Strategic Issues Facing Transportation, Volume 3: Expediting Future Technologies for Enhancing Transportation System Performance

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 750

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Volume 3: Expediting Future Technologies for Enhancing Transportation System Performance

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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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FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

New technologies continually arise that could be useful to DOTs and MPOs. This report presents a process (Systematic Technology Reconnaissance, Evaluation, and Adoption Methodology or STREAM) to compare these technologies to alternatives on the basis of their likely effects on agency goals, including consideration of barriers to implementation. STREAM's use is illustrated in three case studies. This report will be useful to research units within state DOTs and other units responsible for evaluating new technologies.

Major trends affecting the future of the United States and the world will dramatically reshape transportation priorities and needs. The American Association of State Highway and Transportation Officials established the NCHRP Project 20-83 research series to examine global and domestic long-range strategic issues and their implications for departments of transportation (DOTs) to help prepare the DOTs for the challenges and benefits created by these trends. *NCHRP Report 750: Strategic Issues Facing Transportation, Volume 3: Expediting Future Technologies for Enhancing Transportation System Performance* is the third report in this series.

Transportation agencies may use various options to capitalize on technology to improve transportation system performance. For instance, information and communication technology allows for enhanced traveler information, instant re-routing and mode choice, and facilitating pricing-based strategies. Future technologies offer even greater potential to improve safety, reliability, and mobility. Furthermore, this subject area can involve not only adoption of technologies by transportation agencies, but ways in which transportation agencies can anticipate and help shape research and development of various technologies that can affect transportation system performance.

Technology often changes faster than agencies can react. In particular, the results of research can be slow to be implemented into practice. Many transportation agencies do not have the business processes and organizational structures in place that allow rapid adoption and deployment of relevant technologies. Furthermore, many barriers outside the control of transportation agencies affect the ability to advance technologies from research to deployment. Partnerships with the private sector and opportunities for knowledge transfer from other industries may help the transportation sector more effectively adapt in this dynamic environment.

Under NCHRP Project 20-83(02), the RAND Corporation developed a process that transportation agencies can use to identify, assess, shape, and adopt new and emerging technologies to achieve long-term system performance objectives. The process reflects relevant trends in technologies and their applications and helps transportation agencies anticipate, adapt to, and shape the future.

The research team identified and assessed trends in technologies applicable to the mission of state DOTs and barriers to implementation of these technologies. The research team then assessed typical performance objectives adopted by state DOTs that such technologies could be expected to aid in meeting. These insights were instrumental in developing STREAM which was then evaluated using several case studies, including meeting with the Minnesota DOT to discuss how STREAM could be applied to bridge deck evaluation. Case studies were also conducted for driver information and snow removal/ice control to assess STREAM's practicality across the range of state DOT functions.

The STREAM process has five steps. The final step, deciding whether to adopt the technology, must always take into consideration an agency's specific objectives and context; however, earlier steps in the process can be done jointly with other agencies. This approach will reduce costs and staff time and speed the implementation of beneficial technologies.

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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.

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ABP	Agricultural-based Products
AI	Artificial Intelligence
AMPO	Association of Metropolitan Planning Organizations
ARROWS	Automated Real-Time Road Weather System
ASCE	American Society of Civil Engineers
AVL	Automatic Vehicle Location
CAA	Clean Air Act
CACS	Comprehensive Automobile Control System
$CaCl_2$	Calcium Chloride
CAD	Computer-Assisted Drawing
CMA	Calcium Magnesium Acetate
CRn	Concentration Ratio
CSS	Context-sensitive solution design
CV	Commercial Vehicle On-Board
DIC	Digital Image Correlation
DO	Dissolved Oxygen
DOR	Department of Roads
DOT	Department of transportation (generic)
DOT	Department of Transportation
DRIVE	Dedicated Road Infrastructure for Vehicle Safety in Europe
EC	Electronic Credentialing
ER	Emergency Response Center
ES	Electronic Screening
EV	Emergency Vehicle On-Board
FAST	Fixed Automated Spray Technology
FBG	Fiber Bragg Grating
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
FM	Fleet Management Center
FOS	Fiber optics sensor
FP	Fabry-Perot
FTA	Federal Transit Administration
GHG	Greenhouse Gas
GIS	Geographic information system
GPR	Ground penetrating radar
GPS	Global positioning system
HHI	Herfindahl-Hirschman Index
HMCV	Highway Maintenance Concept Vehicle
IAPA	Illinois Asphalt Pavement Association

ISP	Information Service Provider
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
IT	Information Technology
ITS	Intelligent transportation system
IVHS	Intelligent Vehicle Highway Systems
KAc	Potassium Acetate
Kform	Potassium Formate
LOS	Level of Service
LPR	Linear Polarization Resistance
MDSS	Maintenance Decision Support System
$MgCl_2$	Magnesium Chloride
MnDOT	Minnesota Department of Transportation
MPO	Metropolitan planning organization
NaAc	Sodium Acetate
NaCl	Sodium Chloride
NCHRP	National Cooperative Highway Research Program
NDE	Nondestructive evaluation
NOAA	National Oceanic and Atmospheric Administration
NSSRG	National Salt Spreading Research Group
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OIM	Office of Investment Management
PD	Personal Device
PDA	Personal Digital Assistant
PM	Parking Management
PNS	Pacific Northwest Snowfighters
POSI	Probability of Successful Implementation
PSIC	Pavement Snow and Ice Condition
RFID	Radio Frequency Identification
RM	Remote Location
RMS	Resource Management System
RS-C	Roadside Control
RS-D	Roadside Detection
RS-TC	Roadside Telecommunications
RWIS	Road Weather Information System
SDDOT	South Dakota Department of Transportation
SEI	Structural Engineering Institute
SHM	Structural health monitoring
SICOP	Snow and Ice Pooled Fund Cooperative Program
SIE	Safety Information Exchange
TA	Toll Administration
TIG	AASHTO Technology Implementation Group
TM	Transportation Management Center
TMB	Tsing Ma Bridge
TMIP	Travel Model Improvement Program
TP	Toll Plaza
TPF	Taxes/Penalties/Fees
TR	Transit Management Center
TRANSIMS	Transportation Analysis Simulation System
TRB	Transportation Research Board

TRL	Transportation Research Laboratory
TTI	Texas Transportation Institute
TV	Transit Vehicle On-Board
USDOT	United States Department of Transportation
UV	Ultraviolet
VERITAS	Vehicle Road and Traffic Intelligence Society
VM	Vehicle Miles
VS	Vehicle On-Board
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
WMA	Warm-mix Asphalt
WMS	Work Management System

CHAPTER 1

Introduction

The General Motors' Futurama exhibit at the 1939 World's Fair in New York piqued the collective imaginations of Americans and the world. The exhibit promised that in a mere 25 years, the United States would have an automated highway system offering tremendous benefits in meeting transportation objectives. In doing so, it foretold the coming of a fundamental revolution in the surface transportation of passengers and freight. And, indeed, part of this vision was realized when, in 1997, a highly publicized, fully automated highway system was demonstrated on I-15 near San Diego, largely with support from transportation agencies.

But, the sweeping revolution has yet to arrive. Why should transport system technologies which are widely perceived as beneficial, and toward which so much successful research and development has occurred, continue to elude practical implementation? This concern applies not only to such major innovations as the intelligent highways of the Futurama. Significant public and private research efforts have focused on developing technologies for transportation that could transform how transportation agencies perform their tasks and achieve their mission goals; indeed, they could even transform the very nature of those tasks and missions. Yet, the transportation system, and transportation agencies[1] in particular, appear by some measures to be slow adopters of potentially valuable technologies. This is in part because being able to assess, plan for, and integrate technological change into transportation system planning and operations has proven to be difficult and elusive.

ICF International's *Long-Range Strategic Issues Facing the Transportation Industry* (2008), in response to which this project has its origins, observes that rapidly developing technologies in a wide range of areas hold promise for transportation, that agencies can play a key role in shaping and implementing these technologies, but that they face barriers in doing so. The research team was asked to (1) analyze what systemic barriers exist to the accurate assessment and successful adoption of new technologies by transportation agencies and (2) provide recommendations for reducing the influence of these obstacles.

Accordingly, the research team developed STREAM, a practical and systematic technology assessment and decision-making process. STREAM was designed to help agencies

- Assess current and potential technologies according to characteristics directly relevant to agency missions and to the policy environment in which agencies operate;
- Incorporate such assessments more effectively into the existing agency functions, including planning, system maintenance, and operation; and
- Better account for the uncertainties inherent in the distribution, adoption, implementation, and operation of proven technologies as well as prospective future technologies.

STREAM proceeds in five overarching steps as shown in Figure 1-1 and described in detail in Chapter 3.[2] These five steps are an explicit, evidence-based process of framing systematically the decisions faced by agencies in technology evaluation, identifying technologies that are relevant, characterizing technology alternatives in agency-relevant terms and comparing them on a level playing field, and helping agencies decide on the appropriate response. STREAM allows comparison of heterogeneous technologies and evaluating

[1] "Transportation agencies" refers to both state departments of transportation (DOTs) and more regionally focused metropolitan planning organizations (MPOs). These entities have differing responsibilities and also vary greatly among themselves even within agency type, but both face issues related to technological change and technology adoption, both in planning and operations

[2] In this representation, STREAM is shown as a linear process; however, the flow of the assessment and evaluation processes in practice is likely to be recursive and bi-directional, and successive phases will themselves cause a re-evaluation of what has gone before.

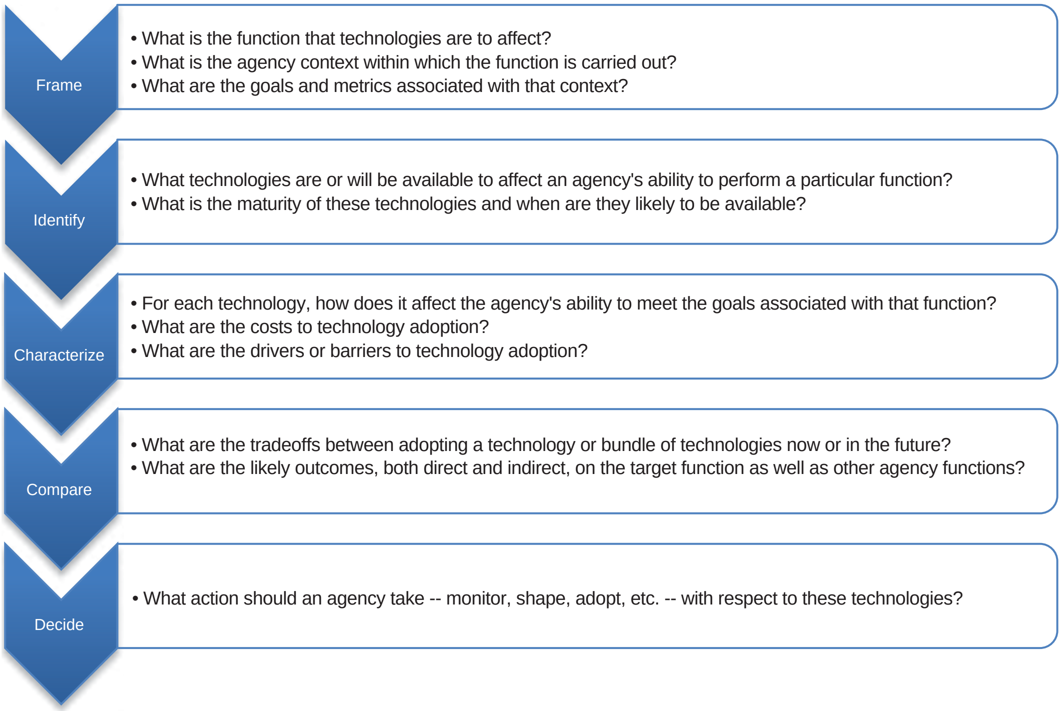

Figure 1-1. The major steps in the STREAM process.

those currently available with those in prospect by allowing comparison on the basis of important system outcomes. STREAM not only provides a method of technology assessment and decision-making, but also serves to

- Emphasize the **decision points** transportation agencies face during such a process;
- Provide a **common framework and vocabulary** for discussion, evaluation, and knowledge sharing within and among transportation agencies, and between transportation agencies and stakeholders;
- Provide a **best practice guide** and a framework for improving the quality of agency evaluation and adoption decisions; and
- Provide a **forensic checklist** for understanding better which steps or stages have proven to be obstacles.

The research team used STREAM to develop approaches that can better address some of these impediments and improve the quality of assessment and outcomes in the application of technology to transportation.

STREAM was developed for transportation agencies and decisionmakers. The research team conducted three specific applications of STREAM to vet the framework and provide illustrations. However, the examples provided herein only outline what might be done by a fully resourced agency or joint evaluation body in actual application—STREAM is a work in progress—a proof-of-principle system to be exercised and refined by the transportation community.

This report is intended to be practical and useful and is organized with two goals in mind:

1. To help transportation agencies and decisionmakers understand when and how to use STREAM, and
2. To help the transportation community as a whole take steps toward applying and improving STREAM.

Chapter 2 describes the barriers that exist to technology adoption in transportation and the principles the research team used to develop STREAM. Chapter 3 describes the STREAM steps; in Chapter 4, these steps are applied to the problem of bridge deck inspection. The report concludes with suggestions for implementation and a few recommendations and conclusions based primarily on interactions with transportation practitioners during the development and testing of the method.

The report also includes appendices that provide supporting materials, including two additional case studies of STREAM applications, detailed case studies of specific examples of technology distribution and adoption by transportation agencies, and a review of the research team's interactions with a specific DOT.

CHAPTER 2

Foundations of STREAM

Much work has been done to bring information about technology research and development to practitioners so that technologies can be implemented in support of transportation agencies' missions. These include

- The Cooperative Research Programs' synthesis reports series on the state of practice in many areas, including transportation[3];
- NCHRP and AASHTO domestic and international scans of transportation innovations; and
- AASHTO's Technology Implementation Group, which highlights valuable, application-ready but little-used innovations[4];

These and other efforts help to increase practitioners' awareness and understanding of available technologies and to facilitate adoption and implementation of these technologies. [5] Yet, agencies continue to face technical, non-technical, and methodological challenges to adopting beneficial technologies.

The research team identified many of these challenges through case studies and a literature review and highlights the main conclusions in the first two sections of this chapter. A central finding is that the most prevalent and significant barriers to expediting technology adoption in transportation lie in realms other than the strictly technical. The barriers emerge from patterns for allocating financial assets, the position of transportation agencies as organizations in a larger governmental and political environment, how such agencies operate internally as hierarchies, and conflicts between desirable goals. Beyond this, there seems to be a fundamental problem of information gathering, framing that information in forms relevant to decision making within the agencies, and transmitting it through levels and departments as well as to the other government bodies with which these agencies must interact.

The final section of this chapter presents seven key principles on which STREAM is based:

1. Assess and compare technologies in relation to agency goals;
2. Derive transportation agency technology needs on the basis of specific functions that require support;
3. Use multiple metrics to assess and compare technologies with respect to the full range of agency goals;
4. Identify and compare existing and prospective technologies by effect on functional performance, rather than by technology type;
5. Include current knowledge about existing and prospective technologies within a common framework for assessment, tracking, and decision;
6. Make the assessment process less disruptive and more integral to regular agency functions; and
7. Provide sufficient information to understand the degree of uncertainty and enable flexible operation under evolving circumstances.

Broad Technology Assessment, Adoption, and Implementation Barriers

Transportation agencies face many challenges in their efforts to assess, adopt, and implement technologies. The literature shows that technological barriers constitute only a small part of the potential obstacles. Much more formidable barriers arise from the context in which agencies operate.[6]

[3] See http://www.trb.org/Publications/PubsNCHRPSynthesisReports.aspx
[4] See http://tig.transportation.org/Pages/default.aspx
[5] The Association of Metropolitan Planning Organizations (AMPO), FHWA, FTA, individual transportation agencies, and several other public institutions also fund and conduct research on transportation technology.

[6] Deakin, Elizabeth. *Mainstreaming Intelligent Transportation Systems: Findings from a Survey of California Leaders,* UC Transportation Center Paper no. 791, 2006, and Deakin, Elizabeth, Karen Trapenberg Frick, and Alexander Skabardonis, "Intelligent Transport Systems: Linking Technology and Transport Policy to Help Steer the Future," *Access,* Spring 2009.

The research team commissioned case studies of specific instances of technology assessment and adoption by transportation agencies to assess a wide range of barriers in greater depth, document lessons learned, and articulate strategies that agencies might consider to overcome barriers. The selected case studies focus on four technology applications:

- ITS,
- Pavement technology and infrastructure,
- Context-sensitive solution (CSS) design[7], and
- Integrated transportation-land use modeling.

These examples were selected because they span a range of technology disciplines, involve different divisions within transportation agencies, are of varying familiarity to agency personnel, and are at different stages of technological maturity. Collectively, they enabled the research team to delve into the array of potential barriers agencies face. The actual case studies were carried out by Dr. Elizabeth Deakin and Karen Trapenberg Frick of the University of California Transportation Research Center. For each case study, Deakin and Frick reviewed the literature and interviewed researchers and analysts, transportation agency staff, elected officials, and those in the private sector.

A synthesis of the four case studies suggests a set of common barriers. (Appendix A presents the full case studies.) This set is neither exhaustive nor conclusive, but highlights the range of technological and institutional challenges with which agencies contend in their efforts to respond to technology.

Some barriers to technology assessment and adoption have to do with the **technology** itself.

- **Technology Uncertainty.** The performance of technology may be inherently uncertain (e.g., because the technology is not yet proven or has complex interactions with the transportation system that are difficult to anticipate and assess). This uncertainty makes it difficult for agencies to weigh the costs, benefits, and effects of technologies. (*Example from Case Studies:* The technical validity of advanced transportation and land use models was a key concern of practitioners.)
- **Other Technical Barriers.** Barriers may be inherent in a technology. *(Example from Case Studies:* The use of several pavement innovations is limited by very cold winter climate in some regions.)

Other barriers are **institutional** (i.e., an agency's own organization, culture, capacity, and resources may stand in the way of it engaging fruitfully in processes to identify, assess, shape, and adopt innovative technologies).

- **Performance Assessment.** Agencies (or their partners) may not have adequate skills, experience, or resources to assess the costs, benefits, and outcomes of technology adoption adequately. Agencies may also have insufficient objectivity in evaluating a technology. (*Example from Case Studies:* Many interviewees expressed concerns that the developers of ITS applications also evaluate their performance and may not be objective evaluators.)
- **Standards, Rules, and Regulations.** Agencies may choose or be required to adhere to technical standards, rules, and regulations that limit or hinder their ability to adopt technology. Although adhering to technical standards may encourage consistency, predictability, and ease of assessment, standards may hinder the adoption of innovations that are rapidly evolving and for which the development and adoption of standards cannot keep pace. (*Example from Case Studies:* Confusion about the role of different standards and regulations hinders the adoption of CSS design.)
- **Internal Organization and Culture.** The hierarchical organizational structures often found in transportation agencies may make it difficult to bring together the correct mix of decisionmakers, technologists, managers, and other stakeholders. Projects may stall because technology assessments were not fully communicated to decisionmakers and agency staff. Agencies may not have a culture of innovation or may lack a comfortable niche for those with technical skills in emerging areas. Personnel may not have resources with which to be innovative or may not be rewarded for taking risks. (*Example from Case Studies:* Reviews suggest that there may be significant inertia and conflicting values among staff that hinders the adoption of CSS.)
- **Inadequate Skill-Mix.** Agencies may not have the required technical knowledge or the human resources to successfully assess and adopt technology. (*Example from Case Studies:* Interviewees expressed significant concerns that agencies may not have technical expertise to evaluate or implement certain ITS projects.)
- **Technical Information.** The information about a technology may also have shortcomings (e.g., if such information is poorly communicated). (*Example from Case Studies:* Decisionmakers in ITS expressed frustration at the use of technical jargon in communicating about projects.)

Other barriers are created by the larger **political, economic, legal, and social context** in which agencies operate and can affect the ability of agencies to assess and adopt technologies.

- **Investment, Legal Requirements, and Markets.** Uncertain or high deployment and maintenance costs, restrictions on funding and the fungibility of available funds, and unfavorable market conditions may make it difficult

[7] This refers to an innovation in transportation system design and process that combines street design, multimodal operations, landscaping, and streetscape investments, coordinated with land uses along the street being remedied.

for agencies to secure or use the resources to successfully adopt technologies. Public agency contracting procedures (e.g., stringent bidding requirements, policies against sole-source supplier relationships, or inefficient bid/award rules) may make it difficult for agencies to employ innovative organizations and devices. (*Example from Case Studies:* The emphasis on low-bid practices has hindered agencies from using advanced pavements that may actually have lower full life-cycle costs than other materials.)

- **Multi-Party Coordination.** Deploying almost any technology requires consensus among parties. There may not be established processes to build consensus or resolve stalemates, particularly when agencies and organizations have conflicting policy objectives. (*Example from Case Studies:* ITS projects often require—but are hindered by—coordination among transportation agencies, local governments, private companies, and public groups.
- **External Acceptance.** The success of technology also depends on consumer preferences. These preferences may not be aligned with technological offerings because of alternative preferences or cultural and social norms that work against a particular technology application. Also, users may not be familiar with or be educated about particular technologies or may misunderstand the risks and benefits of such technologies. These barriers can arise at various times during project development, from the initial inception of an idea to deployment. (*Example from Case Studies:* CSS projects faced difficulty in implementing street redesign projects because of dissatisfaction from local business owners, neighborhoods, and other stakeholders, despite strong outreach efforts.)

Potential Shortcomings of Current Technology Assessment Studies

Efforts exist to provide information on technology choices to transportation agencies. As part of the analysis, the research team wanted to better understand the extent to which such efforts provide the necessary information to address the full range of barriers to adoption. To do so, the research team employed a specific example—nondestructive evaluation (NDE) and monitoring of bridge decks.[8] This became the "laboratory" for examining the issues surrounding technology assessment and decision making in transportation agencies. (This laboratory is used again in Chapter 4 to demonstrate STREAM.) After examining available studies, the research team detected shortcomings that could limit the benefit that agencies might derive from this literature.

Few Studies Provide Guidance on Technology Decision Making

Studies designed to facilitate technology transfer in transportation provide descriptions of technologies, their benefits and drawbacks, assessments of their use, and other key information. However, agencies must ultimately make decisions about which technologies to implement, and when and how. Most reports on NDE technologies for bridge deck inspection provide little guidance on how such decisions should be made. For example, the research could not find reports describing which NDE technologies should be used in different situations (e.g., based on agency size, geography and climate, and financial resources), explaining how costs and benefits for different NDE technologies or technology bundles can be calculated, or recommending certain technologies as best practices.

This need for guidance on technology decision making is not by any means specific to NDE technologies. However, examples of guidance do exist in some technology areas and could be used as a model in others. *TCRP Report 76: Guidebook for Selecting Appropriate Technology Systems for Small Urban and Rural Public Transportation Operators* (2002) provides (1) an overview of technologies that could benefit transit operators; (2) a matrix approach to matching technologies to agencies' needs; (3) guidance on technology, cost, and other concerns; and (4) processes that agencies could use to implement the technologies. It is likely that more guidance on technology decision making would facilitate and encourage technology adoption and implementation.

A Consistent Approach to Guidance on Decision Making Seems Lacking

The studies that provide guidance on technology decision making do not appear to take a consistent approach. *TCRP Report 76* uses a matrix approach to match technologies to applications and contexts. Other studies take a cost-benefit approach.[9] Although specific guidance should be tailored to the technologies being considered, the absence of a consistent framework or integrated decision-making method means that agencies must consider in each instance how to frame the findings about technologies within the frame of reference of their own agency and determine themselves how to apply such technologies. This could pose a challenge to effective technology adoption and implementation.

Synthesis studies offer good examples of technology-oriented studies that have a clear and consistent approach across reports. Reports in the NCHRP synthesis studies series use generally consistent methods for literature reviews and

[8] Bridges consist of the sub-structure, which provides contact with the ground, the super-structure of the bridge itself, and the bridge deck surface on which vehicles travel.

[9] Although not directly related to NDE of bridge decks, see, for example, the objectives posted at http://rns.trb.org/dproject.asp?n=13581 [accessed 30 April 2013.]

surveys of practitioners and have a clear structure that permits easy identification of the objectives, scope, and other features of the report. Each study tailors this approach to the needs of its particular subject. The "tailored template" used in these series could be extended to literature on technology decision-making.

Agencies Perform Duplicate Studies in Order to Make Technology Decisions

Transportation agencies seeking to use technologies often conduct their own studies to inform decision making. Many of these studies assess the same technology application, just in a slightly different context.

In the example of bridge inspection and monitoring, the research team noted several instances of DOTs undertaking their own studies to answer the question, "How well does ground penetrating radar (GPR), a specific NDE technology, work for evaluating bridge decks?" in order to inform adoption decisions. Examples of such studies include

- "DOT Bridge Deck Evaluation Air-Launched Horn Antenna for Bridge Deck Analysis" (Maine DOT, 2006)
- "Use of Ground Penetrating Radar to Delineate Bridge Deck Repair Areas" (New Hampshire DOT, 2002)
- "Bridge Deck Condition Studies in Missouri Utilizing Ground Penetrating Radar" (Missouri DOT, 2001)
- "Feasibility of Using Ground Penetrating Radar (GPR) for Pavements, Utilities, and Bridges" (South Dakota DOT, 2006)

These studies apply similar methods in field testing GPR. Certainly, there is value in ongoing research to address the same problem, particularly as technologies evolve, and to build capacity in using these technologies. Conditions in Maine differ from those in Missouri. However, the same level of knowledge might be achieved with fewer resources because of duplication of technology testing (at the same time, little is spent on the problem of framing the basis for determining if, when, and how to adopt and implement this and other similar technologies).

This duplication raises many questions—What incentives are there for agencies conducting such studies to share them more widely? What prevents the results achieved by one agency from being used directly by another? What kinds of assessments would meet the needs of a range of agencies and how might they be undertaken?

Guidance and Individual DOT Studies May Have Methodological Shortcomings

The review suggested that studies that provide guidance for DOTs as well as DOTs' own studies have methodological shortcomings. For instance, many studies do not consider the effect of a technology on all agency goals, focusing instead on only a narrow set. The study "Feasibility of Using Ground Penetrating Radar (GPR) for Pavements, Utilities, and Bridges" for South Dakota DOT (SDDOT) uses a cost-benefit analysis to assess the value to SDDOT for adopting GPR. The study looks at the costs of technology acquisition and use on the one hand, and benefits to maintenance effectiveness and speed on the other. But, the effects of this GPR on other goals (e.g., safety, sustainability, and system reliability) could be significant and also weighed as system-relevant factors when deciding whether to adopt the technology. These issues are often skirted or treated only cursorily, in part because it is not clear how such effects should be assessed and weighted. To do so would also add considerably more complication (and cost) to the assessment process.

These Factors May Slow the Adoption of Beneficial Technologies

As a result of all these factors, the adoption of technologies may be slowed, even when technologies are mature and offer significant benefits. In the instance of bridge inspection and monitoring, GPR was tested by transportation agencies beginning in the 1980s. Time is needed between the testing of such technology and its final-form embodiment into products and services sufficiently developed to warrant consideration by transportation agencies. However, a survey of transportation practitioners found that "92 percent of the DOT bridge engineers are familiar with NDE techniques, yet the use of such techniques is minimal to nonexistent" (Abudayyeh, 2004.) Moreover, "only 38 percent of DOTs responding indicated they used NDE methods other than visual inspection for assessing bridges, while 62 percent did not use these techniques." The study further found that "DOTs (75 percent of respondents) did not have in-house criteria for selecting the appropriate NDE technique." In other words, 30 years after its development, most agencies are still not using GPR. Agencies continue to apply visual inspection, only supplemented in some cases by chain dragging and hammer sounding techniques.[10] These observations highlight that many of the obstacles that prevent expediting future technologies in transportation also apply to mature technologies.

[10] In chain dragging, a heavy chain fixed at the end of a hollow pipe is dragged across a bare concrete deck to assess the deck's integrity and to determine the extent and quantity of deterioration. In hammer sounding, an engineer taps a hammer on the surface of the bridge, using changes in the sound to detect defects.

Principles for Better Technology Assessment

The key to gaining greater mastery over technology assessment and implementation decision making is to ask explicitly: *What potential benefits to transportation agencies would come as a result of employing the technology being considered?* Technology ultimately is a means to one or more ends. Any technology is a tool for a transportation agency to carry out functions and meet goals. To reflect this relationship, technology assessment should be rooted in several guiding principles.

Principle 1: Assess and Compare Technologies in Relation to Agency Goals

What is it that transportation agencies want to achieve and how can technology assessment and implementation help them to achieve this?

The research team examined the mission documents of many U.S. transportation agencies at the national, state, and regional levels. The research team also conducted interviews with transportation officials. Their broad mission is to provide management and stewardship over their respective transportation systems. The research team further identified four goals that derive from their mission.[11]

- **Safety.** The transportation system should enable transportation that is safe for the passengers and goods being transported as well as for the surrounding communities.
- **Mobility.** The transportation system should enable people to have reliable access to goods, services, and opportunities, and facilitate travel where necessary to have that access.
- **Preservation.** The transportation agencies should apply responsible stewardship to maintain, sustain, and protect the transportation system for use by this and future generations.
- **Sustainability:** The transportation system should move people, goods and information in ways that reduce adverse environmental, economic, and social effects.

[11] Although "goals" and "objectives" are often used interchangeably, it is useful to distinguish between them for the purposes of looking into the future. Goals are broad and constant. Agencies derive goals from their mission and incorporate them into how they do business. For example, safety will always be a goal—even if an agency is satisfied with its safety record, safety will not become obsolete or unnecessary. Objectives, on the other hand, are specific targets. Safety objectives, for example, may be defined by a threshold number of crash fatalities per year in a particular state or region. As this suggests, progress toward objectives is measurable with timetables and target figures, and objectives are tailored to the agency that sets them. Although every transportation agency may have a safety goal, one objective related to a specific number of crash fatalities might be unrealistically low in a large jurisdiction and too high in a small one. Objectives are operational and thus critical to attaining broader goals.

Goals also arise indirectly and stem largely from the principles by which individual agencies seek to carry out their missions with respect to the transportation system, rather than being direct goals for the transportation system itself. The issue of technology assessment and use is a major factor in several of these:

- **Cost-Effectiveness.** Agencies should provide high-quality services and infrastructure at the lowest feasible cost.
- **Efficiency.** The transportation system should move the maximum possible number of people and goods with existing resources.
- **Equity.** The distribution of benefits and costs of the transportation system should be fair and just.
- **Multimodal Mobility.** The system should allow travel via various motorized and non-motorized modes and allow seamless transfers between modes.
- **Reliability.** The system should have predictable travel times and availability.
- **Timeliness.** Agencies should ensure that planning and assessment are carried forward in a manner that leads to decision making with minimum delay.
- **Accuracy.** An agency's technology and program assessments should be accurate in determining their value to the transportation system, drivers and barriers, and other factors or trends that would affect their effectiveness.
- **Ease of Assessment and Implementation.** Such assessment should be integral to agency processes and not disruptive or isolated activities in themselves.

These goals are unlikely to change during the course of the next 10 to 40 years: it is difficult to imagine a future in which values such as safety, mobility or cost-effectiveness are no longer valued.[12]

The examination of transportation agency mission goals on the one hand and the role of technology as a means for helping agencies meet these goals, on the other, suggest that technologies should be evaluated with respect to agency goals.

Principle 2: Derive Transportation Agency Technology Needs on the Basis of Specific Functions That Require Support

Agencies perform several functions to meet their mission goals. These include

- Planning
- Modeling

[12] The list may be added to in the same way that sustainability has become more of a consideration in the past two decades than was previously the case by broadening it to include the environmental dimension.

- Designing
- Financing
- Constructing
- Operating
- Inspecting
- Maintaining
- Researching
- Assessing

Each function involves making decisions and it is rare when the decisions for any one of these functions do not have implications for at least one of the other functions. Put simply, the list implies more of a cycle than a unidirectional flow (although this oversimplifies the relationships among these functions).

This interconnection is all the more true in the case of new technology assessment, adoption, and implementation. It could be useful to assess transportation agency technology needs not by considering technologies themselves as the crucial unit of analysis but rather as instrumental inputs to carrying out the functions the agencies perform. The functions of agencies become the central focus for technology assessment in this perspective. Technologies must be examined within that context.

Principle 3: Use Multiple Metrics to Assess and Compare Technologies with Respect to the Full Range of Agency Goals

Technologies can, in various ways, affect how, or how well, an agency performs its functions. Technologies such as variable message signs can improve traffic flow and congestion, thereby improving system operations. Technologies can also help agencies make better decisions. Often, a technology can affect functions through each of these methods simultaneously. An inspection technology might identify concrete defects more quickly or cheaply than the current state of practice and provide the same quality of information about the material being inspected. This might not change the agency's decision about repairs, but could help it arrive at those same decisions more efficiently. If it also enabled agencies to avoid roadway closures, it would improve how the agency operates the system.

Not all technologies will be beneficial in all respects. Some technologies may offer benefits at too high a cost. Technologies may also have a positive effect on certain goals while causing negative consequences for others. Multiple metrics may be needed to assess the effect of technologies on the complete range of agency goals.

Principle 4: Identify and Compare Existing and Prospective Technologies by Effect on Functional Performance Rather Than by Technology Type

Technologies should not be considered separate from the context of their proposed use. Technologies and transportation agency functions can be seen as having a supply-and-demand relationship. The functions (e.g., plan, model, and construct) and the goals that drive them (e.g., safety and mobility) make up the demand side. Technologies can change how functions are performed and improve the ability to achieve the goals that those functions are intended to serve. Thus the technology applications (e.g., smart pavements and inspection technologies) and the core scientific and technological knowledge that enables them (e.g., nanotechnology and sensors) make up the supply side. The challenge facing transportation agencies is how to identify and assess the supply of technology applications in light of the needs of transportation agency functions. Ultimately, agencies must make decisions about how to react to technological opportunities: stand by and observe developments; adopt in their current state; or seek to shape them and their development.

Figure 2-1 illustrates how state DOTs and MPOs implement technology.[13] Possible technology opportunities resulting from science and technology developments in relevant areas (e.g., civil and mechanical engineering, materials science and engineering, computer science and engineering, information and communications, and NDE) provide the "supply" and are placed within the same function-based frame of reference, even though they emerged from different industrial or technological sectors. The "demand" comes from performance requirements or capability improvements envisioned by the DOT or MPO to meet federal and state directives, as well as agency objectives for the goals of safety, mobility, preservation, and sustainability.

Technology opportunities must then be matched to meet the new performance requirements or weighed against known shortcomings with current practices. The matching process also involves consideration of costs, barriers, and other realities of the technology. Sometimes this requires additional research, either on the supply side to establish whether or not the performance requirements can be met, or on the demand side to specify the requirements and the environmental conditions under which they must be achieved. These are denoted "technology research" and "performance specifi-

[13] The process shown in the figure is intended to be normative, rather than descriptive, of the current process used by DOTs and MPOs. From the literature review and interviews of practitioners, the research team observed that barriers such as those discussed in the previous section are often considered before the matching step. Following the normative process in Figure 2-1 would allow the identification of the full spectrum of available technology applications that should be considered for adoption and implementation.

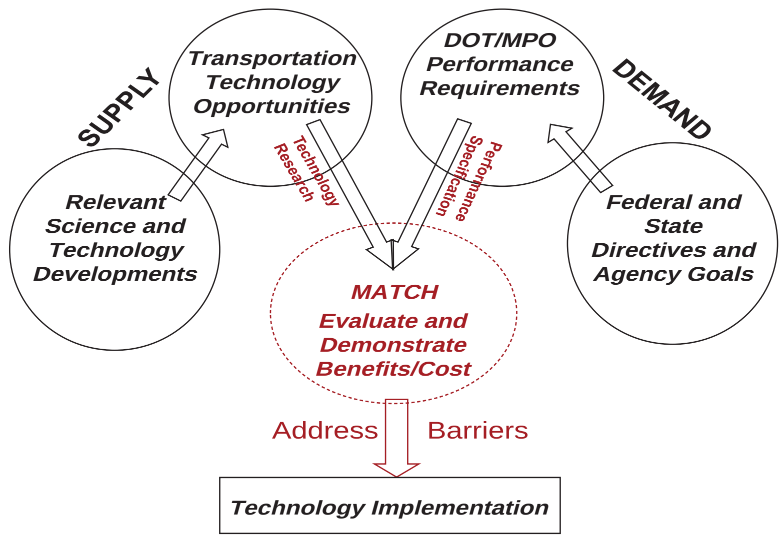

Figure 2-1. The process of state DOT and MPO technology implementation.

cation" in the figure and are necessary before it can be determined that a match can be made.

Once a match is made, two important tasks remain before the technology can be implemented. The first is evaluation and demonstration of the benefits and cost of implementation under the specific conditions of the application when compared to alternatives for accomplishing the same tasks, including the existing means. If, after this first step, the agency decides to move ahead with implementation, the agency must then address barriers such as winning institutional and public support, obtaining funding for implementation and any operations and maintenance support that will be needed, including training. [14]

This perspective suggests that the taxonomy according to which technologies should be examined should not be that of the familiar disciplinary and historical categories (e.g., materials, informatics, and software engineering). Instead, technologies from any and all potential sectors should be considered in light of how they may affect specific agency functions. That is the relevant taxonomy. Positive outcomes in terms of agency mission goals may be achieved by performing a particular function more effectively by using one or more from among a wide range of technological enhancements which assist that function. These should be assessed in relation to each other, rather than within the more narrow technological subdivisions to which most technology assessments confine them.

[14] The less normative and more descriptive the depiction of this supply and demand balance, the more that the barriers we have described above might come into play and affect the outcome of the matching. Different technological approaches to enhancing a particular function may raise different types of objections and be affected by barriers differently.

Principle 5: Include Current Knowledge About Existing and Prospective Technologies Within a Common Framework for Assessment, Tracking, and Decision

One of the largest issues involved in assessing technologies for adoption by transportation agencies is that of technological maturity. There is understandable reticence to make a large investment in technology today only to discover during the planned lifetime of the newly adopted technology that an even newer alternative is available that is superior in performance, cost savings, or both—or may even render the prior innovation obsolete.[15] This problem increases with the rapidity and ubiquity of change, especially if the principle of considering potentially useful applications widely across technology sectors is adopted.

The difficulty in avoiding this situation is precisely that technologies exist at varying levels of maturity. Generally speaking, the more mature a technology along the process leading from prospective vision through design, testing, marketing, application and wide-scale use, the greater the information about inherent capabilities, actual performance, various associated costs, and unforeseen problems. Technologies that may have been immature when a decision was made may be farther along by the time the selected older technology is still being implemented.

Nothing can resolve this uncertainty reliably and with confidence. What is of potential use to agency planners and decisionmakers is to have a framework that permits a more

[15] These concerns may be considered minimal from a purely technical perspective. They loom large in the sociology and psychology of decision making within a hierarchical government organization such as a transportation agency.

sophisticated and easily updated perspective that will allow them to include and reflect the state of knowledge about individual technologies and to include this knowledge within a common field of information.

Principle 6: Make the Assessment Process Less Disruptive to and More Integral with Regular Agency Functions

Several issues make discussion of technological alternatives difficult within transportation agencies. One of the biggest is the difference between the normal flow of work in those departments largely associated with planning functions and those concerned with the actual operations of the transportation system being administered. These offices not only perform different functions but have different time horizons, are attuned to different schedules, and often draw on different resources. This is true to a greater or lesser extent among the various functions that these two broad headings of planning and operations may be divided into.

In addition to this difference in perspective between planning and operations, it is also difficult to assess not only the possible direct effects of a technology but also account for what might be the indirect effects either on that function or on some other agency function not actually under consideration. Gaining cognizance of these indirect effects may be achieved by widening the circle of participants in the technology assessment process. But this may then have deleterious effects on the efficiency and timeliness of the process itself, even if some basis may be found for doing so.

Beyond this, there is a problem that all organizations face when confronting the increasing ubiquity of technology coupled with the rapidity of technological change—translating the results from analysis and assessment into usable input for decisionmakers is difficult. All too often, such analyses are carried out as exceptional exercises that by their nature are either disruptive to or isolated from the main daily activities of the organization carrying out the assessment. This makes such exercises potentially upsetting to normal functions (and therefore perhaps even unconsciously viewed as a threat to being able to carry out those functions) or divorced from the actual terms in which decisions are actively discussed and eventually made.[16]

[16] Those activities carried out by parts of organizations that may be viewed as threatening by most other members of the organization are referred to by managerial theorists as "precarious values." Such activities are under perpetual threat of minimization or elimination by those who often act out of a genuine desire to enhance a focus on primary mission goals.

Minimizing the potential for such actual disruption, or the perception of technology assessment activities as either threatening or irrelevant, is important. To the extent that the actual decisions that eventually will need to be made can become integral to and the basis on which analysis and assessment are conducted will make this transition less abrupt and more seamless.

Principle 7: Provide Sufficient Information to Understand the Degree of Uncertainty and Enable Flexible Operation Under Evolving Circumstances

The assessment process must help agencies compare and choose from among technologies now and in the future. Many technology applications can affect each function that agencies perform. The assessment process must help agencies assess and compare how different technologies affect each of the goals, and then must help agencies make decisions about technologies—which ones to adopt, which ones to shape, which ones to monitor, and so forth. Agencies will need to assess technologies available now and those that will be available in the future. Agencies will also need to assess technologies periodically to keep up with new developments.

The state of knowledge is not perfect nor can it ever be. Uncertainty is an inherent part of technological innovation and adoption: It is not a failure of due diligence but inherent in the enterprise itself. This simple truth is absent from many exercises in technology foresight and assessment. It is sufficiently important, indeed the heart of the difficulties experienced by agencies in technological decision making, that it should be stated explicitly and confronted directly in any assessment method or specific application.

The Virtue of Simplicity

An eighth, over-riding principle governed the research team's work on STREAM. Any assessment method needed to be practical and usable. Complex evaluation methods were avoided and instead the research team asked what was essential; the research team refined the method so that it would provide the greatest benefit while maintaining accessibility. STREAM is intended for the staff in DOTs and MPOs who need to understand and explain the differences in potential between different technology alternatives.

CHAPTER 3

STREAM: A Systematic Technology Reconnaissance, Evaluation, and Adoption Method

The findings presented in the previous chapters suggest the value of a process that overcomes some current barriers while acknowledging and accommodating the realities of others. STREAM is built on the seven principles set forth in Chapter 2. STREAM is

- An **explicit description of a five-step process** for technology assessment and decision making that outlines key decision points;
- An attempt to de-mystify as well as to provide a **common framework and vocabulary** for discussion, evaluation, and knowledge sharing within and among transportation agencies, and between transportation agencies and stakeholders;
- A **best practice checklist** and a framework for improving the quality of agency evaluation and adoption decisions[17]; and
- A means for providing a **forensic checklist** for understanding better which steps or stages have proven to be obstacles;

There are two aspects to STREAM. First, is the technical method itself. STREAM proceeds in five overarching steps as shown in Figure 3-1. In this representation, STREAM is shown as a linear process for ease of explication; however, the flow of the assessment and evaluation processes in practice is not likely to be linear—it is likely to be more recursive and bi-directional, and successive phases will themselves cause a re-evaluation of what has gone before.[18]

Chapter 3 describes these steps briefly. A fuller discussion of STREAM, provided in Chapter 4, grounds the method in a proof-of-principle application, an examination of NDE technologies for bridge deck evaluation. Appendices B and C provide two additional applications of STREAM—first to a materials technology application and then to a problem of information gathering and communications.

The second element is how STREAM should be implemented: by whom, how, and when for each step. This is discussed in Chapter 5. The efforts required from an individual agency may not be equivalent along the full course of a STREAM analysis. In particular, the first three steps could lend themselves to formal collaboration among several agencies, by some collaborative institution, or to informal knowledge transfer among agencies. In each instance, the latter steps would require an agency either to take the initial findings of that joint or external effort and then particularize it by applying the characteristics of its own local situation or to use its own output from itself applying STREAM and carrying out the latter steps. It is the "open architecture" design of STREAM along with the standardization of approach that can make this economy and efficiency of effort possible.

[17] Analyses of successful instances of technology assessment and implementation in transportation might well disclose a pattern in which all or most of the STREAM steps would have been followed. Illuminating the process should help this become the routine, rather than the exception. DOTs and MPOs tacitly but widely regarded as technology "leader" agencies may have in many cases performed well in analyzing adoption decisions regarding technologies that are either mature or may become so within 5 years for functions that they undertake and understand. This is less the case for technologies 5–20 years away and how those technologies might reshape agencies' functions.

[18] Several times when large corporations or other multi-level organizations were confronted with results from the introduction of new technologies that were less than expected, they found it necessary to examine in detail – often for the first time–their process and methods. In this sense, the need to comprehend the possible result from new technology led to a systematic accounting of the function and context of the production process. In this sense, coming to some common methodological framework such as STREAM may mean that new technology assessment and introduction may become the lens for a re-examination by transportation agencies of their own functions and their relationship to mission goals.

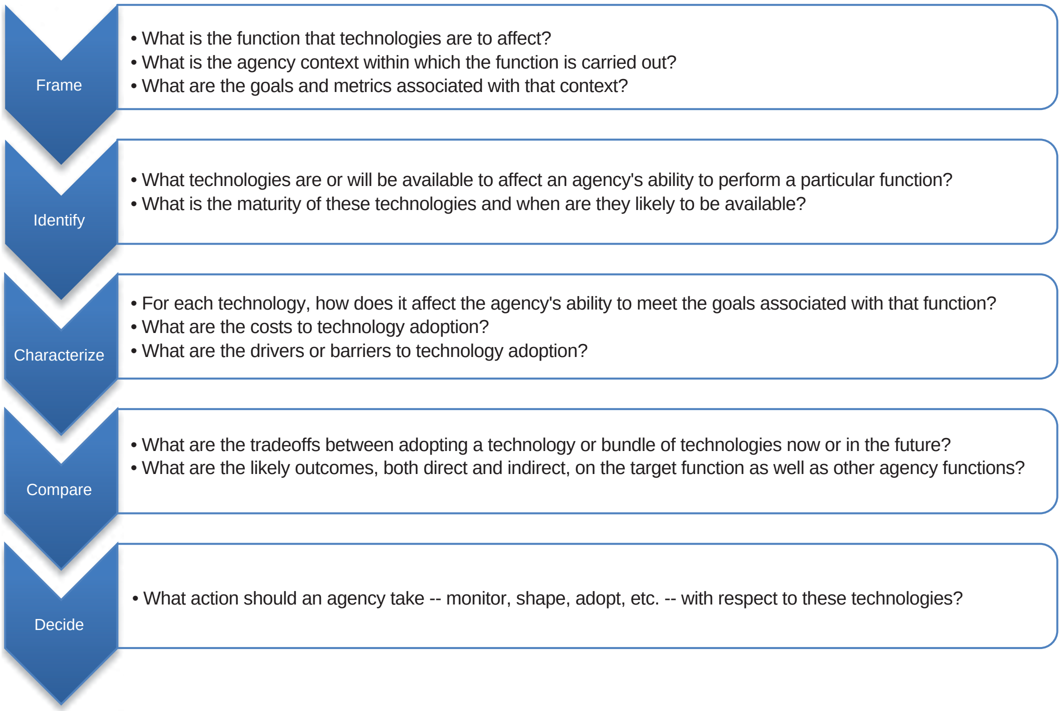

Figure 3-1. The major steps in the STREAM process.

Step 1: FRAME the Problem and Specify Goals

The Frame step is the foundation on which the subsequent steps are based. In this step, decisionmakers make explicit the following:

- The agency functions for which alternative technologies are being considered[19]
- The goals on which the functions bear
- The objectives and metrics by which each goal should be measured

This helps establish a common understanding of the decision's objectives and criteria, both within an agency and for other agencies that may turn to the analysis for guidance.

The Frame step may appear simple and straightforward. That in itself is a problem because in many ways it is both the most important yet also the one most often missing from transportation sector technology analyses or is given only cursory treatment.[20] The absence of explicit framing may contribute materially to many of the downstream difficulties that have previously been presented as barriers to the more rapid adoption of transportation-relevant technologies.

In keeping with the core philosophy embodied in STREAM, the Frame step originates from the demand side (i.e., understanding the needs of the agency).[21] The most important result from this step will be the set of criteria against which any technological solution may be judged. For a single agency function, several transportation agency mission goals might be affected. For each, there should be a specific measure that can then be applied to assess different technologies in the later stages of the STREAM process.

There will be practical considerations. One challenge will be to identify both the function and context at an appropriate level of abstraction. To borrow from the example discussed extensively in the next chapter, NDE technologies are aimed at the inspection function but also affect the agency role in maintaining infrastructure and perhaps even in better modeling.

The framing of particular functions and goals should lead to similar results, even if undertaken by different agencies.

[19] In this step it will be important to specify how the function is being served, so that, in the next step, technology applications can be considered as improvements within the current approach or introducing a new approach.

[20] Organizations are charged with identifying and disseminating best practice or more widely publicizing the results of trials performed at DOTs or the federal level. Although these organizations provide a valuable service, they do not routinely incorporate the explicit contextual discussion intended with the Frame step.

[21] This step could be part of a grand, comprehensive assessment of transportation agency missions, functions, and capabilities assessment. This would be a massive undertaking. Something similar is conducted annually by TRADOC, the U.S. Army's Training and Doctrine Command. Rather, the research team envisions activities resembling the assessments of capability gaps and potential technology solutions performed by the Centers of Excellence (see National Institute of Justice, 2011, pp. 93–94, available online at https://www.justnet.org/pdf/NLECTC-System-2011-Annual-Report-508-compliant.pdf).

Agencies may perform the functions of surface transportation stewardship slightly differently, but the existence of a document such as the AASHTO *Bridge Inspection Manual* (and other similar widely used standard documents such as the *Highway Capacity Manual* for other routine functions) suggests that agencies are performing the same essential functions with similar mechanisms and for similar purposes. Thus, interagency collaboration at this stage of STREAM may be beneficial in contrast to having agencies do so in a manner that masks this fundamental similarity.

Step 2: IDENTIFY Potentially Appropriate Technology Applications

The Identify step is a comprehensive screening process to determine which technologies are within or beyond the scope of the decision at hand. This step identifies technologies or differing applications of technology that are available, will become available, or prospectively could be available to affect an agency's ability to perform the functions noted in the Frame step. Identifying appropriate technologies requires some characterization of each of them, including a description of

- The technology itself (i.e., what it is and how it works);
- How it could improve on the current approach to the agency's function, or introduce a new approach;
- The literature that establishes performance and maturity, with references.

The initial description begins the process of fully characterizing technologies, the focus of the next step.

Step 3: CHARACTERIZE Alternative Technology Applications

This step builds on the first two to provide quantitative and qualitative assessments of key characteristics of each technology and how each may affect agency functions and goals. This step also involves selecting those technologies or technology bundles that will be compared in the next step.

Whereas the Frame step is the most challenging conceptually, this is in many ways the most technically challenging step. It requires assessing key characteristics of technologies (e.g., how well they work, risks, costs, and benefits). This process is likely to bear largely common results for different agencies. If conducted in a formally collaborative manner or with informal communications between agencies, the results are also likely to be more systematic across such technology application assessments as well.

Again, an aspect of STREAM that may at first appear to be obvious or even simplistic is none the less crucial: characterizations will be in terms relevant to the agency's functions and decision process rather than in terms of more technology-specific attributes.

Technology can be characterized according to the following dimensions:

- The effects of the technology on agency functions and their resulting influence on (all) agency mission goals,
- Performance requirements to achieve the overarching function and goals,
- Net costs of adopting the technology, and
- Potential barriers to the successful implementation of the technology.

These quantitative and qualitative characterizations will require subject matter expertise and should be made based on the best available data on technology development and demonstrated performance, taking into account the current state of practice of DOTs and MPOs in carrying out the functions in question. That notwithstanding, the goal is not necessarily to achieve consensus in these characterizations. For both current and potential technologies, there are often legitimate, irreducible uncertainties about their impacts, costs, and barriers to implementation. STREAM helps make these explicit and useful in comparing technologies.

STREAM also accounts for the time dimension, allowing comparisons between technologies with different expected maturities while supporting comparison among technologies expected to be of the same vintage.[22] This last feature enables an agency to make a single evaluation of technologies that are ready for implementation as well as more prospective technologies. STREAM would tend to rate the latter less highly (largely because of the inherently greater uncertainty, as will be seen later), but it would allow agencies to make better-informed decisions about when and to what degree to commit to a given technological course in light of possible development

Characterizing Effects on Agency Missions

The potential benefits to agencies from successful implementation of a given technology would be framed in terms of the goal-based measures developed in the Frame step. The relationship between agency functions and mission goals and the potential for achieving more favorable outcomes by enhancing the capacity to perform these functions are characterized in detail. For each goal, a scale of measurable benefit

[22] An assessment could consider a technology in the 0–5 year time frame along with those expected only to appear in the 5–10 year time frame or could use the same approach to only look at technologies that would fall into the same (e.g., 5–10 year or later) period of envisioned implementation.

Table 3-1. Sources of impediments that reduce POSI.

Category of Impediments	Specific Barriers Affecting POSI
Technology	Unfamiliarity with core or applied technology
	Uncertainty concerning actual performance
	Additional implementation requirements (training, standards, etc.)
Agency Process or Institutions	Need for new or conflict with existing regulations or standards
	Non-fungibility of funding for required expenditures
	Extended or problematic approval processes
External to Agency	Inertia of existing processes and methods
	Insufficient political or public acceptance
	Lacking presence of necessary vendor or support base

is applied and each candidate technology is rated according to that scale. The ranges of informed opinion on each potential benefit are retained at this point. Too-early consensus, especially in the absence of data that could conclusively dispose of uncertainty and ambiguity, would actually be wasteful of the information currently available. Rather, ambiguous information and divergent opinions will be retained in the STREAM analysis and become an important aspect of the later step involving detailed comparisons among technological alternatives.

Characterizing Barriers to Successful Implementation

The next task of characterization is to weigh and evaluate things that could go wrong, especially those that go beyond the purely technical. For this purpose, the Characterize step requires developing for each alternative a composite measure, or score, that represents the probability of successful implementation (POSI).

The research team developed the POSI score by synthesizing the information received from the interviews, the literature, and the empirical case study work conducted by University of California, Berkeley, researchers, as well as input from staff at Berkeley PATH. The STREAM procedure for determining POSI consists of looking at three major categories of impediments—those that arise from

1. The technology itself,
2. Process or institutional issues at the level of or within the agency, and
3. External concerns.

Each of these three categories of impediments is judged to be of

- Negligible or no concern,
- Small concern,
- Major concern, or
- Significant concern.

A small concern is one that can be dealt with relatively easily as judged in local terms, a major concern is one that would require actions that could be difficult or challenging to carry out, while a significant concern would require action that might not be possible or practicable. These definitions are deliberately loose. Those conducting a STREAM assessment would provide their reasoning behind such assessments. Assessments carried out on a collaborative basis or by another agency will provide a rationale behind the POSI component scores. These then may be modified or accepted by other transportation agencies in light of local circumstances.

For each large category, there are three specific barriers as shown in Table 3-1. Each one would be subject to quantitative or qualitative assessment. STREAM was designed to allow for simplification where this would not lead to serious misjudgment. Though a limited list, these nine impediments account for most obstacles that arise.

Technologies of different vintages would likely be scored differently from those currently available. Current technologies would presumably present fewer concerns about several of the barriers because agencies are more familiar with them and processes may be in place to support their implementation. For the same reason, there may be less uncertainty about barriers to implementing currently available technology. This is one way that STREAM allows technologies of dissimilar maturity to be assessed within the same analysis. It also provides a convenient entry point for updating as more information becomes available.

Once these assessments are made, a single POSI value is assigned to the technology according to the scale shown in Table 3-2. The conditions in Table 3-2 are not necessarily the only ones on which the POSI score could be assigned.[23]

[23] This approach displayed in the table was arrived at after considerable theoretical and empirical discussion that considered a wide range of alternative approaches. It appears to meet the design criteria sought by the research team, particularly the balance for both explicit expression of underlying assumptions and simplicity of application. For these reasons, the research team chose to use four-level measures at several points in the STREAM process. This simplification did not appear to constrict the ability to use sophisticated reasoning in the actual valuation assignment process while allowing for considerable generality.

Table 3-2. POSI evaluation for a technology based on level of expected impediments.

POSI Score Level	Conditions for Achieving POSI Score Level
4	Number of Major concerns = 0
3	Does not meet criteria for POSI score level of 1, 2, or 4
2	Number of Significant concerns=1[24] -**or**- Number of Major concerns > 2
1	Number of Significant concerns > 1

The advantage is that this allows a single metric to be constructed from what otherwise would be a heterogeneous set of potential obstacles, some of which might be quantifiable in natural unit terms while others of which could only be reasonably assigned a qualitative measure. The three examples of STREAM in application (in Chapter 4 and Appendices B and C) demonstrate the flexibility inherent in this approach to POSI scoring.

Characterizing Costs

Several aspects of cost shaped the approach to incorporating the cost factor into STREAM.

- Costs must be considered apart from barriers because they are fundamentally different.
- Costs should be calculated on a net basis.
- Local context is of great concern in measuring costs.

A simple approach to cost is necessary but difficult to achieve. The STREAM design team concluded that an approach that places cost information at the disposal of a transportation agency when considering technology adoption alternatives but that does so in a simple, tractable manner is most appropriate.[25]

Complicating Features of Cost

Costs are not simply another potential barrier to adoption and they cannot just be made another component of POSI. The probabilistic approach used to construct the POSI score cannot be applied to cost. A key feature of the POSI score is that the larger the number or severity of barriers, the less chance for successful implementation. This is not true for costs. Although a less expensive alternative is preferable to a more expensive one when all else is held constant, it is rarely the case that such a direct comparison can be made. Sometimes the more expensive alternative might be considered desirable if it yields a higher probability of success, a greater expected benefit, or both. Thus, costs need to be considered on their own.

All costs should be calculated on a net basis. So, for example, costs of acquisition, personnel, and maintenance should be net the value of redundant equipment that could be sold on the secondary market, personnel and maintenance that otherwise might have been required, and so forth. This would include consideration of tasks that no longer need to be performed as a result of adopting an alternative technology under consideration. Further, one-time costs required at the time of adoption should be distinguished from recurring costs that will be required during the effective life of the adopted technology.

Local issues are of great concern in measuring costs. We have previously spoken of the problem of fungibility among sources of funds which we have accounted for in the POSI score. Budgets may differ in the extent to which either category of cost, fixed or recurring, might prove a problem on the local level. Cost also has both absolute and relative dimensions. Although a particular capital investment may cost $1M no matter where it is purchased, one DOT may require ten, while another requires one hundred. There is also a local, relative dimension to the consideration of costs that is particular to each DOT. The $10M required of a smaller DOT may be viewed locally as a greater challenge than the $100M required of a large DOT, or vice versa.

Cost Characterization Method

Given these considerations, cost considerations in STREAM are separate from but similar to the POSI measure. The characterization of cost within STREAM, shown in Table 3-3, is similar to the one the research team designed for assessing the constituent factors of the POSI score. It divides costs into fixed and recurrent costs and lists the different potential categories of such costs.

[24] While it might appear counter-intuitive that any technology with a Significant concern should receive a POSI score other than 1, this classification scheme accounts for possible uncertainty in evaluation. It is probably also best to think of the difference between Significant and Major concern as more of a gradient than a strict division. Therefore, and perhaps over a longer period of time, it would seem that if there is only one major Significant concern it could well become a focus of greater attention which might result in accommodations allowing it to be re-categorized as a Major concern.

[25] Costs could be rigorously traded off against benefits in a manner consistent with decision theory but only through significant data gathering and complicated mathematical algorithms made even more complex, if not insoluble, by the presence of uncertainty. In keeping with the philosophy behind STREAM, the research team developed a more straightforward way to bring cost into the realm of agency decision making.

Table 3-3. Factors affecting fixed and recurring cost and discounted net cost.

Category of Cost	Specific Cost Factor	Discounted Net Cost
Net One-Time Costs	Acquisition (net the value of redundant equipment)	
	Taxes/Penalties/Fees (net TPF no longer required)	
	Licenses, Royalties, etc. (net)	
Net Recurring Costs	O&M (net O&M costs of equipment made redundant)	
	Training (net training no longer required)	
	Taxes/Penalties/Fees (net TPF no longer required)	
	Licenses, Royalties, etc. (net)	
	Personnel (net personnel made redundant)	

Table 3-4. Cost evaluation for a technology based on agency-specific considerations of cost.

Cost Score Level	Conditions for Achieving Cost Score Level
4	No net cost or net cost savings
3	"Little" net cost
2	"Major" net cost
1	"Excessive" cost

The range of estimates for the discounted net cost produced by each specific cost factor will, in sum, determine the range of total fixed and recurring costs for the candidate technology being evaluated.[26] The output must state how the scale of deployment (e.g., the necessity to purchase one versus 100 units) affects cost, so that in future iterations (e.g., one that would require acquisition of 50 units) the analysts can also calculate costs. This scaling can help other transportation agencies use the same calculation method for their own needs.

In addition, the factor used to discount future costs back to the present must be made explicit. This, too, is something that will vary given the situation of each transportation agency and so must be amenable to being tailored.[27]

The result of this process is a calculation of estimated discounted net cost associated with each technology alternative by component of cost as well as in aggregate. However, this is not applied as a raw score directly into STREAM because the effects of costs vary among agencies. Instead, each transportation agency assesses what this balance of cost means for them. One possible approach to doing so is illustrated in Table 3-4.

This assessment carries some subjectivity and the meanings associated with each score level are designed as relative terms: what may be "Little" net cost to one agency may, because of various factors, be seen as "Major" cost by another. These weightings can be subject to different opinions and assessments and so, as with both POSI and the calculation of benefit, would be amenable to a Delphi-type treatment in which the assessments of individual assessors can be aggregated and uncertainty ranges disclosed.

Several issues associated with costs are not accounted for in the quantitatively based assessment of net cost presented in Table 3-4. Different technology alternatives may involve a shifting of cost centers either within or between organizations. This is related to but distinct from the question of differential fungibility discussed above. These issues provide additional reasons for rejecting the purely mathematical treatment of costs in relation to benefits. The goal is not to provide a *deus ex machina* approach that will automatically derive a solution on technology adoption decisions by agencies, but to create a framework that will fully account for and present actual decisionmakers with the factors necessary for decision while also accounting for the nuances that will affect that decision.

Step 4: COMPARE Technology Alternatives and Tradeoffs

This step uses a series of visualizations and other presentation techniques to compare key characteristics of each technology which may have differential effects on agency functions and goals.[28] Decisionmakers can use these visualizations,

[26] Taxes, penalties, and fees, as well as licenses and royalties, appear as both fixed and recurring costs. This is to allow for the possibility of both one-time and recurring charges being required for a particular technology being assessed.

[27] The discount rate will determine the extent to which the benefit or burden between generations will be shared. Discount rates may differ because of differences in philosophical approach, local law or regulation, or local financial considerations.

[28] During this study, the research team developed an Excel-based software tool for use in the Compare step to generate figures that plot the characterization data developed in the previous step.

together with the context in which the technology applications are to be applied, to examine the tradeoffs between alternative technology applications.

This step is discussed in greater detail in the next chapter in which an in-depth treatment is presented by application to a specific function performed by transportation agencies. These visualizations offer a consistent approach for comparison, as opposed to requiring each agency to determine what techniques should be used for evaluating technology options. With wide use of a common approach, the experience of one agency can be made more meaningful to another and collaborative assessments can also be produced. It then would fall to the agencies to carry out the comparison but with greater hope of consistency, foundation in a wider range of goals, and with more definitive results with greater integration into other existing ongoing processes.

Step 5: DECIDE: Adopt, Shape, Monitor, Research

In this final step, decisionmakers determine what the agency's response should be to technological opportunities for enhancing agency functions and the ability to achieve mission goals. The decision framework takes into account tradeoffs described in the previous step and the local context and constraints. The purpose of STREAM is to present a plausible basis for making these decisions by creating a detailed guide to which an agency may then refer.

Transportation agencies may adopt different postures when presented with technological alternatives:

- Ignore such an opportunity entirely
- Monitor developments and the accumulation of more information
- Engage in research to generate information about one or more technological options
- Engage in various shaping activities to influence the pace and directions of development of promising technologies
- Move forward with adoption and use within their own agency

Given that the ultimate decision rests with the individual transportation agencies themselves, agencies require a sound basis for their decisions. Agencies also require an understanding of the choices available to them. In some cases, the decision is simply one of whether to adopt a particular technology application or not. In many cases, the combination of differences in technologies, different applications that embody those technologies, differences in likely dates of maturity among technologies, and the differing specific characteristics of technologies will suggest a richer set of possible choices. A decision to monitor developments is one that would be warranted by sufficient uncertainty about what the eventual characteristics might prove to be for a rapidly developing technology. In addition, agencies can, either individually or collectively, seek to shape the course of development. This step therefore requires sufficient preparation by performing the preceding steps as well as a means to determine the stance best taken given the circumstances of each agency.

CHAPTER 4

STREAM in Application: Bridge Deck Evaluation

Researchers at the Georgia Institute of Technology are developing a novel technology that would facilitate close monitoring of [bridge] structures for strain, stress, and early formation of cracks. Their approach uses wireless sensors that are low cost, require no power, can be implemented on tough yet flexible polymer substrates, and can identify structural problems at a very early stage. The only electronic component in the sensor is an inexpensive radio frequency identification (RFID) chip. Moreover, these sensor designs can be inkjet printed on various substrates, using methods that optimize them for operation at radio frequency. The result would be low-cost, weather-resistant devices that could be affixed by the thousands to various kinds of structures.[29]

This chapter presents an application of STREAM to illustrate how each step could be applied to bridge deck inspection and monitoring. This allows us to discuss STREAM more fully while keeping the treatment rooted in practical application. This chapter presents only a cursory analysis of the various technologies associated with bridge inspection and monitoring.

The research team selected the function of bridge deck inspection and monitoring for several reasons:

- There are many different alternative technology approaches to performing these functions, with no clear indication that one dominates the others. Some are emerging, while others (e.g., GPR) have been available for some time. This presents an instance where many technology choices are present at differing states of maturity but there has been no clear movement toward any one – or, indeed, for moving beyond the state of practice current for most of the 20th century.
- These technologies represent a wide range of different technological sectors and approaches. This allows us to examine how they can be placed in a common field for assessment.
- This example is relevant to many stakeholders in that it spans planning (and long perspectives) and operations (and shorter term concerns). All participants in the technology assessment and adoption decision at the agency level need to find sufficient value in STREAM for it to be accepted for wider utilization.
- The research team possessed some prior exposure to this area.

Step 1. Framing Bridge Deck Evaluation for STREAM

The United States has approximately 600,000 bridges (AASHTO, 2008). This represents the largest inventory of bridges in the history of the world and one that has had a remarkable safety record. However, the inventory is aging during a time of unprecedented cost increases and limited resources for making repairs. The 2008 AASHTO report, *Bridging the Gap,* points out that 50 percent of the nation's bridge capacity, measured in terms of deck area, is between 35 and 55 years old – the age range during which structural repair needs increase (p. 11). The same report notes that "[b]ridge rehabilitation needs dwarf the amount of funds currently available and compel states to remain in a 'triage' mode of managing deficiencies as best they can for the next foreseeable decades" (p. 30). Sustaining this bridge inventory is a critical issue for the nation (p. 13).

Motivating the Use of STREAM for Bridge Deck Evaluation

Bridge inspection is the basis for identifying and prioritizing maintenance. The most frequently used form of inspection

[29]"Wireless "smart skin" sensors to provide remote monitoring of infrastructure," R&D website, 17 April 2013 (http://www.rdmag.com/news/2013/04/wireless-smart-skin-sensors-provide-remote-monitoring-infrastructure?et_cid=3201021&et_rid=524660799&linkid=http%3a%2f%2fwww.rdmag.com%2fnews%2f2013%2f04%2fwireless-smart-skin-sensors-provide-remote-monitoring-infrastructure. Last accessed 1 May 2013.)

Table 4-1. AASHTO guide manual condition states for bridge decks.

Condition State 1	Condition State 2	Condition State 3	Condition State 4
Do Nothing Protect	Do Nothing Protect	Protect Repair Rehabilitate	Rehabilitate Replace

is by human vision. However, the subjectivity of inspections and the absence of coordination among inspection, maintenance, and bridge design are seen as significant technical barriers to effective bridge management (Oh et al., 2009; Aktan et al., 1996; ASCE-SEI, 2008; Graybeal et al., 2002). One study notes:

> There is uncertainty in measuring bridge performance as it is not well defined, understood or documented. It relies too heavily on expert opinion and not on objective data, and it is based on significant assumption or generalization based on very simplistic understanding of bridge behavior. (ASCE-SEI, 2008, p. 21)

Accurate data on bridge performance has been noted as particularly important in facilitating an integrated approach (ASCE-SEI, 2008). Coupled with the growing need for bridge repairs and declining resources available to carry them out, this suggests that improving inspection methods and "encouraging a circular design process that better integrates design, construction, inspection, maintenance and research" (Spy Pond Partners, 2010, p. 55 referencing ASCE-SEI, 2008) are matters of urgency.

These considerations provide an explicit framing for STREAM. We focus on the technological possibilities of improving the function of nondestructive evaluation of bridge decks as carried out by transportation agencies.[30] As emerged through discussions with experts and DOTs, this function addresses transportation agency mission goals of preservation and mobility.[31]

[30] We illustrate the method with the example of bridge deck inspection. However, bridge decks/slabs are one of 12 "national bridge elements," and complete bridge inspection requires determining the condition state of each of these elements, as well as 5 "bridge management elements" (e.g., joints and approach slabs). Carrying out a STREAM exercise for all of the elements that exist on a specific bridge or bridge type would identify the best technology alternatives for each element and would elucidate any synergies that might make a particular technology attractive when the entire bridge is considered.

[31] STREAM focuses decisionmakers' attention on a function's main mission goals, though a function may have many secondary goals. Bridge deck inspection also affects safety, to the extent that cracks in the bridge deck create unsafe driving conditions and inspection is a safety hazard for inspectors. It also affects environmental sustainability, e.g., through added emissions from delays on a bridge undergoing inspection. These minor mission goals for bridge deck inspection are ignored so as to concentrate on the major mission goals.

Definition of Metrics for Bridge Deck Evaluation

First, a metric for each of the mission objectives of preservation and mobility needs to be developed. One could try to measure these in their end-units, e.g., preservation in terms of the cost of maintaining bridges or mobility in terms of the number of vehicles-hours of delay; however, these measures are difficult, if not impossible, to estimate as they are functions of many uncertain factors (e.g., traffic volumes) which vary from location to location and over time. In practice, it is effective and appropriate to consider more directly measurable differences in the technologies. For this example, we measure preservation in terms of a technology's ability to distinguish the condition state of the bridge, and we measure mobility in terms of the number of hours a bridge lane must be closed in order to use the technology for inspection. For each metric, performance thresholds on a 1–4 metric value scale have been developed, which allow comparison of performance across metrics with different natural units.

Metric for Preservation

In this example of bridge deck inspection, preservation is measured in terms of how well each of the technology alternatives can determine the condition state of the bridge deck. The AASHTO Bridge Guide Manual referenced above defines four condition states for several types of defects (e.g., cracks, spalls, delaminations). The higher the condition state, the greater the underlying damage and so the greater the need for action. For each Condition State, the Manual recommends different feasible actions, as shown in Table 4-1.

For Condition States 1 and 2, either nothing is done or some prophylactic measures are taken. For Condition State 3, repair and rehabilitation are considered. For Condition State 4, protection and repair are not even considered, and, in addition to rehabilitation, replacement is considered. The value of an inspection technology resides in its ability to distinguish between condition states, and especially in its ability to distinguish Condition States 3 and 4 from Condition States 1 and 2, as well as from each other, because the actions to be considered differ significantly in the last three condition states. Thus, failure to correctly identify Condition State 3 or 4 may lead to not recognizing the necessity of repair, rehabilitation,

Table 4-2. Preservation metric for bridge deck evaluation technologies.

Metric Value	Metric Definition
1	Inability to distinguish Condition State 3 or 4 from Condition State 1 or 2
2	Ability to distinguish Condition State 3 or 4 from Condition State 1 or 2, but inability to distinguish Condition State 4 from Condition States 1, 2, or 3
3	Ability to distinguish Condition State 3 or 4 from Condition State 1 or 2, plus ability to distinguish Condition State 4 from Condition States 1, 2, or 3;
4	Same as Metric Value 3, plus ability to characterize bridge element condition sufficiently to provide quantitative input to bridge design models.

Table 4-3. Mobility metric for bridge deck evaluation technologies.

Metric Value	Metric Definition
1	Lane closure required for more than 10 hours
2	Lane closure required for 5-10 hours
3	Lane closure required for more than 1 but less than 5 hours
4	If lane closure required, duration is less than 1 hour

or replacement with potential negative influence on the goal of preservation. Preservation metrics are defined in Table 4-2.

Metric for Mobility

Effects on mobility of bridge deck inspection will primarily result from bridge closures and the associated traffic jams. This metric is based on the extent to which lane closures are required to complete an inspection of the bridge deck, with the metric values provided in Table 4-3.[32]

Step 2. Identify Technology Applications for Bridge Deck Evaluation

Current State of Practice

This step includes establishing the current state of practice in the function of concern. This forms the baseline against which other technologies are characterized and compared in the Characterize and Compare steps. Accepted practice for bridge deck NDE in the United States is for an inspector to walk the bridge deck and perform a **visual inspection**. The inspector sometimes augments visual inspection with **audible inspection** methods, such as chain dragging or hammer sounding. Visual inspection has been shown to be relatively inaccurate. In one controlled study, multiple inspectors were asked to rate the same bridge deck. The study found that only 68% of inspectors agreed to within one ranking out of ten, and that important defects are likely to go undetected (Graybeal et al., 2002, p. 82). Visual inspection also requires one or more lanes of traffic to be closed during the inspection which can take from 1½ hours (for visual inspection) to as much as 12 hours (if audible inspection methods are used).

Current and Prospective Technology Alternatives

The next step is to scan and inventory current and prospective technology alternatives. Many diverse technologies for bridge deck inspection and monitoring exist and Table 4-4—drawing on studies from the Minnesota DOT (Gastineau et al., 2009) and a workshop on bridge performance (ASCE-SEI, 2008)—provides an initial inventory.

These technologies vary along several functional dimensions. They can be used for short- or long-term monitoring, to assess local or global bridge features and performance, and can be continuous or triggered by specific events (ASCE-SEI, 2008, p. 52). They also monitor different properties such as strain or corrosion. They further vary in their technological basis (e.g., radar and optics), technological and market maturity, and whether they have been used in practice. An initial scan might note these various features in the inventory. The research team noted whether, during review of the literature, there was evidence that a particular technology is being used for bridge inspection and monitoring.[33]

[32] Other thresholds for both of these metrics are possible (e.g., lane closure for less than 30 minutes, 30 minutes to 2 hours, etc.) This may be tuned to bridge type, bridge usage, and local conditions.

[33] That no evidence was found in the review to date does not necessarily mean that a given technology is *not* being used.

Table 4-4. Bridge inspection and monitoring technologies.

Item	Technology	Evidence of Use
1	3-D Laser Scanning	
2	Accelerometers	
3	Acoustic Emission (AE)	
4	Automated Laser Total Station	
5	Chain Dragging	Yes, (Gastineau et al., 2009)
6	Concrete Resistivity	
7	Digital Image Correlation (DIC)	
8	Electrochemical Fatigue Sensing System	
9	Electrical Impedance (Post-Tensioning Tendons)	
10	Electrical Resistance Strain Gauges	
11	Fatigue Life Indicator	
12	Fiber Optics	
13	Global Positioning System (GPS)	
14	GPR	Yes, (ASCE-SEI, 2008)
15	Impact Echo	Yes, (ASCE-SEI, 2008)
16	Infrared Thermography	Yes, (ASCE-SEI, 2008)
17	Linear Polarization Resistance (LPR)	
18	Linear Potentiometer (String Pots)	
19	Linear Variable Differential Transformer	
20	Macrocell Corrosion Rate Monitoring	
21	Potential Measurements/Chloride Content	
22	Scour Devices	Yes, (Gastineau et al., 2009)
23	Tiltmeters/Inclinometers	
24	Ultrasonic C-Scan	
25	Vibrating Wire Strain Gauge	
26	Radiography	Yes, (ASCE-SEI, 2008)
27	Dye penetrant	Yes, (ASCE-SEI, 2008)
28	Magnetic particle	Yes, (ASCE-SEI, 2008)
29	Eddy Current	Yes, (ASCE-SEI, 2008)
30	Magnetic Flux Leakage	Yes, (ASCE-SEI, 2008)
31	Hammer Sounding	Yes, (ASCE-SEI, 2008)
32	Ultrasonic Pulse Velocity	Yes, (ASCE-SEI, 2008)
33	Spectral analysis of surface waves	Yes, (ASCE-SEI, 2008)
34	Ultrasonic Acoustic Emissions	Yes, (ASCE-SEI, 2008)

The list in Table 4-4 is not exhaustive. These technologies can assist or augment the functional capabilities of bridge inspection to

- Enable inspectors to measure properties more accurately than could be done otherwise (e.g., using visual techniques);
- Enable inspectors to measure new properties that are not routinely part of current inspection practice (e.g., such new properties might be related to modeling, design or operation of the bridge); and
- Reduce the need for visual inspection by continuously collecting data that instead could be analyzed by the inspector or others in order to provide information about whether or not the bridge is operating according to design models and within safety margins.

Sufficiently revolutionary changes in technology can also change agency functions. A STREAM analysis could inform agencies on how the functions may themselves change in the future and what, if anything, they should be doing to prepare. For example, while today's NDE technologies are used for periodic inspection, structural health monitoring, in which sensors embedded on the bridge continuously monitor it, may well be the future. Thus, the function of "bridge inspection" may itself become obsolete having been replaced by the function of "bridge monitoring".[34] In this case, agencies might choose to undertake pilot studies and processes to facilitate structural health monitoring. In any case, STREAM is flexible enough to detect when embedded sensors may evolve to the point at which they begin to emerge from the analysis as an important alternative to then-current technologies.

The research team examined the use of fiber-optic sensors (FOS) for structural health monitoring (SHM) as an example of how technologies may change the function under consideration or even eliminate it.[35] Many projects have used forms of FOS technology applications for research and demonstration purposes to advance the state of practice. Yet there is evidence that in application these may also affect the monitoring function in fundamental ways. A survey of 40 SHM projects from the last 15 years suggests that SHM is increasingly being

[34] This would also require changes in the federal regulations to which local and state transportation agencies must respond.

[35] Examples of FOS projects are listed in Table D.1 in Appendix D.

used to extend bridge life and confirm designs and has moved beyond the demonstration stage (Inaudi et al., 2009a.)

For this illustration of STREAM, the research team identified six technology bundles to be examined in the next steps of the assessment. The current baseline in all agencies consists of using visual inspection with or without the assistance of audible inspection. These provide the first two alternatives. The other four were selected to provide a range of technology applications, levels of maturity, and prospective benefit:

- **GPR.** GPR sends a microwave signal that penetrates the bridge deck and then analyzes the return signal to highlight cracks, delaminations, and other defects at or below the surface, including those that may not have visible effects on the surface of the bridge deck. It can be performed from a moving vehicle, so does not require lane closures during inspection.
- **NDE Suite.** This represents a suite of methods and tools chosen to allow comprehensive evaluation of the bridge deck surface and subsurface and that can be performed from a moving vehicle, so does not require lane closures during inspection. Such a suite might include GPR, ultrasonic inspection, and ultraviolet (UV) inspection. By combining microwaves, sound, and UV, the suite of NDE methods provides a means to image defects that might be missed by any one of the individual methods.
- **Robotic Inspection.** This bundle would use any of the other NDE methods, most likely an NDE suite, via an unmanned vehicle that could be operated during traffic flow and would not require lane closures.
- **FOS Systems.** FOS systems differ from the other NDE methods in that they facilitate SHM, rather than periodic inspection. FOS are embedded in the bridge deck, either when the bridge is constructed or repaired, or placed on the surface of the bridge in places not subject to traffic. FOS can collect data continuously or at desired intervals and can identify surface or subsurface damage through changes in the optical signal.

Step 3. Characterize

The characterize step applies the measures from the Frame step to the candidate technologies identified in the Identify step. We illustrate this in two ways. First, we provide an example of an analytical reasoning process based on literature review and interviews that would lead to characterization of the six alternative approaches we have selected. For simplicity, we focus here on only the value metrics. Second, we describe a survey exercise to gather input from subject matter experts to gain an aggregate assessment of the same six technology applications. Here we consider POSI scores and cost estimates, in addition to value metrics. In each case, resources and efforts were sufficient only to provide an illustration and are intended to be neither as conclusive nor detailed as would be the case in actual application within a transportation agency or in a collaborative effort by several agencies and other bodies.

Before applying the measures, however, we first describe how the POSI, introduced in Chapter 3, would be estimated in the case of bridge deck inspection.

Table 4-5. Analytical characterization of value metrics for bridge deck evaluation technology alternatives.

Technology Application	Preservation Value (Max 4)	Mobility Value (Max 4)
Visual	1	3
Visual + Audible	2	1
FOS	3	4
GPR	3	4
NDE Suite	4	4
Robotic	4	4

Illustration of Analytical Characterization

Table 4-5 summarizes the metric value characterization based on the analysis of each technology's technical capabilities and use cases. As noted above, the current methods of inspection introduce uncertainty into the determination of the condition state and are likely to miss important defects. However, depending on the specific characteristics of the bridge and the damage, visual inspection may or may not be able to distinguish Condition States 3 and 4 from Condition States 1 and 2. Visual inspection requires closing at least one traffic lane for more than an hour, which corresponds to a value of 3 for mobility.[36]

Supplementing visual inspection with audible inspection methods will provide subsurface information that would improve the chances for distinguishing Condition States 3 and 4 from Condition States 1 and 2. Therefore, we assign a value of 2 for the value of preservation to visual inspection plus audible inspection. With audible inspection, lane closure can be more than 12 hours, which corresponds to a value of 1 for the mobility value measure.

Because they provide data on the full substructure of the bridge, both GPR and FOS should be able to distinguish Condition State 3 or 4 from Condition States 1 and 2, and also distinguish Condition State 4 from Condition States 1,

[36] Throughout this analytical characterization, only whole numbers (1, 2, 3, and 4) are used to characterize value metrics. However, analysts could use real numbers (e.g., "3.2") to indicate that performance may fall between the defined performance levels. Analysts could also use ranges of values to reflect uncertainty in judgments.

Table 4-6. Characterization of bridge deck evaluation technology alternatives, expert survey result.[37]

Technology Application	Preservation Value (Max 4) [std. deviation]	Mobility Value (Max 4) [std. deviation]	POSI (Max 4) [std. deviation]
Visual	1.1 [0.33]	1.3 [0.50]	3.8 [0.05]
Visual + Audible	2.0 [0.71]	1.2 [0.44]	3.6 [0.12]
FOS	2.2 [1.09]	2.7 [0.87]	1.7 [0.35]
GPR	3.1 [0.33]	2.7 [1.00]	2.6 [0.40]
NDE Suite	3.1 [0.33]	3.1 [0.60]	2.2 [0.36]
Robotic	2.9 [0.97]	2.9 [0.78]	1.5 [0.34]

2, and 3. However, each method uses only one type of probing excitation (microwave for GPR and optical for FOS), so they may miss some defects. We would therefore assign equal metric value for safety of 3 for GPR and FOS. Neither method requires lane closures, given that GPR can be performed from a moving vehicle and FOS are embedded in the structure itself. Thus we assign a value of 4 for mobility to both.

Use of a suite of NDE methods allows the combination of several types of probing excitations (e.g., microwave, acoustic, and UV), which should allow for a complete subsurface characterization of the bridge deck to definitively identify the condition state. Thus the research team assigned a value for preservation of 4. The suite of NDE methods can be performed from a moving vehicle, not requiring lane closure, so the research team assigned a metric value for mobility of 4.

The research team assumed that a robotic inspection system would use a suite of NDE methods and would be performed from a moving vehicle—the difference being that the vehicle would not require a driver but could be operated remotely. This would eliminate the need for one or more staff (e.g., driver or sensor operator) during the inspection, but would not change the basic information obtained or how it is analyzed. Thus the robotic inspection will have the same values for the safety and preservation measures as the suite of NDE methods. Assuming that the vehicle can be operated in a manner that does not require lane closure, the research team assigned a value for Mobility of 4.

Illustration of Survey-Based Characterization

One can also use surveys of experts to characterize technologies instead of, or in addition to, analytical characterizations as shown above. On 12 April 2012, the research team visited the Minnesota DOT (MnDOT) at their headquarters in St. Paul, Minnesota. During a full day, the research team conducted several sessions with staff and administrators on the work of the project. For the final session of the day, the research team asked the 10 participants from headquarters and field offices and planning and operations staffs who were selected for their familiarity with bridge inspection to provide their own ratings of the benefits, barriers, and costs of the six alternative technology approaches for bridge deck evaluation that had been discussed.

This exercise was more than just a field test of STREAM itself. Because of the level of experience and familiarity with specific technology alternatives gained by MnDOT through studies they performed following the collapse of the I-35W bridge over the Mississippi River, these results would serve as a proxy for the results that would be produced by an expert panel or a survey of experts in the field.

Table 4-6 shows the result of this proxy expert survey. The single-view assessment of value metrics provided in Table 4-5 is largely consistent with these results. In this table we report the mean of the expert inputs for each of the three measures along with the standard deviation across the survey responses in brackets.[38]

Characterization of Costs for Alternatives

Cost characterizations were framed according to the fixed and variable cost structure described in the previous chapter and based on the review of the literature of each of these

[37] In Appendix D we provide Table D-2 giving the coefficient of variation for each technology to provide a more intuitive feel for the degree of uncertainty or difference of opinion these survey scores represent.

[38] In the case of the POSI measure, we asked each individual to assess each of the nine underlying barrier issues that constitute the POSI index. We then used the mean score for the ratings from each respondent across the nine categories. The score reported in Table 4-6 is the mean of those means. We did not apply different weights to the nine different potential barrier areas. This is in accord with the findings from the investigation of obstacles to innovation by transportation agencies that any significantly large barrier may be sufficient to affect POSI seriously and that it is not possible to point to any one of these areas as being consistently a dominating problem. Individual agencies may choose to apply a weighting system.

Table 4-7. Fixed and recurring costs for candidate bridge inspection technology applications over 5-year period following implementation.

Cost Factors	Technology	Visual	Visual +Audible	GPR	Fiber Optics (New)	Sensor Suite (GPR +IR)	Sensor Suite on Robotic Platform
Net Fixed Costs	Acquisition (net value of redundant equipment)	$87,285	$87,285	$129,463	$4,404,041	$217,311	$471,246
	Taxes/Penalties/Fees (net TPF no longer required)	$0	$0	$0	$0	$0	$0
	Training (net training no longer required)	$0	$0	$43,200	$10,000	$97,200	$97,200
	Licenses, Royalties, etc. (net)	$0	$0	$15,000	$6,186	$24,405	$61,518
Net Recurring Costs	O&M (net O&M of eqpt. made redundant)	$278,588	$278,588	$269,813	$278,588	$282,975	$282,975
	Training (net training no longer required)	$52,647	$52,647	$115,822	$67,271	$194,792	$194,792
	Taxes/Penalties/Fees (net TPF no longer required)	$0	$0	$0	$0	$0	$0
	Licenses, Royalties, etc. (net)	$0	$0	$0	$0	$0	$0
	Personnel (net personnel made redundant)	$1,491,652	$2,680,586	$2,024,867	$1,491,652	$2,249,852	$2,249,852
Total		**$1,910,172**	**$3,099,106**	**$2,598,165**	**$6,257,738**	**$3,066,535**	**$3,357,583**

technologies.[39] Table 4-7 shows the breakdown of net fixed and recurring costs for each technology during the initial 5-year period of its use.

Weighing Indirect Effects

Adoption of different technologies may have indirect effects in addition to the anticipated direct costs and benefits. Assessing unintended consequences is important but, by definition, not easy. Specifically, consideration must be given to the questions:

- What are the potential positive or negative indirect effects of using this technology?
- How could positive effects be enhanced and negative effects mitigated?

Although the literature review and interviews did not reveal specific unintended consequences, the research team can anticipate several potential issues. On the one hand, bridge preservation and mobility may be key desired effects, but bridge inspection technologies may also have positive effects on safety, environmental goals, and improved bridge designs.

On the other hand, the research team can hypothesize several negative unintended results from employing some technologies. There could be overreliance on sensors or complacency, though there is not yet evidence of this. The opposite might also be true—too much information may lead to a type of hypochondria, especially if some bridges have advanced sensors and others do not:

- False positives may lead to needless concern or repairs that would, in themselves, have indirect consequences for mobility, budgets, and highway operations.

[39] Key base cost assumptions are provided in Table D-3 in the appendix.

Table 4-8. Value-based comparison for bridge deck evaluation technology alternatives.

Technology Application	Preservation Value (Max 4)	Mobility Value (Max 4)	Value Metric = Preservation x Mobility (Max 16)	POSI (Max 4)	Expected Value = VM x POSI (Max 64)
Visual	1.1	1.3	1.5	3.8	5.6
Visual + Audible	2.0	1.2	2.4	3.6	8.8
FOS	2.2	2.7	5.9	1.7	10.1
GPR	3.1	2.7	8.4	2.6	21.8
NDE Suite	3.1	3.1	9.7	2.2	21.3
Robotic	2.9	2.9	8.3	1.5	12.8

- Highly sensitive sensor systems could lead to discovery of previously imperceptible anomalies that either may never manifest as problems or for which amelioration may be beyond current financial or technical means.

For these reasons, the research team advocates the use of STREAM as a framework and as a platform for discussion and analysis to occur but not as a substitute for agency-level decision making. STREAM is designed to make assumptions explicit and to allow comparison among alternatives on a level playing field of assessment.

Step 4. Compare

The next step helps decisionmakers compare technologies across multiple dimensions, all of which will play a role in choosing an ultimate course of action. The approach uses the best available data to compare explicitly how well each technology alternative (including the current approach employed by DOTs and MPOs) allows the function being assessed to meet mission objectives. The research team draws on the previously defined metrics for mission values as well as the POSI metric that measures the relative difficulty of implementing each technology alternative. Exposing the distribution and range of uncertainty of these values is a central feature of the method. Explicit representation of uncertainties can help decisionmakers clarify their understanding of the technology alternatives (as well as gain insight into what may have led to differing expert assessments), debate potential contributions to achieving mission goals, and identify the most important issues associated with successful implementation.

Value and Implementation of Current Methods and Technology Alternatives

The research team uses the values found in Table 4-8 to illustrate the Compare step for bridge tech evaluation technologies. (The values in the first two data columns of Table 4-8 reproduce the means found in the first two columns of Table 4-6, while the fourth data column of Table 4-8 is the third column from Table 4-6).

First, the research team can compare the NDE options by creating an overall Value Metric that provides an aggregate measure of the benefit across all relevant agency goals (in this case, preservation and mobility). This value is the product of the preservation metric and the mobility metric and is listed in the third column in Table 4-8.[40] Second, the research team can multiply this overall Value Metric by the POSI and obtain an expectation of the actual benefit from application of the technology alternative when implemented, which the research team calls the Expected Value of the technology alternative.[41] These last two values are shown in the fourth and final columns of Table 4-8, respectively.

Table 4-8 illustrates the tradeoffs involved in implementing each of the technology alternatives, as well as the tradeoff involved in supplementing visual inspection with audible inspection methods. For example, while the addition of audible methods improves the determination of the bridge deck condition state (reflected in a higher preservation value), it has a negative effect on mobility. So the decision depends on how much lane closure an agency is willing to endure for the

[40] The statistical reasoning behind this simple approach is more sophisticated than might first appear. Each metric value can be regarded as a random variable measuring how each technology alternative may affect each of these outcomes. The distribution of this random variable depends on how the technology is implemented and used as well as the specific characteristics of the bridge to which it is applied. We could then provide an estimate of the Value Metric of the overall effect of implementing the technology alternative as the product of these distributions. Distributions of such observable variables often take the form of a log-normal distribution. Because the observable variable appears in the exponential of such a distribution, the product distribution gives the combined effect. This distribution of the resulting product, in this case the Value Metric, also takes the form of a log-normal distribution.

[41] Both the Preservation Value and Mobility Value in Table 4-8 carry an implicit presumption that the weight to be given each mission-specific value is equal. This is a factor that could be modified at the level of the individual transportation agency—in some settings, the factor of mobility may be given a different weight than that for preservation. In this example, these implicit weights are set equal to 1.

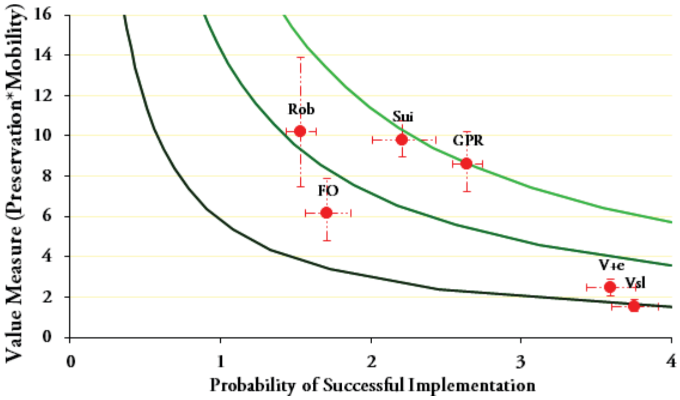

Figure 4-1. Value measure (preservation × mobility values) compared to implementation barriers

benefit of audible methods that may better determine the condition state. All of the technology alternatives improve the ability to determine condition state compared to the current visual or visual plus audible approaches. Of these, GPR appears to be easiest to implement because it requires less of a change from current practice and has a well-documented set of demonstrations. It achieves the highest Expected Value calculation as a result.

Figure 4-1 shows the Value Metric (the product of the preservation and mobility metric values as shown in the third column of Table 4-8) on the vertical axis against the qualitative measure of POSI (the fourth column of Table 4-8) on the horizontal axis. Each point plot represents the mean values while the "cross hairs" show the revealed uncertainty in each dimension as measured by the dispersion of expert opinion. This shows that GPR, the NDE suite, and the robotic inspection have very close value metrics, but that GPR is judged the most likely to be successfully implemented. Additionally, there is much less uncertainty in the implementation judgments than in the value metric judgments, with the robotic inspection system having a high degree of uncertainty in terms of meeting agency goals.

The plot also shows a tradeoff between the Value Metric and POSI: technologies that significantly improve mobility or preservation (high Value Metric) may be more difficult to implement (POSI) because they reflect a greater departure from the state of practice. This tradeoff is captured by the expected value measure in Table 4-8. To facilitate comparison, the research team plotted equivalency curves, which identify points on the graph that have the same expected value. For example, the expected value for GPR is 21.8.[42] It is the highest such value among the six technologies. Any point connected by the equal-value curve that also passes through the GPR point would have the same expected value of 21.8. The low equivalency curve passes through the point with the lowest expected value. This is visual inspection, with an expected value of 5.6. The middle curve captures the points on the graph that have the middle expected value (between the highest and the lowest, in this case (5.6+21.8) / 2 = 13.7.) These curves help identify technologies that have different expected impact on agency function.[43]

A view such as the one in Figure 4-1 makes it possible to present complicated information clearly: the consensus expert opinion, the range of uncertainty among experts, and the tradeoffs between the characteristics (e.g., assessed ability to enhance disparate agency mission goals and likelihood of obstacles of various heterogeneous types) of a group of technologies now placed on the same scale. It does have limitations in that it presents only a 2-dimensional slice through a space with multiple dimensions. But this shortcoming can be addressed by providing other 2-dimensional slices that may serve to illuminate more clearly the relevant tradeoffs. This may be done easily as well as examining the consequences of weightings and preferences among mission goal effects as well as different examinations of how to treat uncertainty.[44]

One such view is shown in Figure 4-2. The logic is similar to that of Figure 4-1. In this case, the two principal mission values – preservation and mobility – are placed on the two axes and the characteristics of six candidate technology applications are shown. This view helps explain the placement of the technologies along the value metric (vertical) axis in Figure 4-1. The current approaches, visual and audible inspection, score the least well with the use of both together providing some additional benefit on the preservation axis. In the case of Visual+Audible, however, it shows how the addition of chain dragging or hammer sounding represents a tradeoff between improved performance for one mission value (preservation) while causing a deterioration in another (mobility.) The three alternatives of GPR, the NDE suite, and the robotic platform suite cluster together at the highest level with uncertainty ranges that cause them to be largely indistinguishable.

These visuals were shared with the MnDOT experts group. In the discussion that followed, the reaction was favorable in two ways. First, the results seemed to capture the actual relationship among these technological alternatives as understood individually and collectively by this group. Second, even

[42] The Value Metric is 3.1 (preservation) multiplied by 2.7 (mobility) or 8.4 as shown on the vertical scale. As shown in the figure, the POSI is 2.6. Multiplying this number times 8.3 yields 21.6.

[43] This figure and others of this type presented in this report were generated by a simple Excel-based model developed for this purpose. This tool allows the entry of many differing expert opinions (and allows for two different rounds of voting to support a Delphi-like expert panel process) and then converts these inputs into a series of plots similar to that shown in Figure 4-1 and the others found in this report. This tool is available on the TRB website and can be found by searching on "NCHRP Report 750, Volume 3".

[44] In this example we merely plotted the high and low responses, thus the full range of responses. The dotted lines of uncertainty may also be made to reflect standard deviations, coefficients of variation, and other representations of uncertainty and distribution of opinion.

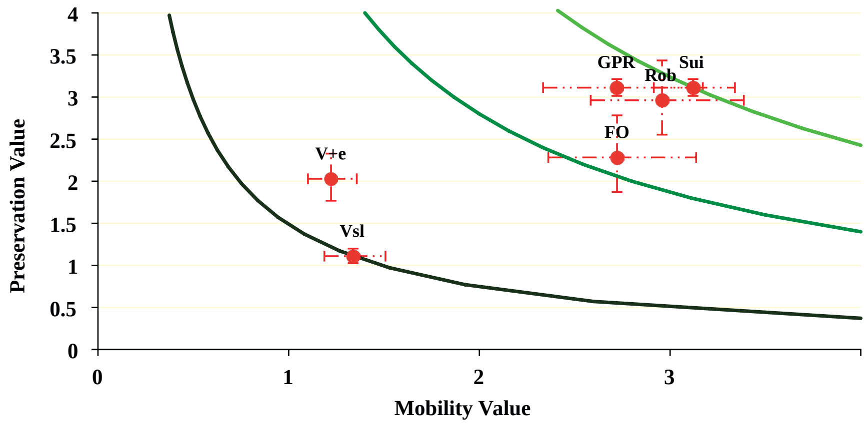

Figure 4-2. Preservation values compared to mobility values.

though not surprising (given that the outputs were generated from inputs by the same group,) the results provided insights that were considered valuable. They provided a comprehensive means to represent disparate information in a manner that could be understood and could (and did) provoke additional rounds of discussion that could then be most usefully focused toward specific agency purposes. There was appreciation of the fact that the goal was not to cause the computer to spit out "the answer" *deus ex machina,* but rather to provide a platform to facilitate weighing of alternatives within a group of technical staff, managers, and decisionmakers.

Cost of Current Methods and Technology Alternatives

The analysis presented so far deals only with the value of different NDE options in meeting mission objectives and the likelihood that they can be successfully implemented. To finish the comparison, the research team looked at the cost of implementing such alternatives. The costs can be represented in the Compare step in STREAM in views similar to those shown in Figures 4-1 and 4-2: one could retain the same axes but report the mean (as well as other measures that might be deemed useful such as range) of the cost scores for each technology alternative in text associated with the points representing the technology alternatives in the resulting plane (see Figure 4-3).

Another approach would be to produce a view similar to these figures, retaining the benefit score on the vertical axis but replacing the POSI score with the cost score on the horizontal axis. Both views can be of value in presenting the choices and tradeoffs presented by a particular set of technology alternatives. However, in this case, one cannot then also include the level-set contours showing equivalent values: this would imply a cost-benefit tradeoff that the analysis developed by the current STREAM method would not represent

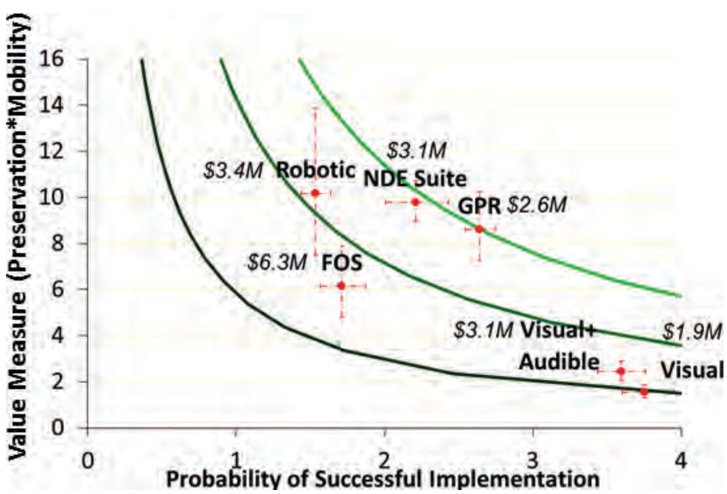

Figure 4-3. Value measure (preservation × mobility values) compared to implementation barriers with notations on equivalent costs

accurately.[45] It is one thing to strive for simplicity; it is another to go beyond a firm grounding in decision theory and statistics or imply such a foundation when it is not present. In designing STREAM the research team strove to create simplicity without violating sound analytical practice.

Step 5. Decide

The previous step, Compare, should yield a set of tradeoffs and other comparative information about different actions that the agency may take in response to different technologies, rather than any one simple answer. The step should have also generated considerably more interaction among those on whom the ultimate decision rests, as well as more meaningful interaction with the body of knowledge that exists on each alternative, than is supported by most current practices in transportation agencies. In the final step, both these formal assessments via STREAM and the informal interactions that have occurred during the conduct of the STREAM process are used to come to a decision.

In particular, the cost analysis coupled with the value metrics suggests that a key question is whether the benefit of improved condition state determination and reasonable likelihood of successful implementation is commensurate with cost. A comparison of alternatives in Figure 4-3 suggests that the NDE sensor suite and GPR are lead contenders for improvement over the state of practice: they have the highest expected values of all other new options and have lower cost than the FOS and robotic systems. Between these two, GPR has a higher POSI score while the sensor suite has a higher value metric score. GPR costs less as well—$2.6 million compared to $3.1 million.

The research team did not implement a formal, quantitative cost-benefit assessment for the reasons discussed in the prior sections. The same data can have different implications for different agencies. With respect to the data given here, an agency prioritizing on cost concerns or one that seeks to avoid higher-risk options might prefer GPR out of all others: it is lower cost than other alternatives but could still substantially improve the state of practice. In meetings with MnDOT, participants suggested that such results would lend weight to arguments for investing in research or taking administrative measures to improve the POSI of GPR, thereby increasing its expected value and reducing uncertainty around its performance and other characteristics.

Alternatively, an agency with interest in pushing the technology boundaries might pursue an NDE suite, or even experiment with robotic systems. As one pathway for preparing for major shifts in bridge deck inspection, agencies could monitor advancements in structural health monitoring and FOS through working groups, fund research, or undertake pilot studies. Other agencies might choose to do none of the above, preferring to wait until benefits are further proven or costs decrease further. This, too, is a valuable result from the STREAM process because it is made explicitly and supported by analysis, rather than implicitly due to lack of information.

Decisions such as these depend on the specific agency context. Different agencies face different barriers to adoption and implementation, cost concerns, cost versus benefit preferences, and so forth. The value that STREAM provides is greater clarity over the characteristics of most importance and the bases on which decisions should be made. It also allows for drilling down to understand on what explicit bases and assumptions the apparent results depend.

Other Applications of STREAM

The STREAM application for bridge deck inspection served well during the period in which the research team were developing STREAM. However, the research team also wanted to make certain that the method as it evolved was not affected by the particular transportation agency function the research team chose to examine. The research team wanted to ascertain that STREAM is, indeed, a generalizable approach to expediting technology adoption in transportation. The research team could not preclude the possibility that different technology applications and different agency functions might lead to problems in applying STREAM at the agency level.

The research team also recognized that it would be desirable to have a wider, more disparate set of examples. Doing so could increase the chances of conveying the value of STREAM to potential users in transportation agencies and national bodies while also perhaps suggesting new applications. In this sense, having more examples will enhance the outreach portion of the project.

For these reasons the research team conducted two further STREAM applications. The first is intended to be firmly in the realm of operations. It examines alternative approaches to road de-icing and ice prevention. This study is provided in Appendix B. The second approach, a focused look at one aspect of ITS by applying STREAM to alternative means for providing real-time traffic information to drivers, is provided in Appendix C.

[45] See footnote 25 for an explanation.

It is tempting to present a three-dimensional representation similar to Figures 4-1 and 4-2 that retains the same x-axis and y-axis but projects a third, z-axis for cost that results in a cube rather than a plane. We do not do so because of the great possibility of misunderstanding. This would in effect be to place cost and POSI on the same basis from a decision theoretic perspective when, as we have discussed above, their interpretation must be different.

CHAPTER 5

Implementation of STREAM

The benefits to the individual user of STREAM will increase as the number of total users rises. Agencies may benefit significantly from being able to access and learn from each other's applications of STREