although some GPR units can detect single layers of composition to significant depths, delineating more than two layers, regardless of depth, has proved to be difficult for GPR units. Newer systems are working to alleviate this problem, however. More developed systems are also now gathering information at varying levels of detail directly relating to the speed of the vehicle, with the fastest nearing highway speeds.

Technical data processing and analysis currently is done by trained professionals able to interpret these data. Significant research has been put into the advancement of this

TABLE 21
GPR STRENGTHS AND WEAKNESSES

	Strengths	Weaknesses	Common Transportation Applications
GPR	• Non-intrusive • Relatively quick • Newer systems are easy to work with • Information gathered at near highway speeds is possible	• Costly systems • Exterior conditions may hinder performance • May require technical staff to analyze data • Regulations require systems to be certified • Does not work with clay soils	• Roadway surface analysis • Subsurface pavement analysis • Bridge pier scour analysis • Utility mapping • Geotechnical subsurface conditions aid

technology to alleviate such hindrances by states including New Hampshire, Ohio, Texas, Maine, and Mississippi. These projects have continually shown progressive results in terms of speed, accuracy, and ease of use gaining and using gathered data. Strengths and weaknesses of GPR are listed in Table 21.

Current Uses of GPR in Transportation

QA/QC

GPR provides a current map of beneath-grade roadway structure and deterioration levels. The Maine DOT used GPR in some asphalt reclamation projects in 2007 to determine the accuracy level of this technology. Although significant variations exist in the depth of layers of roadway, GPR and ground cores were found to be generally consistent (Mallick 2007).

Similar conclusions were drawn in the New Hampshire DOT, which found favorable results when using GPR to analyze concrete cover over reinforcing bar, determining scour under bridge piers, and delineating bridge deck deterioration. When GPR was used to analyze geotechnical conditions, it was found to be a helpful aid but did not take the place of specific borings. The New Hampshire DOT has been investigating GPR for more than a decade and several publications are listed on their website.

Current and planned use of step-frequency (SF) GPR in transportation projects was preceded by Scott et al. (2010). SF GPR uses an increasing series of frequencies to determine subsurface conditions at varying detail levels according to project-specific needs. Research work was undertaken by the FHWA to determine the emission levels of electromagnetic frequencies for electronic interference with other tools. Both bounce-back and penetrating signals were evaluated in this work. The National Telecommunications and Information Administration (NTIA) sets regulations for out-of-band frequency operations, such as those used by GPR (Manual 2010). It was determined that SF GPR, when properly calibrated, meets NTIA requirements for intentional frequency emissions. Some unintentional emissions below 140 MHz may require a waiver to be obtained. This result is particularly important in GPR work surrounding airports. In those cases, planned work needs to be cleared with the FAA and the particular airport.

Direct Analysis Studies

The Ohio DOT investigated the level subsurface detail that can be quantified with GPR. The reasoning for this study was because its asphalt reclamation projects involve rubblizing the surface until particles are 6 in. in their largest dimension. Results were positive, but showed that current techniques are not able to determine the sizes of rubblized particles down to the 6-in. level required (Rajagopal 2011).

A benefit-versus-cost analysis of the use of GPR in pavement rehabilitation design was conducted for the Mississippi DOT. A thorough literature review of more than 60 sources involving GPR was performed. Cited within were AASHTO test standards PP40-00 and the experience of neighboring states Texas, Louisiana, and Florida as sources used for specifications and guidelines (Uddin 2006).

The New York DOT entered into a similar study involving a thorough literature review, implementing a pilot study, and synthesizing the results. In addition to asphalt reclamation evaluation, New York examined underground utility mapping with this technology (Grivas 2006).

Mapping of inductance loops used for vehicular detection at stop lights was the topic of research by the Maryland DOT. An SF mobile GPR unit was used. This work resulted in the successful analysis and optimization of this system (Scott et al. 2011).

One of the main drawbacks of GPR has been that trained personnel are needed to analyze the data. However, current proprietary advances of software interfaces are automating the process. New software also uses powerful layer detection algorithms. Fully automated GPR systems were not found to be available during the Mississippi study, whereas the Maine DOT integrated it just a year later. This confirmed that this software is alleviating one major obstacle and making its way into the mainstream (Uddin 2006; Mallick 2007).

UNMANNED AIRBORNE VEHICLES

UAVs, also known as unmanned aircraft systems (UASs), are airborne vehicles (small planes, helicopters, or hybrids) flying without the aid of an on-board pilot. These are commonly referred to as drones. Typically, hobbyists pilot UAVs remotely with a controller. However, for geospatial usage, UAVs usually employ a predetermined flight path to acquire data such as images. Uses for these images include aeronautics, surveillance, mapping, pollution identification and monitoring, agriculture monitoring, and obstruction identification. Similar to other technologies, new applications are emerging quickly.

UAVs can employ the use of GNSS, multispectral imagery, stereo pairs, or other remote sensing techniques. The LIDAR industry is working to achieve consumer sensors small and light enough to be integrated into UAVs. UAVs can also be used in conjunction with other mapping technologies to provide additional viewpoints on objects of interest.

FAA restrictions currently limit the widespread use of UAVs ("Unmanned Aircraft Systems" 2012). Full clarification of these important guidelines is expected by May 2014, with the potential for significant airspace for UAVs being opened (Schrock 2012).

Six UAV test sites mandated by Congress will be selected by the FAA in December 2012 to ensure this technology is implemented safely. This will aid in the successful integration of UAVs into the nation's airspace by 2015, a requirement set forth by the FAA ("FAA Makes Progress . . ." 2012). It is important to note that no specific money is designated to the confirmed sites; however, the sites will provide a location for the research to be conducted.

The University of Alaska, Fairbanks Geophysical Institute has a testing facility for UAVs called the Poker Flat Research Range and is applying to become one of these FAA-approved testing facilities. The Institute has been awarded $5 million and upward of $47 million in grants from the Alaska legislature (2012) and the Navy (Buxton 2010), respectively.

The University of Minnesota is an example of another site vying for this FAA designation. The university has published three reports that assess and validate flight control, safety applications, and system identification. Another research report published by the university explores the feasibility of a UAV flight research facility. These reports are available at the university's UAV Research Group webpage ("UAV Research Group . . ." 2012).

Others agencies with interest in obtaining this designation are Oregon State University, Ohio University, Oklahoma University, and New Mexico State University (the FAA currently operates one there). Michigan even has a resolution written by its senate in support of this technology.

Strengths/Weaknesses

A key benefit of UAVs is their rapid, low-flying, remote sensing capability. These vehicles allow physical human interaction with the project to be minimized, reducing potential safety risks. If federal airspace were freely accessible, UAVs would be an inexpensive means for aerial remote sensing for small areas and one that requires much fewer logistics.

Airspace restrictions set forth by the FAA are currently the most significant hurdle facing this technology. These guidelines require a pilot-in-command (PIC) as well as an observer. The PIC may be required to hold a current pilot license in some applications. Detailed flight plans, chase vehicles, adequate training, currency (e.g., repeated demonstration of successful take-off and landings), medical training, air traffic control communication, and other specific application requirements are also required before an air-worthiness permit is granted. Currently, federal, state, and local authorities may apply for air-worthiness permits, while commercial permits remain unavailable ("Aviation Safety . . ." 2008). When obtained, these permits are a fixed length of 24 months. A new office, the UAS Integration Office, has been created by the FAA to oversee specific details of guidelines for this emerging technology ("FAA Makes Progress . . ." 2012).

Mapping grade UAVs have moderate up-front costs associated with them. However, small, lightweight sensors can be expensive or may not yet be available. Safety concerns of falling parts, collisions, and interference of federal airspace, mainly near airport facilities, are concerns for UAV operation. It can be noted that, to date, UAVs are not able to directly compete with the accuracy and coverage of traditional photogrammetry. However, comparable results involving mapping less than 4 square miles have been reported (Whitehead 2011).

Strengths and weaknesses of UAVs are summarized in Table 22.

Current Uses of UAVs in Transportation

The New Jersey DOT implemented a plan using UAVs to map and prescriptively remove trees obstructing airport approaches. Because New Jersey is such a small state, space is at a premium, and airports attempt to utilize their runway and takeoff/landing areas as effectively as possible. The New Jersey DOT employed a remote-controlled helicopter, about 5 feet in length equipped with a camera, GPS unit, receiver, and compensation units. It determined that this system was effective at accurately locating trees encroaching on FAA sight distances. Trees could then be located on the ground and removed. It should be noted that FAA permits are required every time a UAV utilizes airspace (Szary 2007).

The Washington State DOT recognizes the potential benefits of using UAVs in real-time roadway monitoring for both hazards and traffic parameters. These surveillance and monitor-

TABLE 22
STRENGTHS AND WEAKNESSES OF UAVs

	Strengths	Weaknesses	Common Transportation Applications
UAV	• Non-intrusive • Low safety risks for surveyors • Cheap to operate • Fast mobilization	• Airspace is restricted currently • Liability issues with falling parts • High start-up cost • Limited lightweight sensors	• Tree encroachment identification • Feasibility studies being conducted

ing benefits were found to exist and be of use to transportation agencies. These benefits are not possible to achieve, however, owing to the restriction of airspace under FAA guidelines, liability issues in the event of a crash, and to a lesser extent, system costs, and privacy issues (McCormack 2008).

The Ohio DOT is evaluating the potentials of UAVs in the agency's workflows. In a presentation at the 2012 National Conference on Transportation Asset Management, the agency outlined the basics in operating UAVs under the FAA requirements (Puente 2012).

The U.S.DOT entered into a research project to examine UAVs for use in traffic surveillance applications. The report examines several different systems at different universities, research organizations, and private companies. The report also provides an overview of some of the systems and general remote sensing uses possible at the time of print. Conclusions were similar to those of other studies of UAVs; relaxation of FAA guidelines may enable further utilization of this technology by transportation agencies to occur (Puri 2005).

OTHER ADVANCED GEOSPATIAL TOOLS

Automating surveying practices have been commonplace in transportation agencies as manufacturers have made these tools available. These techniques allow not only less field time, but also reduced crew sizes and human error to accomplish similar jobs. This section discusses noteworthy advancements to traditional technologies used in transportation.

Digital Levels

Digital levels replaced many traditional Dumpy and automatic levels. This was seen as an enhancement of leveling projects by increasing both speed and precision, as well as reducing human error. This system uses a vertical rod with a barcode that can be read by the digital instrument. To ensure this rod is kept vertical, a level bubble is in place on the rod itself, similar to traditional leveling techniques. The difference is that the machine person no longer has to read the level lines off the rod, thus reducing human error.

Total Stations

Total stations are a well-established surveying technology within most transportation agencies, which measure angles and distances electronically. Capabilities of total stations continue to evolve. Total stations can include one or more of the following capabilities:

- **Prism measurement—**The total station is sighted (horizontal and vertical angles) to the center of a prism and the electronic distance meter measures the distance to the center of the prism, enabling the measurements of angles and distances between points as well as coordinates.
- **Reflectorless measurement—**Enables measurements to be collected more rapidly and on features not accessible with a prism. These are generally not as accurate as prism measurements.
- **Robotic—**These systems allow a tracking system to follow the reflective prism and collect survey points. They reduce the number of field crew and field time needed to complete a survey. The system can be automated entirely by choosing either specified time durations of point collection or by employing Bluetooth functionality. Alternately, an instrument person may be used to tell the instrument when to take each individual shot. Although the latter does not reduce the amount of field crew, it can reduce the amount of field time needed by manually sighting in the reflector for every point. Robotic systems are commonly used in machine control applications.
- **Imaging—**Enables geo-referenced, 360-degree (panoramic) digital images to be collected with the total station data. The imaging capabilities also aide the instrument operator during collection.
- **Integrated GNSS—**Both static and RTK GPS measurements can be recorded for the instrument location, providing added flexibility in geo-referencing total station data.

Video Logging

Video logging has become the state of the practice for most DOTs (see chapter two). This technology currently is used for traffic metrics, current conditions, construction progress, and emergency response situations. As shown in Table 1, 90% of DOTs consider video logging the state of the practice. These logs are often available to the public in the form of real-time traffic visualization. Video logging also has important legal implications for vehicle crash analysis as well as construction liability. Some drawbacks of this technology are the associated cable wiring and power and storage requirements.

Smart Cars/Integrated Vehicle-Based Safety Systems (IVBSS)

The Michigan DOT and the University of Michigan Transportation Research Institute have received a $15 million grant from the U.S.DOT to investigate the safety applications of smart cars. This research looks to install GPS and wireless technology in cars that enables them to share information about their location with other vehicles on the road. The Michigan DOT has been looking into this technology since 2005. They are leaders in this technology and hope to bring safer, smarter, and greener vehicular travel to our nation's roadways. This pilot study will run through 2013, at which time it will be evaluated for possible regulatory integration into connected vehicle technology ("Michigan DOT Receives . . ." 2011).

This research follows an initial 5-year pilot study conducted from 2006 to 2011. The initial study used a combination of heavy truck and passenger vehicle subjects and was evaluated at specific stages to determine progress in each. Further research has been granted in each case, and complete research reports are available ("Integrated Vehicle-Based . . ." 2010).

The Minnesota DOT originally worked with IVBSS technology aimed toward aiding the guidance of their snowplows. Developed at the University of Minnesota Intelligent Vehicles Laboratory the system is currently in place in Alaska. It is discussed in this chapter in the section Current Uses of Machine Control and Automation in Transportation.

Tablets and Smartphones

There is an increased use of tablets and smartphones by transportation agencies. Individuals are looking to navigate the web from a mobile environment with queries, utilizing geospatial data. A representative from an online mapping service stated that the percentage of hits coming from tablets or smartphones at any given time exceeds 50% of the service's traffic ("Global Geographical . . ." 2012). Several transportation agencies see this trend and are working to increase the operability of their Internet websites with mobile devices. It is thought that all transportation agencies will eventually migrate toward this operability. Field crews can use tablets that can automatically sync with central databases, reducing redundancy and enabling a live, central database.

Low-Distortion Coordinate Projections

Armstrong (2010) discusses the development of low-distortion projection coordinate systems for the state of Oregon, termed the Oregon Coordinate Reference System (OCRS). The document also provides best practices for developing and using low-distortion projections. These practices include minimizing the number of zones, developing threshold criteria for distortions, using common map projections, carefully selecting coordinate values, and working with software vendors, to name a few. Finally, the report also includes comprehensive testing and evaluation from GPS occupations of several monuments and comparisons with NGS baselines and electronic distance measurements to ensure that grid versus ground measurements are within the thresholds established.

Mobile Platforms

Mobile data collection at highway speeds is being developed, validated, and implemented. One example of this validation process exists in Strategic Highway Research Program (SHRP) 2 Safety Research Report S03, *Roadway Measurement System Evaluation* (Hunt 2011). Data collected in these efforts were geometrics, road profile, pavement texture, edge, and roadway assets such as barriers, pavement markings, and road signs. These items were to be compared against a set of survey data collected and verified by a licensed land surveyor. The service providers were free to use any collection instruments they wished in this project, and these instruments were not reported by the authors.

This project was deemed successful in prequalifying some of the service providers for the next phase of this project, S04B, *Mobile Data Collection.* However, all had difficulty in meeting some of the requirements. Two other main objectives of the research were successfully addressed as well; the evaluation of the precision and accuracy of mobile data collection and the listing of elements to be collected in S04B. Elements that were deemed critical to this upcoming work were:

1. The creation of a safety data collection manual that defines the data elements to be collected and reports on the pertinent aspects of these elements; and
2. The development of short test sites (0.2- to 0.3-mile) for the validation of distance measurement instruments, GPS, image interval and quality, cross-slope, grade, and the contractor take-off process.

S04B is expected to cost from $350 to $1,000 per survey mile validated (Hunt et al. 2011).

CHAPTER SIX

DATA MANAGEMENT AND SOFTWARE

This chapter discusses the data management tools and techniques for managing geospatial data acquired by transportation agencies. This is becoming increasingly important for personnel in a variety of divisions. Managing this resource effectively requires appropriate platforms and careful planning. Once acquired, software to process, analyze, visualize, share, manage, and maintain these data is needed. Several software suites can be necessary to support this critical need.

Singh (2008) presents a vision for data management within the Oregon DOT. Data are centrally stored and updated so that current information is available to all divisions. Singh discusses various technologies that make this feasible. Singh also argues that the most thorough survey for an infrastructure project should be performed after the project is completed to record as-built conditions, rather than before the project, as is traditionally done. Then, any modification/maintenance/update would be documented geospatially in the central database to keep it current.

Geospatial data can be used for multiple applications; therefore, storing it in its original form will allow integration into all applicable uses. Two major methods of storing roadway data used by transportation agencies are LRS and GIS. LRS is a more historical method that is well established in some agencies. GIS is a newer, more advanced technology that is in various stages of implementation in numerous agencies and being explored by several others. Comparisons of these two structures are presented in Table 23, and more complete definitions are in the following sections.

GEOGRAPHICAL INFORMATION SYSTEM

GISs store and manage geospatial databases as vector features (polygons, points, polylines, and so forth) or raster grids, tying feature attributes to geospatial positioning information. Once data are integrated into a GIS platform, attributes can be associated, allowing an infinite number of layers to be created, analyzed, and output to end users. These users can also employ technologies such as online mapping services and CAD to promote interactive, useable maps. GISs are becoming essential tools for city and state municipalities. Many of these organizations have detailed standard operating procedures and best practices to support information dissemination. It is beneficial for these organizations to continually look for ways to improve the operability of their data management system.

GIS and CAD have evolved independently over the last few decades. Both systems have several similarities and key differences. Both CAD and GIS support multiple layers to organize and view data. However, the focus of GIS is mapping features and their attributes to geospatial locations with database integration, whereas CAD focuses on the graphical presentation of drawings for designs. Both support imagery for base maps. GIS provides advanced coordinate system support and projection on the fly; although some CAD packages are integrating this support. Geometric data can be transferred from CAD to GIS and vice versa; however, traditional CAD software does not provide database support for attribute information. Newer, parametric CAD software, such as BIM platforms, enable attributes to be stored with line work.

GIS offers much of the functionality available in CAD for line work and mapping; however, GIS provides many more spatial analysis tools. Although some highway design can be done in GIS, most design is done in CAD packages because of lower software costs, a design-focused interface, and familiarity of personnel who are already trained in using CAD. Further, design of a complicated structure such as a bridge, for example, is simpler using tools available in CAD.

A research report investigating current trends and forecasting future market development of global GIS for transportation projects was published recently ("Global . . ." 2012). The analysts forecast that this market will grow at a rate of 12.5% from 2011 to 2015. The report also highlights the introduction of 3D virtual navigation in GIS. This report includes an analysis of and observations from several leading geospatial service providers on future opportunities and growth. Finally, the report discusses the impact of government regulations.

LINEAR REFERENCING SYSTEM

LRS is a location system based on linear dimensions following the centerline of the road or railway from a predetermined point, such as the start of a highway. An LRS allows one to quantify and qualify resources based on their spatial location. Higher-accuracy GPS mapping of road centerlines aids manual cartography efforts in LRS creation.

An LRS can be an intuitive system for maintenance crews and the traveling public. LRSs generally do not require special equipment for location information because the locations

TABLE 23
GIS AND LRS COMPARISON TABLE

System	GIS	LRS
Location Storage Type	Geographic coordinates	By linear length along a road
Main Users	State and federal departments, general public	Maintenance crews, emergency responders
Capable of Attribute Data	yes	yes
Benefits	• Ease of specific map creation • Interoperability of several software packages • Wide capability of uses • Integrates well with GNSS • Tied to specific datums • Visualization tool • Can easily be converted to LRS • All highways can be projected on the fly to a single coordinate system	• Simple, intuitive system • Allows easy road quantification • Needs only one measure of location attribute (approximate distance) • Ease of asset inventory
Limitations	• Some personnel may not have editing capabilities for GIS due to limited licenses • Need field equipment (e.g., GPS) for 2 or 3 location attributes (*x,y,z*) • Need for software updates (Some freeware GIS exist)	• Less accurate positioning compared with GIS • Effective for only specific users • Provides only one measure of location attribute (approximate distance) • Difficult to analyze multiple highways together

can be approximately derived by mile markers posted along the highway. In addition, they have commonly been used with emergency response systems. However, LRS does not provide the same level of accuracy and navigability in 3D space as does GIS. Further, LRS coordinates require additional software to be derived from GPS coordinates.

NCHRP Report 460 sets standardization methods for LRS. The researchers distributed a state-of-the-practice questionnaire to draw out some common inferences that create a "consensus-based, functional requirement" approach to standardization. "A comprehensive data model and implementation guideline" for this model were final products of the project (Adams et al. 2001).

Multilevel LRS is an enhancement to traditional LRS that increases functionality but has not been implemented by many transportation agencies. This technology enables improved interoperability of separate linear referencing models. Numerous linear referencing models can be more successfully conflated, updated, cross-referenced, and represented in different manners (e.g., varying scales, temporal maintenance, and analysis). An example of proprietary software with these capabilities is discussed in a white paper by Intergraph Mapping & GeoSpatial Solutions (2012).

CLOUD COMPUTING

Cloud computing is a new technology in which computational resources (both hardware and software) are provided to individuals or organizations remotely through the Internet rather than directly on one's own computer. These systems can include data storage, specific software, computing platforms, operating systems, and computer infrastructure. This technology offers users the flexibility to access cloud-based applications not only from desktop or laptop computers, but also from tablets or smartphones, which have less computing power, through secure Internet connections. This can be beneficial to organizations by reducing the time required for integration of new applications and investment in hardware that quickly becomes obsolete.

CURRENT DATA MANAGEMENT AND SOFTWARE IN TRANSPORTATION

Asset Management

The integration of LIDAR data into a GIS is an effective means of storing, analyzing, and visualizing data. The public works department in San Juan County, Washington, determined to explore this technology, found it had significant benefits to be realized. After a proprietary company spent roughly 600 hours scanning the county's roads, feature extraction was done on the data set for several areas of asset management. The public works department urged other departments to use markings, such as reflective paint or flags, to aid in asset extraction workflows. Those who did not enter into the up-front effort can utilize the resulting point clouds delivered to the Washington State DOT in the future (Trojak 2011).

The Oregon DOT (2012) completed a proof-of-concept project to evaluate earthmine as an asset management tool to integrate digital video logs, Mobile LIDAR, and traditional field data. It determined that the tools were reliable and provided significant gains in staff efficiency and safety benefits. The agency also evaluated a variety of implementation strategies. An important criterion for Oregon DOT in the evaluation was that the tool needed to be accessible to multiple staff across division boundaries. Many of the initial challenges with its use during the study were able to be resolved. Finally, the report discusses lessons learned, including that it required a low learning curve because most staff thought they received sufficient training. Fifty percent of the staff reported that it took them only a few hours to become proficient with the tool.

The Florida DOT analyzed the agency's current transit performances and needs using GIS, social-demographic information, and transit forecasting software. This study reports the need to develop a GIS data clearinghouse with data QA/QC methods, interface design for end users as well as input users, standards, and data conversion techniques (Cevallos and Catala 2011).

Many organizations such as the West Virginia DOT have been developing and implementing LRSs throughout past decades. With the improvements of geospatial locating, the West Virginia DOT decided to update the agency's LRS to a seamless, accurate, current picture of roadways and assets. Portions of this system are functioning currently, but further work needs to be done to fully integrate all of the necessary data (Yoo 2010).

The Florida DOT has been using both GIS and LRS for more than two decades. When it was determined that the agency's system was becoming ill-equipped to handle the large amounts of geospatial data coming in, they looked to employ new techniques to their LRS system, termed straight-line diagram. A prototype system has been explored to address these complications in web-based application modules (Ibaugh et al. 2007).

Geospatial Enablement

The Kansas DOT has documented a geospatial enablement plan with the agency's GIS system. This document aims to determine specific geospatial goals related to GIS and, one by one, put together a framework to attain these goals. The key goals of this enablement involve incorporating geospatial referencing to existing business functions, allowing geospatial information to be freely viewed by stakeholders (e.g., the general public, state organizations, and overseeing regulatory committees), serving geospatial operability through a hosted website, seamlessly incorporating data to and from other business entities, and bringing geospatial solutions to the forefront of popular workings with Kansas DOT through training and education. Through this geospatial enablement plan, certain developed standards, specifications, and best practices were synthesized and recommendations were made as to how these standards could be incorporated into the Kansas DOT workflow. These standards include Kansas DOT internal LRS, Open Geospatial Consortium, Federal Geographic Data Committee (FGDC), FGDC metadata, Kansas DOT internal metadata, Topologically Integrated Geographic Encoding and Referencing, NGS, Digital Orthophoto Quadrangle, Kansas GIS Policy Board, FHWA cartographic standards, and USGS national map (Intergraph 2005).

The Minnesota DOT has grown its use of GIS into a statewide Geospatial Information Office, with other states creating similar system structures. This office, following initial objectives set forth by the 2004 document and beyond, has the responsibility of maintaining statewide GIS data across all statewide government. A main goal of storing these types of offices in place was to standardize collected data, enhance the uses of GIS data, create accountability for these data, evaluate the ROI of governmental GIS hardware and software purchases, and more (*Minnesota Governor's Council* 2005).

The state of Oregon has a Framework Implementation Team (FIT, http://www.oregon.gov/DAS/EISPD/GEO/pages/fit/fit.aspx), which coordinates GIS data among various agencies. The data are made available online and shared among all state agencies. The team also develops standards and specifications for various types of GIS data within several themes, including administrative boundaries, bioscience, cadastral, climate elevation, geodetic control, geoscience, hazards, preparedness, hydrography, imagery, land use/land cover, transportation, utilities, and reference. The Oregon DOT is an active participant in this team.

Pavement Management Systems

In a typical DOT, roughly 60% of assets are related to pavement structure. In 2004, Flintsch et al. compiled a synthesis of pavement management systems (PMSs) and how they can be used in conjunction with GIS. Similar to this geospatial synthesis, information was evaluated from a questionnaire distributed to geospatial representatives from DOTs and a thorough literature review was completed involving case studies from Tennessee, Virginia, Illinois, Iowa, Ohio, Florida, Wisconsin, Pennsylvania, Georgia, Kansas, Arizona, and several local jurisdictions. Some of the problems identified with using a PMS with a GIS were consistent referencing methods, the labor required to maintain database information, GNSS accuracies, effectively incorporating temporal aspects, the differing levels of details needed, unrealistic expectations from end users, and learning curve requirements to some GISs. At the time of print, this research showed that the main uses for GISs was map generation and database integration. It did, however, show need-based GISs and PMSs.

General Transportation

Freight transport is an important concern for many states. The Washington State DOT examined the feasibility and effectiveness of a GIS-based freight transport module. Key research went into the concept of resilience in this industry. This knowledge was applied to the freight transport module of two important industries in Washington: diesel fuel and potatoes. Conclusions come for specific questions asked of discrete industries contained in this freight transport framework. It is clear this valuable QA/QC quantification technique can be applied to many different areas of freight transport (Goodchild 2009).

In 2005, the Illinois DOT created a GIS-based signalized intersection inventory system throughout district 6 of the agency. This system incorporates approaching photos and video, as well as signal and detection types of location-based, signalized intersections. A training course for employees to use software effectively has been noted as a beneficial part of the deliverables in this study (Sun et al. 2005). Other efforts under way at the Illinois DOT are a GIS-based structure inventory to aid with asset management (Conlon 2010).

Geotechnical

New Hampshire has created a hazard rating system utilizing a GIS platform; 380 rock cuts on highways throughout the state with hazard implications were identified and logged into a GIS along with photos and descriptions. This addresses safety concerns with the identification, hazard rating, and tracking and monitoring of these cuts (Fish and Lane 2002).

Hydrological and Environmental

The Indiana DOT (INDOT), in response to the EPA requirement of the permitting of stormwater discharge systems in site developments, uses GIS to help manage these efforts. Researchers at Purdue University and INDOT created a GIS layer to manage the geospatial location of manholes and receiving waterways. Although GIS was not used as an analysis tool for the stormwater pollution levels, it was essential to provide the geospatial framework of the system as a whole. Now that this information is in the GIS, they are able to use it in many different applications, and when new manholes are created, the integration into the system is easy (Corson 2004). Other uses of GIS at INDOT are the evaluation of potential environmental impact of DOT facilities on their surrounding environment and an analysis of pavement friction data for asphalt rehabilitation (Zhu 2000; Corson 2003).

CHAPTER SEVEN

QUALITY MANAGEMENT PROCEDURES

Many agencies [FGDC 1998; National Digital Elevation Program (NDEP) 2004; NOAA 2010; FAA 2011; USGS (Heidmann 2012)] have provided recommendations, guidelines, or standards for delivering geospatial data. However, given the rapid pace of technology development, the trend is to develop guidelines that enable flexibility as technologies evolve, rather than rigid standards that may stifle innovation. In addition, many standards remain in draft form, rather than being officially released as a final document owing to the time and effort necessary for their creation. Performance-based standards and guidelines are becoming increasingly common because they can ensure the desired results are obtained, while still enabling flexibility in how the work is done.

Technical documents that provide help to develop quality management procedures can be categorized as follows (in order of increasing rigidness):

1. White papers, technical documents
2. Best practices
3. Guidelines
4. Specifications
5. Standards

Several organizations are involved in general standards creation, including

- American National Standards Institute, www.ansi.org
- ANSI INCITS L1—Geographic Information, www.incits-l1.org/
- ASTM international, www.astm.org
- Federal Geographic Data Committee Standards, www.fgdc.gov/standards
- Federal Emergency Management Agency, www.fema.gov
- United States Geological Survey, www.usgs.gov
- General Services Administration, www.gsa.gov
- International Standards Organization, www.iso.org
- ISO Technical Committee 211—Geographic Information, www.isotc211.org/
- National Institute of Standards and Technology (NIST), www.nist.gov
- Open Geospatial Consortium, www.opengeospatial.org
- Standards Setting Organizations, www.consortiuminfo.org/links/
- Standards.Gov. standards.gov

(Note: This list was modified from ASPRS.)

In addition, several agencies have created internal standards, guidelines, and best practices to suit their needs (Table 24). Often these documents are used as reference by multiple other agencies, outside of their original intent owing to the time and effort necessary to develop the documents for each organization. In addition, many state DOTs (as discussed in chapters two and three) have developed their own standards and manuals to fit their needs (Table 25). Note that some form of geospatial standards were found for 38 of 50 (76%) state DOTs. This compares well with the results of the DOT questionnaire, in which 75% of the DOTs indicated that they had available standards. However, note that this does not indicate that the standards cover advanced technologies for all of the DOTs. Just as it is difficult for national standards to keep pace with technologies, many transportation agencies are struggling to produce adequate standards for some of the newer technologies.

Common themes and needs among documents include:

1. Verify geometric accuracy (and in some cases, classification accuracy).
2. Provide appropriate deliverables.
3. Provide documentation showing a lineage for the data that documents data manipulation from acquisition to processing.

An important consideration is that QA/QC procedures that have worked in the past may not work with newer technologies. Given the large size of the data sets, it becomes increasingly difficult to detect errors. Certification sites are one possibility that has received attention:

1. National Centers for Coastal Ocean Science (NCCOS), NGS, NOAA, National Park Service (NPS), and USGS have created a bathymetric mapping test site in the U.S. Virgin Islands.
2. The NGS maintains a LIDAR calibration site in Virginia.
3. Utah DOT has established a certification site for a recent Mobile LIDAR request for services. The agency also required an independent QA/QC firm for the certification and project.

GEOSPATIAL DATA ACCURACY

The Federal Geographic Data Committee (1998) developed the National Standard for Spatial Data Accuracy (NSSDA), which provides guidance for reporting spatial data accuracies,

TABLE 24
CURRENT AND PENDING GEOSPATIAL GUIDELINES

Technology	Published Documentation	Pending Documentation
Geospatial	• FGDC-STD-007.3, 1998 • NDEP, 2004 • ASPRS procurement guidelines, 2009	• ASPRS procurement, 2011 • FAA Advisory Circular 150/5300-17C, 2011
CAD	• USDA\USFS CAD standards manual, 2010	
GIS	• OGC Standards (various) • GSDI Cookbook (Wiki) • International Organization for Standardization (ISO) Technical Committee 211 (TC 2110) • ASPRS Style Guide for GIS, 2007 • ASPRS Manual of GIS, 2009	
GPS	• USDA\BLM, Cadastral surveys using GPS, 2001 • NOAA Technical Memorandum NOS NGS 59 GPS-derived Orthometric Heights, 2008 • NGS CORS guidelines	• USFS GPS data accuracy standard, 2003 • FGDC, Geometric Geodetic Accuracy Standards for GPS, 1989
GPR	• AASHTO PP40-00 • NTIA, 2011 • AASHTO TP36, 1993 • ASTM D6432-11 • ASTM D6087-08 • ASTM D478-10	
LIDAR	• ASPRS LAS format V1.4, 2011 • ASPRS Vertical Accuracy for LIDAR (airborne), 2004 • ASTM E57 3D imaging exchange format • NOAA SOW Airport Surveying, 2009 • FEMA's Mapping and Surveying Guidelines and Specifications • USGS-Base Specification v1.0	• NCHRP 15-44—Mobile LIDAR for transportation applications • ASPRS Mobile Mapping Committee • ASPRS Horizontal Accuracy for LIDAR (airborne), 2004 • ASTM E-57 • NOAA SOW Shoreline Mapping, LIDAR, 2009 (DRAFT) • ASPRS Airborne Topographic LIDAR Manual
Automated Machine Guidance		• NCHRP 10-77—Use of Automated Machine Guidance (AMG) within the Transportation Industry
Photography Imagery	• ASPRS (Photogrammetry) • NOAA Shoreline Mapping, 2004 • U.S. Army Corps of Engineers	
Surveying	• NGS, Benchmark Reset Procedures, 2011 • NGS CORS Site Monumentation, 2006 • FGDC Standards and Specifications for Geodetic Control Networks	

Note: Many titles have been abbreviated.

including the need for confidence intervals. This document provides the backbone for reporting in most available standards and guidelines. The NSSDA uses a root mean square error to estimate positional accuracy. However, the accuracies are reported in ground distances at 95% confidence. Data sets should be tested with a minimum of 20 control points and reported as:

Tested ____ (meters, feet) vertical (or horizontal) accuracy at 95% confidence level

However, in cases where the data were not tested but accuracy merely has been estimated, the following statement is used:

Compiled to meet ____ (meters, feet) vertical (or horizontal) accuracy at 95% confidence level

The National Data Elevation Plan (*Guidelines* 2004) was developed by representatives from several federal organizations to provide guidance on digital elevation data in various forms. These guidelines further developed the concepts of the NSSDA to include three types of accuracy reporting: fundamental vertical accuracy (open terrain, best conditions), consolidated vertical accuracy (combined accuracies for all land covers), and supplemental vertical accuracy (accuracies reported for individual land covers). It also provides guidance on integrating bathymetric data and modeling hydrologic features (e.g., culverts under roadways).

TABLE 25
STATE REFERENCE MANUALS AVAILABLE ONLINE

State	Survey	LIDAR	Photo	GPS		State	Survey	LIDAR	Photo	GPS
AL						MT	X		X	X
AK						NE		X		
AZ	X	X	X	X		NV	X		X	X
AR	X			X		NH	X			
CA	X	TLS	X	X		NJ	X		X	X
CO	X		X	X		NM	X		X	
CT	X		X			NY	X	TLS	X	X
DE						NC	X	X	X	X
FL	X	X				ND	X		X	X
GA	X	X	X	X		OH	X		X	X
HI						OK	X	X	X	
ID						OR	X	X	X	X
IL	X		X	X		PA	X	TLS	X	X
IN	X		X	X		RI				
IA	X					SC	X		X	
KS	X					SD	X		X	X
KY	X		X	X		TN	X		X	X
LA	X					TX	X			X
ME						UT	X			
MD						VT				X
MA	X					VA	X		X	X
MI	X		X	X		WA	X		X	X
MN	X		X			WV				
MS	X					WI				
MO	X		X			WY	X		X	X

TLS = terrestrial laser scanning.

GENERAL REMOTE SENSING GUIDELINES

The FAA has produced a draft Advisory Circular discussing remote sensing technologies for airport surveys (specifically, aerial imagery, digital orthoimagery, LIDAR, satellite imagery, and subsequent deliverables).

PROCUREMENT GUIDELINES

ASPRS has produced a draft document to help entities with the best approach to commercial geospatial products, defined with a COTS specification. The document distinguishes between professional/technical services and commercial geospatial products. It also recognizes state and federal laws. A proposed procurement methodology of license data terms and conditions, cost/value, service provider-defined technical specification, services to support geospatial products, and deliverables are covered.

LIDAR GUIDELINES

Because LIDAR technology has been evolving rapidly, there are limited standards and specifications in place. Currently, the industry tends to favor guidelines to provide leeway for future technological developments. A key challenge with LIDAR is data management and storage. Although data formats for other geospatial technologies have been standardized through CAD and GIS, work is still in process to standardize LIDAR data for delivery and exchange. Two important efforts are the ASPRS LAS and ASTM E57 data formats. Relevant information sources regarding LIDAR acquisition and processing are listed here. Note that many are in draft form and are meant as guidelines to support future changes in the technology. Many are specific to airborne LIDAR, whereas others can be applied to multiple LIDAR platforms.

- ASPRS vertical accuracy guidelines for airborne LIDAR (draft). This document reinforces the NSSDA and NDEP guidelines and provides guidance for establishing control specific to airborne LIDAR.
- ASPRS horizontal accuracy guidelines for airborne LIDAR (draft). This document provides background on the difficulties in determining horizontal accuracies from airborne LIDAR.
- The USGS developed base LIDAR specifications (airborne focus) focused on accuracy, resolution, and classification of LIDAR data for mapping purposes.

- The ASPRS Mobile Mapping Committee is developing guidelines for mobile mapping systems. This document is a work in progress at the outline stage.
- A current NCHRP project (15-44) is under way to develop performance-based, technology neutral guidelines for the use of Mobile LIDAR in transportation applications. This project will be completed in March 2013. These guidelines will be applicable to a wide range of transportation personnel.
- The FAA circular mentioned previously includes a section discussing considerations for the use of several forms of LIDAR (static, mobile, and airborne) for airport surveys and anticipated accuracies and resolutions for each form.
- Chapter 15 of the Caltrans (2011) Surveys Manual is one of the first developed sets of specifications that explicitly addresses the required information and data quality that should be provided with a static or Mobile LIDAR survey. The Florida DOT (2012) has adapted this document into a draft document.
- ASPRS has developed the LAS format for LIDAR point cloud exchange. This is the de facto standard format in the airborne LIDAR industry. This format supports classification schemes and metadata for the point cloud. A recent development, LASzip, enables a significant reduction in required storage space for archiving point cloud data.
- The ASTM E57 subcommittee has developed an exchange format for 3D imaging systems. This format is being adopted as an exchange and archive format for static and mobile laser scanned data.
- Knaak (2012) has developed a set of best practices for Mobile LIDAR project requirements based on consulting experience. The document defines three distinct levels of data collection as well as requirements for vehicle trajectory, point cloud, file management, and images.

CHAPTER EIGHT

CONCLUSIONS AND FUTURE RESEARCH NEEDS

CONCLUSIONS

This Synthesis project focuses on the use of advanced geospatial data, tools, technologies, and information as they apply to transportation projects. The key objectives were to summarize and document the current state of the practice through detailed literature reviews and online questionnaires. In addition, recommendations on the need for additional research were requested.

Ninety-seven responses from department of transportation (DOT) staff (states, District of Columbia, Puerto Rico, and Alberta, Canada) were obtained, with 42 of the geographical information system for transportation (GIS-T) representatives participating (40 of 50 state DOTs plus Puerto Rico and the District of Columbia). In addition, a total of 13 highly experienced, early adopter, private sector service providers were interviewed by phone for additional insights.

Nearly 85% of the DOT respondents regularly use geospatial technologies, with more than 50% indicating they are proactive in researching new technology. Almost two-thirds of the DOTs stated that most divisions had integrated advanced geospatial technologies into their daily workflows. The technologies most frequently used by DOTs are global positioning system (GPS), transportation (GIS), and video logging.

The top three factors holding back adoption of new technologies, according to the DOTs, are cost, inertia, and technical expertise. The service providers stated that the top three factors that make DOTs successful at introducing new technologies is an early adopter attitude, an internal champion, and improved safety.

The DOTs are experiencing a paradigm shift in their geospatial workflows as the technology moves from two-dimensional (2D) to three-dimensional (3D). Slightly more than 50% of the DOTs reported they have either implemented 3D model-based design or are in the process of doing so. Fifty percent of the DOTs reported that geospatial data are managed centrally, 30% reported the data are managed by department, and the rest reported management by multiple groups.

Sixty percent of the DOTs publish the results of research only internally. The service providers agreed with this. The DOTs reported that 85% conducted pilot projects to investigate new geospatial technologies. A similarly high percentage was in favor of the use of a centralized website to more effectively disseminate research results. The service providers also supported this idea and the use of focused research demonstration projects.

The top three geospatial technology research needs identified by the DOTs were data management, data integration, and the transition from 2D to 3D. The service providers agreed with this. Most DOTs also reported the development of standards was important but were split as to whether they prefer national or state-level standards. The service providers preferred national standards and performance-based specifications.

To streamline procurement, the service providers were in favor of prequalifying bidders and establishing indefinite delivery, indefinite quantity (IDIQ) contracts.

The literature search revealed several relevant reports and information related to technology use. However, little was available in terms of in-depth analysis and/or consensus on state-of-the-art practices involving advanced geospatial technologies. As noted previously, the DOTs have been reluctant to publish this information if it exists. A number of potential resources have been identified with hyperlinks to their online location, when possible.

In some cases, individual states have developed manuals and standards of practice for the use of geospatial technologies and related data accuracies. This includes California, Connecticut, New York, and Massachusetts. GIS data models are also being implemented to standardize the way in which geospatial data are being managed.

Some states have established GIS data clearinghouses to better communicate with the public, typically through the Internet. Examples include Georgia, Illinois, South Carolina, and Maine. In some cases, advanced data layers for light detection and ranging (LIDAR), orthophotography, and aerial imagery are also available.

Research related to the return on investment in advanced geospatial technologies has been conducted, in some cases with multiple transportation agencies pooling their resources.

The ability of geospatial technologies to improve safety, both for the traveling public and transportation agency employees, was indicated by the questionnaire respondents as one of most important drivers of research and adoption. This certainly applies to the use of Mobile LIDAR, which one service provider indicated could be used to collect as much as 70% of the FHWA-mandated Highway Performance Monitoring System data.

This is the key to the use of Mobile LIDAR—"collect once—use many." However, the challenge is data management. A concurrent research project (NCHRP 15-44) is in progress to establish the guidelines for the use of Mobile LIDAR for transportation applications.

The Global Navigation Satellite System (GNSS) is the primary surveying technology in use today by the transportation agencies. It can be used for the entire range of positioning applications, from high precision to mapping grade. GNSS is one of the core technologies for Mobile LIDAR and Automated Machine Guidance (AMG). Most states have networks of reference stations established to provide enhanced real-time performance.

The Oregon and Kansas DOTs have both published forward looking reports that establish a model for what the future transportation agency might look like; these reports have been effective for geospatial technology adoption. They outline a roadmap with reasonable goals and benchmarks. This is a critical first step in the organizational change process.

A significant portion of the previously mentioned Oregon DOT automation document is dedicated to the use of AMG or machine control. This technology is a key component of the move to 3D digital workflows. The concepts can also be applied to other activities, such as snow plowing.

Photogrammetry and photography are perhaps the most mature geospatial data acquisition technologies, but there are a lot of new techniques, including 3D applications, that are being developed.

3D model-based computer-aided design and GIS are also critically important emerging technologies within the transportation agencies. These readily support powerful visualization workflows that can increase productivity and make it easier to explain proposed projects to the public. Specific applications, such as pavement roughness and bridge inspections, are also being developed.

One of the most challenging geospatial data collection needs is underground utilities. Maine, New Hampshire, and Ohio have experimented with ground penetrating radar as a possible solution. Recent advances in software have made this technology more viable.

The use of tablet computers and smartphones is in its infancy. Once the issue of public perception is addressed, these mobile devices will become more commonly used in construction and inspection.

FUTURE RESEARCH NEEDS

Based on research gaps identified in this study, further research in the following areas may be beneficial: documentation, quality control, implementation, and technology development.

Documentation

Information related to geospatial technologies is currently scattered and fragmented for the most part. This Synthesis identified the strong need for improved integration and coordination of information regarding geospatial technologies. Particularly, further research could address:

1. An improved understanding and documentation of cost implications of accuracy and precision requirements and what is needed to support specific applications.
2. More effective coordination and dissemination of research project results, both successes and failures, across all transportation agencies and to other interested parties.
3. Case studies examining transportation agencies that are leaders in innovation and why they are leaders, in order to share lessons learned.
4. Experiences with geospatial technology of other federal and transportation agencies [e.g., Federal Emergency Management Agency, U.S. Army Corps of Engineers, and metropolitan planning organizations].

Standards

Currently, few standards or guidelines are available for assisting transportation agencies with using advanced geospatial technologies. Potential research topics include:

1. Explore development of standards of practice involving the collection and processing of geospatial data, including quality management procedures, certification methods, accuracy, and lineage.
2. Determine the effectiveness of a standard geospatial data model/infrastructure for transportation.
3. Discover and document effective procedures and sites for certification processes.

Implementation

In addition to the technological barriers, several organizational barriers can limit the effectiveness of advanced geospatial technologies. Potential research topics to assist with implementation include:

1. Identify barriers and effective learning procedures to improve the ability of nonexperts in geospatial technology to be able to utilize the technologies and understand their value.
2. Evaluate the effectiveness of committees to promote and assist with 3D technology implementation on behalf of the transportation agencies.
3. Develop a systematic approach to reduce potential barriers to the adoption of new geospatial technologies.
4. Pinpoint necessary adjustments to the procurement process that recognize disruptive workflows using new technologies.
5. Identify transportation staff technology operability requirements. This could be completed through a questionnaire evaluating the impact of age distribution of transportation personnel, level of technical expertise, training, potential future gap in expertise, and hiring freezes.

Technology Development

Given that these technologies are rapidly evolving, there are several opportunities to research the technologies. Primary issues include:

1. Determining potential applications of emerging geospatial techniques, such as unmanned airborne vehicles.
2. Understanding the role of visualization enabled by geospatial technologies.
3. Exploring the extent to which transportation agencies are using the following new technologies: inertial measurement unit and/or GPS in photogrammetry, digital photogrammetry, digital cameras, and orthophotographs.
4. Researching the integration of geospatial tools, technologies, and information. Quantifying the benefits of such integration.
5. Evaluating the benefits and difficulties for centralized data management.
6. Developing and documenting procedures and strategies for fully digital workflows.

ABBREVIATIONS

ACSM	American Congress on Surveying and Mapping
ALS	airborne laser scanning
AMG	Automated Machine Guidance
ASPRS	American Society of Photogrammetry and Remote Sensing
CAD	computer-aided design
CAIT	Center for Advanced Infrastructure Technology
COGO	Coalition of Geospatial Organizations
CORS	Continuously Operating Reference Stations
COTS	commercial off the shelf
DOQ	Digital Orthophoto Quadrangle
DOT	department of transportation
DTM	digital terrain model
ELMF	European LIDAR Mapping Forum
FEMA	Federal Emergency Management Agency
FGCS	Federal Geodetic Control Subcommittee
FGDC	Federal Geographic Data Committee
FIG	International Federation of Surveyors
GE	Geospatial Enablement
GIS	geographical information system
GIS-T	GIS for Transportation
GNSS	Global Navigation Satellite System
GPR	ground penetrating radar
GPS	Global Positioning System
GUI	graphical user interface
HEEP	Highway Engineering Exchange Program
HLS	helicopter laser scanning
ICP	iterative closest point
IDIQ	indefinite delivery, indefinite quantity
ILMF	International LIDAR Mapping Forum
IMU	inertial measurement unit
LIDAR	light detection and ranging
LRS	linear referencing system
MLS	mobile laser scanning
MTLS	mobile terrestrial laser scanning
MUTCD	*Manual on Uniform Traffic Control Devices*
NACO	National Association of Counties
NDEP	National Digital Elevation Program
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NSSDA	National Standards for Spatial Data Accuracy
NTIA	National Telecommunications and Information Administration
OGC	Open Geospatial Consortium
PMS	pavement management systems
PIC	pilot-in-command
ROI	return on investment
ROW	right of way
RTK	real-time kinematic
SF	step-frequency
TIGER	Topologically Integrated Geographic Encoding and Referencing
UAV	unmanned airborne vehicle
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

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APPENDIX A

Department of Transportation Questionnaire

NCHRP 20-05/TOPIC 43-09 GEOSPATIAL QUESTIONNAIRE

Dear Geospatial Professional,
The Transportation Research Board (TRB) is preparing a synthesis on NHCRP 20-05/Topic 43-09, "Use of Advanced Geospatial Data Tools, Technologies, and Information in DOT Projects." This is being done for NCHRP, under the sponsorship of the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration.

Geospatial data tools, technologies and information generally refer to methods for collecting, processing, analyzing, and managing data that has a real world location component, as well as physical attributes. A variety of platforms and technologies exist to obtain dense, geospatial data rapidly, such as LIDAR. These data are typically managed with a Geographic Information System or GIS, which combines a graphic representation of the location of the element, usually in the form of a map, with a linked database of attributes.

Your organization has been identified as an important contributor to this Synthesis project. As part of NHCRP 20-05/Topic 43-09 "Use of Advanced Geospatial Data Tools, Technologies, and Information in DOT Projects" the research team needs to acquire information related to the following objectives:

1. Determine the usage of geospatial technologies within DOTs.
2. Identify which DOTs have expertise and experience with key geospatial technologies.
3. Determine where DOTs publish research reports related to geospatial technologies.
4. Identify key geospatial personnel within the DOTs.
5. Determine whether standards and specifications are available.

Your organization's expertise and experience is critical to the success of this important project. We thank you in advance for your time and thoughtful consideration.

This questionnaire is being sent to geospatial professionals in all 50 U.S. state departments of transportation. Your cooperation in completing the questionnaire will ensure the success of this effort. **If you are not the appropriate person within your division or department to complete this questionnaire, please forward it to the correct person. If you know other people who can contribute, please pass this survey onto others who could add value to this effort. Please do not distribute to people who are not involved with geospatial tools.**

Please compete and submit this survey by ***March 27, 2012.*** We estimate that it should take approximately 20 to 30 minutes to complete. If you have any questions, please contact our principal investigator Michael Olsen, michael.olsen@oregonstate.edu, (541)-737-9327. Any supporting materials can be sent directly to Michael Olsen by email or at the postal address shown at the end of the survey.

QUESTIONNAIRE INSTRUCTIONS

To view and print the entire questionnaire, Click on the following link and print using "control p" http://web.engr.oregonstate.edu/~olsen/NCHRP/NCHRPquestionnaire.pdf.

1. To save your partial answers and complete the questionnaire later, click on the "Save and Continue Later" link in the upper right hand corner of your screen. A link to the incomplete questionnaire will be emailed to you from *SurveyGizmo.* To return to the questionnaire later, open the email from *SurveyGizmo* and click on the link.
2. To pass a partially completed questionnaire to a colleague, click on the on the "Save and Continue Later" link in the upper right hand corner of your screen. A link to the incomplete questionnaire will be emailed to you from *SurveyGizmo.*" Open the email from *SurveyGizmo* and forward it to a colleague.

3. To view and print your answers before submitting the survey, click forward to the page following question *36*. Print using "control p."
4. To submit the survey, click on "Submit" on the last page.
5. **DO NOT USE YOUR BROWSER'S BACK AND FORWARD BUTTONS**. Use the links provided in survey gizmo.

Thank you very much for your time and expertise!

Please enter the date (MM/DD/YYYY).

____

Please enter the name of your agency/organization and select your division.
Agency/Organization (e.g., DOT)*: ______________________________
Division?*

[ ] Asset Management/Inventory
[ ] Construction
[ ] Engineering Design
[ ] Geomatics/Surveying
[ ] Maintenance
[ ] Operations
[ ] Project Planning
[ ] Project Development
[ ] Research
[ ] Safety
[ ] Other (Please Identify :)

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1) Please provide the name and contact information for the primary point of contact in your organization regarding geospatial data tools, technologies, and information.
Name: ____________________
Title: ____________________
Division: ____________________
Organization\Agency: ____________________
Phone: ____________________
Address: ____________________
Comments: ____________________

2) Does your division use geospatial technologies? Please note that if you select rarely or never that this will be your last question.*

( ) Regularly ( ) Often ( ) Sometimes ( ) Rarely ( ) Never

---

3) Which of the following best describes your organization when it comes to adopting advanced geospatial data tools, technologies and information?*

( ) Proactive in researching new technology to develop initial Standard Operating Procedure - SOP
( ) Proactive in researching new technology to help modify existing SOP
( ) Proactive in researching new technology after SOP has been developed and proven
Please comment on how readily your organization implements geospatial technology.*

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4) Please provide your department/division's level of engagement with the following technologies:*

	Standard Operating Procedure	**Implement-ing**	**Investigat-ing**	**Research-ing**	**Not Using**	**No Interest**	**Not Sure**
3D model-based design	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
GIS	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Online Mapping Services	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
GPS	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Statewide CORS network	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
OPUS (Online Positioning User Service)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Statewide GNSS real-time networks	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Low distortion coordinate systems	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Machine Control	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Airborne LIDAR	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Static 3D laser scanning	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Mobile LIDAR	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
InSAR/IFSAR (Interferometric Synthetic Aperture Radar)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Photogrammetry	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Oblique Photography	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Unmanned Airborne Vehicle (UAV)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Video logging	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Ground Penetrating Radar	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Electromagnetic imaging	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Software as a Service	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Open source software	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Cloud computing	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Tablet computers/smart phones	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

Other (please specify):

5) For each technology that your department/division is using please identify the applications. Multiple selections OK.*

	Plann-ing	**Right of Way**	**Design**	**Con-struction**	**Operations**	**Other**	**Not Using**	**Not Sure**
3D model -based design	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
GIS	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Online Mapping Services	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
GPS	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Statewide CORS network	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
OPUS (Online Positioning User Service)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Statewide GNSS real time networks	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Low distortion coordinate systems	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Machine Control	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Airborne LIDAR	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Static 3D laser scanning	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Mobile LIDAR	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
InSAR/IFSAR (Interferometric Synthetic Aperture Radar)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Photogrammetry	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Oblique Photography	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Unmanned Aerial Vehicle (UAV)	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Video logging	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Ground Penetrating Radar	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Electromagnetic imaging	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Software as a Service	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Open source software	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Cloud computing	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Tablet computers/smartphones	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

Other (please specify):

6) For each application please provide brief explanation (key words) for selecting that technology (if using that technology).

Technology	Reason
3D model-based design	___
GIS	___
Online Mapping Services	___
GPS	___
Statewide CORS network	___
OPUS (Online Positioning User Service)	___
Statewide GNSS real time networks	___
Low distortion coordinate systems	___
Machine Control	___
Airborne LIDAR	___
Static 3D laser scanning	___
Mobile LIDAR	___
InSAR/IFSAR (Interferometric Synthetic Aperture Radar)	___
Photogrammetry	___
Oblique Photography	___
Unmanned Aerial Vehicle (UAV)	___
Video logging	___
Ground Penetrating Radar	___
Electromagnetic imaging	___
Software as a Service	___
Open source software	___
Cloud computing	___
Tablet computers/smart phones	___

Other, please specify.

7) What is your organization's overall level of expertise with advanced geospatial data tools, technologies and information?*

No Experience Expert
( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

8) What is the current level of integration of geospatial data tools, technologies and information into your organization's daily workflows?*

( ) Used by most divisions in our DOT
( ) Used by a few divisions in our DOT
( ) Used only by our surveying division
( ) Used only by a few individuals
( ) Currently at the research\investigation level only
( ) Not sure

9) Is your organization collecting geospatial data internally?*
( ) Yes ( ) No ( ) Not sure
If yes, what hardware and software is being used to collect and process the data?

10) Is your organization interfacing with external geospatial data sources?*
( ) Yes ( ) No ( ) Not sure
If yes, please identify

11) Is your organization involved with the 50 states initiative to develop Spatial Data Infrastructure (SDI) plans?
( ) Yes ( ) No ( ) Not sure

12) Are you tracking local government's geospatial data initiatives?
( ) Yes ( ) No ( ) Not sure
Please provide details.

13) Is your division tracking the cost-effectiveness of implementing advanced geospatial data tools, technologies, and information?
( ) Yes ( ) No ( ) Not sure

14) How are new geospatial data tools and technologies investigated/researched in your organization?*
( ) Individually ( ) By Geographic Region
( ) By Department ( ) Centrally ( ) Not sure
If by Department, which one? If centrally, what group?

15) Where are your agencies' research results typically published? Multiple selections OK.*
[ ] Internally only [ ] Internally behind DOT firewall
[ ] Public Website [ ] Print
[ ] Not sure
Please provide link to public website.*

16) Does your organization conduct pilot projects to investigate new geospatial data tools and technologies?
( ) Yes ( ) No ( ) Not sure
If yes, where are the results typically published?

17) Are these results made publicly available on the web?
( ) Yes ( ) No ( ) Not sure

---

18) Does your organization document failures and decisions not to use a new technology?
( ) Yes ( ) No ( ) Sometimes ( ) Not sure

If yes, are these reports made public?
( ) Yes ( ) No ( ) Not sure

19) How does your organization manage the introduction of advanced geospatial data tools, technologies and information?*
( ) By Individual ( ) By Geographic Region
( ) By Department ( ) Centrally
( ) Not sure
If by department which one? If centrally please provide the name of the group.

20) How is geospatial data managed in your organization?*
( ) By Geographic Region ( ) By Department
( ) Centrally ( ) Not sure
If by department which one? If centrally please provide the name of the group.

21) Does your organization provide training in the use of advanced geospatial data tools and technologies?
( ) Yes ( ) No ( ) Not sure

22) How is this training offered? Multiple selections OK.
[ ] Hands on [ ] Workshop [ ] Vendor demonstration
[ ] Peer to peer [ ] Not offered

23) Please rate the effectiveness of your geospatial training programs.
Poor Excellent
( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

---

24) What are the top 3 factors holding back the use of new geospatial data tools and technologies in your department/division?*
[ ] Value proposition [ ] Cost
[ ] Inertia [ ] Technical expertise
[ ] Lack of technical results/case studies demonstrating accuracy [ ] Lack of approved standard operating procedure
[ ] Lack of training [ ] Senior management
[ ] Risk of failure [ ] Other
Other, please specify:

25) Who does your organization look to for advice on advanced geospatial data tools, technologies and information? (multiple selections OK)

[ ] Internal champions
[ ] Consultants
[ ] Other DOTs
[ ] FHWA
[ ] HEEP
[ ] NGS
[ ] AASHTO
[ ] TRB
[ ] Universities
[ ] Service providers
[ ] Publications
[ ] Other

Other, please specify:

---

26) How important is it for your organization to be investigating new geospatial data tools and technologies*

Not Important — Critical to Future

( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

27) How important are standards, specifications and best practice guides to the adoption of new geospatial data tools and technologies?*

Not Important — Essential

( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

28) Would your organization prefer to implement its own standards or adopt a nationally approved version if it was available?

( ) Own ( ) National ( ) Not sure

Why?

29) Has your organization implemented any standards, specifications, quality management procedures, and/or best practice guidelines regarding geospatial technologies?

( ) Yes ( ) No ( ) Not sure

If yes, please provide details.

30) Does your organization have a quality management program in place to ensure that the geometric accuracy of geospatial data acquired using multiple technologies is being properly specified?

( ) Yes ( ) No ( ) Not sure

If yes, please provide details

---

31) What are the top 3 geospatial technology research needs in your organization?*

[ ] Transition from 2D to 3D workflows
[ ] Data Acquisition Technologies
[ ] Data Accuracy
[ ] Data Processing
[ ] Data Management
[ ] Data Storage
[ ] Data Security
[ ] Data Integration
[ ] Data Access
[ ] Quality management procedures
[ ] Technological evaluation
[ ] Cost/Benefit analysis
[ ] Other

Other, please specify:

32) How can transportation agencies more effectively research new geospatial technologies and systematically disseminate their findings? (multiple options OK)*

[ ] With more federal support/coordination (*e.g.*, FHWA)
[ ] A centralized website to disseminate geospatial research performed by DOTs
[ ] More dedicated geospatial sessions at the annual TRB conference
[ ] University collaborations
[ ] Other

Other, please specify:

33) How can transportation agencies more effectively share and transfer the lessons learned from hands on experience with advanced geospatial data tools, technologies and information? (Multiple selections OK)*

[ ] With more federal support/coordination (*e.g.*, FHWA)
[ ] A centralized website to disseminate geospatial research performed by DOTs
[ ] More dedicated geospatial sessions at the annual TRB conference
[ ] University collaborations
[ ] Other

Other, please specify:

34) How can transportation agencies more effectively reduce the risk associated with the adoption of advanced geospatial data tools, technologies and information? (multiple options OK)*
[ ] Additional research funding to identify best practices
[ ] Ability to obtain results of pilot studies from other DOTs
[ ] Cost share demonstration projects with other organizations and/or service providers
[ ] Public/private partnerships
[ ] Other

35) Other, please specify:

36) What level of interest would your organization have in supporting an online central clearinghouse where information could be published and discovered relating to geospatial data tools, technologies and information as it applies to highway projects?
None Extremely Interested
( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

37) How likely would your division be to contribute information to the site?
Not Likely Very Likely
( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

View and Print Results

Thank You!
Thank you for taking our survey. Your response is very important to us. If you have any questions or comments, please feel free to contact Michael Olsen at:

- E-mail: michael.olsen@oregonstate.edu
- Phone: (541)-737-9327
- Mailing Address: Michael Olsen, Ph.D.
  Assistant Professor of Geomatics
  School of Civil and Construction Engineering
  Oregon State University
- **220 Owen Hall**
  Corvallis, OR 97331

TABLE A1
ANALYSIS METHODS USED FOR EVALUATING DATA FOR QUESTIONNAIRE

Question #	Analysis Method
1	Data compiled into the Geospatial Contacts spreadsheet provided in the appendix.
2	By Respondent
3	By Respondent
4	Highest ranking indicated by all respondents within a DOT
5	Combined responses within a DOT
6	Integrated as text in the report.
7	Max and Averages reported per DOT
8	Highest ranking indicated by all respondents within a DOT
9	Highest ranking indicated by all respondents within a DOT
10	Highest ranking indicated by all respondents within a DOT
11	Highest ranking indicated by all respondents within a DOT
12	Highest ranking indicated by all respondents within a DOT
13	Highest ranking indicated by all respondents within a DOT
14	Representative response per DOT, if they differed, classified as multiple
15	Combined responses within a DOT
16	Highest ranking indicated by all respondents within a DOT
17	Highest ranking indicated by all respondents within a DOT
18	Highest ranking indicated by all respondents within a DOT
19	Still need to process
20	Still need to process
21	Highest ranking indicated by all respondents within a DOT
22	Combined responses within a DOT
23	Max and Averages reported per DOT
24	By Respondent
25	Combined responses within a DOT
26	Average for DOT
27	Average for each DOT
28	Representative response per DOT, if they differed, classified as not sure
29	Highest ranking indicated by all respondents within a DOT
30	Highest ranking indicated by all respondents within a DOT
31	By Respondent
32	Combined responses within a DOT
33	Combined responses within a DOT
34	Combined responses within a DOT
35	N/A
36	Average for each DOT
37	Average for each DOT

N/A = not available.

APPENDIX B

Service Provider Questionnaire and Contact List

NCHRP SYNTHESIS 20-05/TOPIC 43-09: USE OF ADVANCED GEOSPATIAL TOOLS, TECHNOLOGIES, AND INFORMATION IN DOT PROJECTS—SERVICE PROVIDER

Dear Survey Participant,

Your organization has been identified as an important contributor to this AASHTO, Transportation Research Board sponsored Synthesis project. As part of NHCRP 20-05/Topic 43-09 "Use of Advanced Geospatial Data Tools, Technologies, and Information in DOT Projects"** the research team is compiling information related to the following objectives:

1. Determine the current usage of advanced geospatial technologies within the DOTs.
2. Identify which DOTs have expertise and experience with key geospatial technologies and determine how best to systematically make this knowledge available to the entire transportation community.
3. Determine where DOTs publish research reports related to geospatial technologies and what topics require additional research.
4. Identify key geospatial personnel within the DOTs.
5. Determine whether geospatial standards and specifications are available, particularly as they relate to performance based accuracy requirements.

Your organization's expertise and experience is critical to the success of this important project. The survey should take approximately 20–30 minutes to complete. Once again we thank you in advance for your time and thoughtful consideration. The final report of this project will be provided to your organization.

If you know other people who can contribute, please pass this survey onto them. Should you have any questions or concerns, or if you would like more information regarding this project, please contact:

Michael Olsen, Ph.D.
Assistant Professor of Geomatics
School of Civil and Construction Engineering
Oregon State University
Email: michael.olsen@oregonstate.edu
Phone: (541)-737-9327

** Geospatial data tools, technologies, and information generally refer to methods for collecting, processing, analyzing, and managing data that has a real world location component, as well as physical attributes. This data is typically managed with a Geographic Information System or GIS which combines a graphic representation of the location of the element, usually in the form of a map, with a linked database of attributes. Please note that you can also answer "Not sure" to any of the following questions.

---

1) Please provide the date.*____

2) Company Name*____

3) Department Name (if applicable)*____

4) How long has your company been involved with geospatial technologies, data tools and/or information products? ________ years* ____

5) What type(s) of geospatial services or products does your company offer?*

	Yes	No	In the near future	No Interest	Not Sure
3D model-based design	[]	[]	[]	[]	[]
GIS	[]	[]	[]	[]	[]
Online Mapping Services	[]	[]	[]	[]	[]
GPS	[]	[]	[]	[]	[]
Statewide CORS network	[]	[]	[]	[]	[]
OPUS (Online Positioning User Service)	[]	[]	[]	[]	[]
Statewide GNSS real time networks	[]	[]	[]	[]	[]
Low distortion coordinate systems	[]	[]	[]	[]	[]
Machine Control	[]	[]	[]	[]	[]
Airborne LIDAR	[]	[]	[]	[]	[]
Static 3D laser scanning	[]	[]	[]	[]	[]
Mobile LIDAR	[]	[]	[]	[]	[]
InSAR/IFSAR (Interferometric Synthetic Aperture Radar)	[]	[]	[]	[]	[]
Photogrammetry	[]	[]	[]	[]	[]
Oblique Photography	[]	[]	[]	[]	[]
Unmanned Airborne Vehicle (UAV)	[]	[]	[]	[]	[]
Video logging	[]	[]	[]	[]	[]
Ground Penetrating Radar	[]	[]	[]	[]	[]
Electromagnetic imaging	[]	[]	[]	[]	[]
Software as a Service	[]	[]	[]	[]	[]
Open source software	[]	[]	[]	[]	[]
Cloud computing	[]	[]	[]	[]	[]
Tablet computers/smart phones	[]	[]	[]	[]	[]

6) What percent of your company's annual revenue involves a DOT?*______________________

7) What percentage of the DOTs would your company estimate are using advanced geospatial technologies?*

____

8) Who would your company consider to be some of the leading DOTs with regards to geospatial technologies?*

Alabama	Alaska	American Samoa	Arizona
Arkansas	California	Colorado	Connecticut
Delaware	District of Columbia	Federated States of Micronesia	Florida
Georgia	Guam	Hawaii	Idaho
Illinois	Indiana	Iowa	Kansas
Kentucky	Louisiana	Maine	Marshall Islands
Maryland	Massachusetts	Michigan	Minnesota
Mississippi	Missouri	Montana	Nebraska
Nevada	New Hampshire	New Jersey	New Mexico
New York	North Carolina	North Dakota	North. Mariana Islands
Ohio	Oklahoma	Oregon	Palau
Pennsylvania	Puerto Rico	Rhode Island	South Carolina
South Dakota	Tennessee	Texas	Utah
Vermont	Virgin Islands	Virginia	Washington
West Virginia	Wisconsin	Wyoming	

9) Which technologies are they using?*

	Yes	**No**	**Not Sure**
3D model-based design	[]	[]	[]
GIS	[]	[]	[]
Online Mapping Services	[]	[]	[]
GPS	[]	[]	[]
Statewide CORS network	[]	[]	[]
OPUS (Online Positioning User Service)	[]	[]	[]
Statewide GNSS real time networks	[]	[]	[]
Low distortion coordinate systems	[]	[]	[]
Machine Control	[]	[]	[]
Airborne LIDAR	[]	[]	[]
Static 3D laser scanning	[]	[]	[]
Mobile LIDAR	[]	[]	[]
InSAR/IFSAR (Interferometric Synthetic Aperture Radar)	[]	[]	[]
Photogrammetry	[]	[]	[]
Oblique Photography	[]	[]	[]
Unmanned Airborne Vehicle (UAV)	[]	[]	[]
Video logging	[]	[]	[]
Ground Penetrating Radar	[]	[]	[]
Electromagnetic imaging	[]	[]	[]
Software as a Service	[]	[]	[]
Open source software	[]	[]	[]
Cloud computing	[]	[]	[]
Tablet computers/smart phones	[]	[]	[]

---

10) What has made them successful at introducing these technologies into their DOTs?

[ ] Early adopters/progressive

[ ] Supportive procurement procedures

[ ] Internal champion

[ ] Return on investment

[ ] Peer pressure

[ ] Top down edict

[ ] Innovative technology group that facilitates process

[ ] Allowed to fail

[ ] Use pilot projects

[ ] FHWA requirement

[ ] Research interest

[ ] Safety

[ ] Legislative

[ ] Budget

[ ] Training

[ ] Other

11) How can "best practices" information be more systematically disseminated?

[ ] With more federal support/coordination and/or mandate (e.g., FHWA)

[ ] A centralized website to disseminate geospatial research performed by DOTs

[ ] More dedicated geospatial sessions at the annual TRB conference

[ ] University collaborations

[ ] Financial incentive

[ ] Webinars

[ ] Other

---

12) What is holding back the adoption of the underutilized technologies?*

[ ] Value proposition
[ ] Cost
[ ] Inertia
[ ] Technical expertise
[ ] Lack of technical results/case studies demonstrating accuracy
[ ] Lack of approved standard operating procedure
[ ] Lack of training
[ ] Senior management
[ ] Risk of failure
[ ] Other

13) The use of focused research demonstration projects would help to overcome this?

( ) Agree ( ) Disagree

---

14) Are the results of your company's DOT advanced geospatial technology projects generally documented?*

( ) Regularly ( ) Often ( ) Sometimes ( ) Rarely ( ) Never ( ) Not Sure

15) Are the results typically made public?*

( ) Regularly ( ) Often ( ) Sometimes ( ) Rarely ( ) Never ( ) Not sure

If yes, where are the results published?

[ ] Internally only
[ ] Internally behind DOT firewall
[ ] Public Website
[ ] Print
[ ] Not sure

If not, what are the primary reasons?

[ ] Senior management policy
[ ] Service provider reluctance
[ ] Security
[ ] Takes too much time
[ ] No incentive
[ ] Liability
[ ] Lack of central repository
[ ] Other

---

16) In general, do the DOTs have written geospatial standards and/or specifications?

( ) Yes ( ) No ( ) Not sure

If yes, which DOTs and what do they cover?

State: ____________________

17) What can be done to improve the effectiveness of these standards?

[ ] Seek input from more departments
[ ] Make use of national standards whenever possible
[ ] Involve industry group in development
[ ] Peer review
[ ] Emphasize performance rather than procedure
[ ] Integrate with procurement

18) Which DOTs, if any, have performance-based accuracy requirements for advanced geospatial technologies?

State: ____________________

19) Is it necessary for a geospatial technology service provider to report on their methodology as part of the project deliverable, or just certify as to the final accuracy? Please explain.*

---

20) What percent of DOTs that your company works with are:
Only using 2D/2.5 CAD and GIS software ___%

Currently transitioning from 2D/2.5D to 3D model-based workflows ___%

Have transitioned from 2D/2.5D to 3D model-based workflows in software such as CAD and GIS ___%

Not sure

21) What can the DOTs do to streamline the procurement process for geospatial technologies?*

[ ] Establish IDIQ contracts
[ ] Align procurement with new 3D workflows
[ ] Establish a service provider advisory panel
[ ] Focus on results not methods
[ ] Pre-qualify bidders

22) What are the top 3 geospatial technology research needs in the DOTs?*

[ ] Transition from 2D to 3D workflows
[ ] Data Acquisition Technologies
[ ] Data Accuracy
[ ] Data Processing
[ ] Data Management
[ ] Data Storage
[ ] Data Security
[ ] Data Integration
[ ] Data Access
[ ] Quality management procedures
[ ] Technological evaluation
[ ] Cost/Benefit analysis
[ ] Other

---

23) How does your company perceive that geospatial data is currently managed within the DOTs?*

( ) Centrally located and updated by each department

( ) Differently within each individual department

( ) Not sure

24) Please identify key geospatial personnel within the DOTs?
State: ____________________________

25) Do you have any additional comments or concerns?

Thank You!
Thank you for participating in our survey. Your response is very important to us. If you are interested in the results of the project please contact Dr. Michael Olsen.

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

Company Name	Department	Address	Phone Number	Website
Autodesk	Americas survey	111 McInnies Parkway, San Rafael CA, 94903	415-507-5000	http://usa.autodesk.com
DEA	Emerging business	2100 SW River Parkway, Portland OR, 97201	800-721-1916	www.deainc.com
Esri	Geospatial	380 New York Street, Redlands CA, 92373	909-793-2853	www.esri.com
Google	Infrastructure/ collaboration	1600 Ampitheater Parkway, Mountain View CA, 94043	650-253-0000	www.google.com
HNTB	Transportation	715 Kirk Drive, Kansas City MO, 64105	816-472-1201	www.hntb.com
Mandli	Incubation	4801 Tradewinds Parkway, Madison WI, 53718	608-835-3500	www.mandli.com
McKim and Creed	None	1730 Varsity Drive, Suite 500, Raleigh NC, 27606	919-233-8091	www.mckimcreed.com
R.E.Y. Engineers	None	905 Sutter Street, Folsom CA, 95630	916-366-3040	www.reyengineers.com
Terrametrix	Remote sensing	4852 S 133rd Street, Suite 105, Omaha NE, 68137	402-618-1099	www.terrametrix3d.com
Topcon	Survey	7400 National Drive, Livermore CA, 94550	925-245-8300	www.topconpositioning.com
Trimble	Survey and geomatics	935 Stewart Drive, Sunnyvale CA, 94085	408-481-8000	www.trimble.com
Tuck Mapping	None	4632 Aerial Way, Big Stone Gap VA, 24219	276-523-4669	www.tuckmapping.com
Woolpert	None	4454 Idea Center Boulevard, Dayton OH, 45430	937-461-5660	www.woolpert.com

APPENDIX C

Database—EXCEL, Geographical Information System, and Google Earth Versions

These documents are provided as electronic attachments. Two databases are provided. First, the technology usage by state from the questionnaire results is provided as MS Excel (xls), GIS (mxd and shp), and Google Earth (kmz) files. These are discussed in the text. The research reports by state are provided as Excel (xls) and GIS (mxd and shp) files. Figures C1 through C3 are screenshots of the interactive database of research reports available by state.

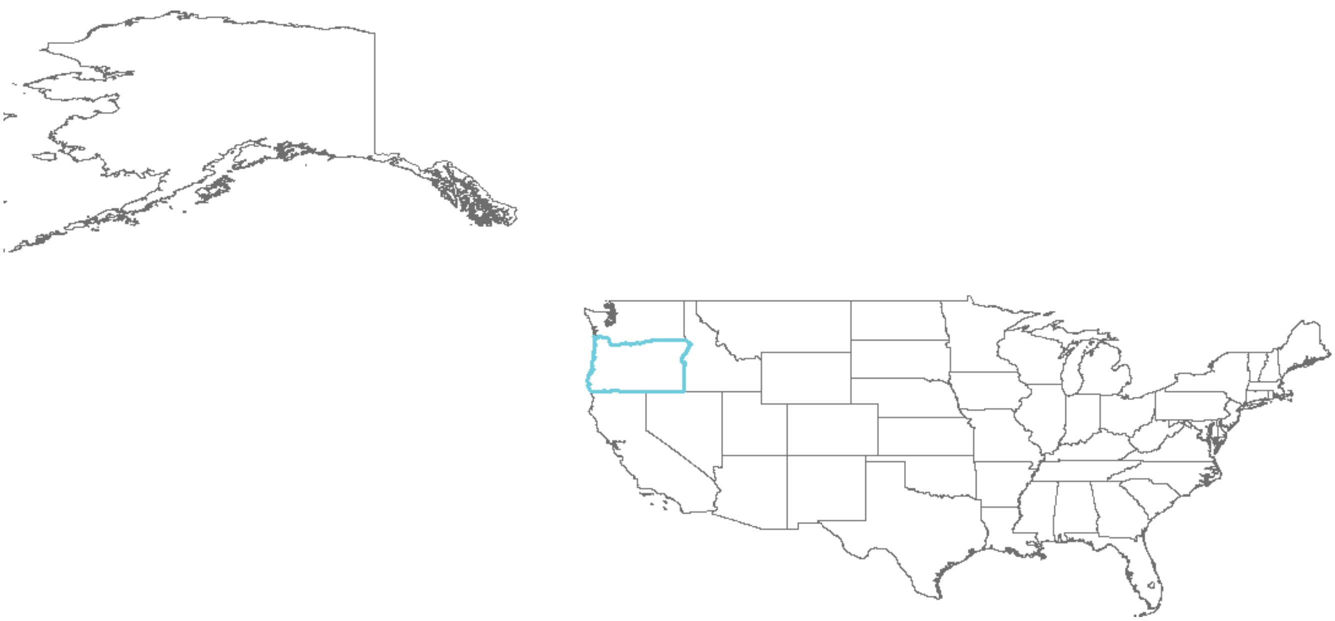
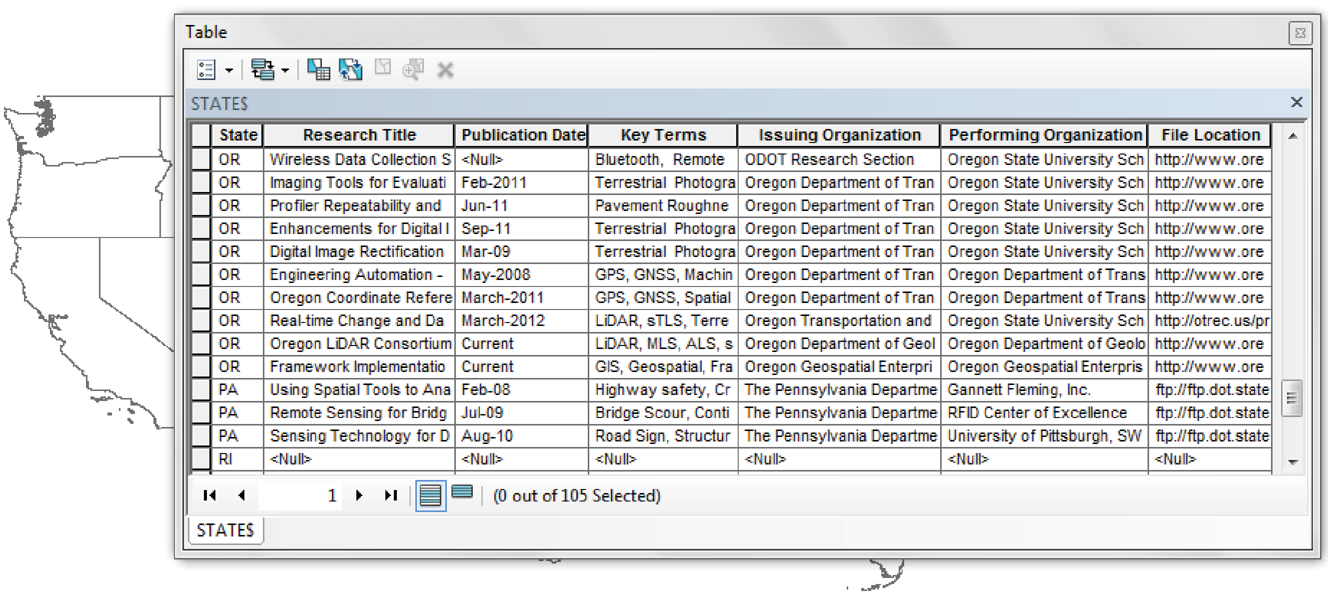


FIGURE C1 GIS database of states.



State	Research Title	Publication Date	Key Terms	Issuing Organization	Performing Organization	File Location
OR	Wireless Data Collection S	<Null>	Bluetooth, Remote	ODOT Research Section	Oregon State University Sch	http://www.ore
OR	Imaging Tools for Evaluati	Feb-2011	Terrestrial Photogra	Oregon Department of Tran	Oregon State University Sch	http://www.ore
OR	Profiler Repeatability and	Jun-11	Pavement Roughne	Oregon Department of Tran	Oregon State University Sch	http://www.ore
OR	Enhancements for Digital I	Sep-11	Terrestrial Photogra	Oregon Department of Tran	Oregon State University Sch	http://www.ore
OR	Digital Image Rectification	Mar-09	Terrestrial Photogra	Oregon Department of Tran	Oregon State University Sch	http://www.ore
OR	Engineering Automation -	May-2008	GPS, GNSS, Machin	Oregon Department of Tran	Oregon Department of Trans	http://www.ore
OR	Oregon Coordinate Refere	March-2011	GPS, GNSS, Spatial	Oregon Department of Tran	Oregon Department of Trans	http://www.ore
OR	Real-time Change and Da	March-2012	LiDAR, sTLS, Terre	Oregon Transportation and	Oregon State University Sch	http://otrec.us/pr
OR	Oregon LiDAR Consortium	Current	LiDAR, MLS, ALS, s	Oregon Department of Geol	Oregon Department of Geolo	http://www.ore
OR	Framework Implementatio	Current	GIS, Geospatial, Fra	Oregon Geospatial Enterpri	Oregon Geospatial Enterpris	http://www.ore
PA	Using Spatial Tools to Ana	Feb-08	Highway safety, Cr	The Pennsylvania Departme	Gannett Fleming, Inc.	ftp://ftp.dot.state
PA	Remote Sensing for Bridg	Jul-09	Bridge Scour, Conti	The Pennsylvania Departme	RFID Center of Excellence	ftp://ftp.dot.state
PA	Sensing Technology for D	Aug-10	Road Sign, Structur	The Pennsylvania Departme	University of Pittsburgh, SW	ftp://ftp.dot.state
RI	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>

FIGURE C2 Database of reports and publications for the state of Oregon.

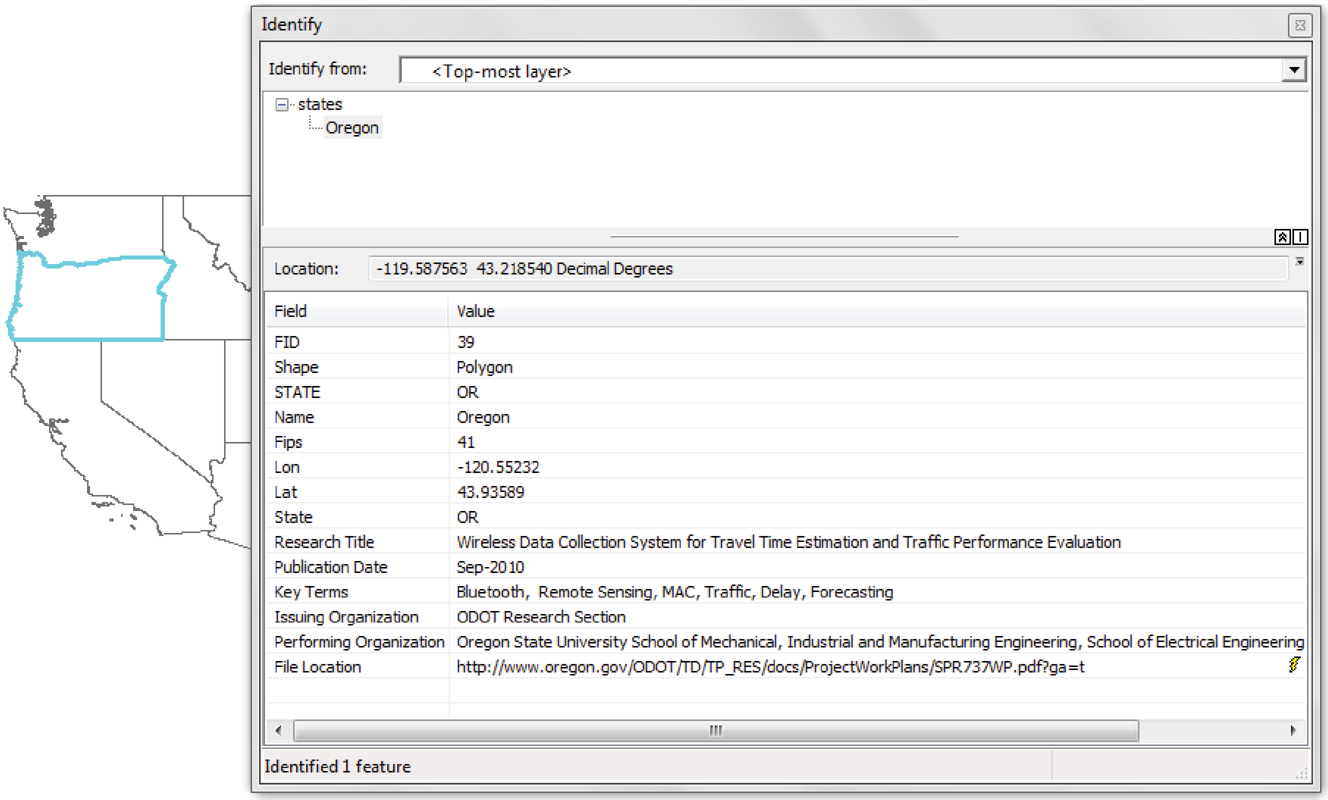


FIGURE C3 Example of details of a single report for Oregon.

APPENDIX D

Primary Geospatial Contacts

Contact information for the primary geospatial contacts is provided in a spreadsheet at www.trb.org, search on "NCHRP Synthesis 446."

Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation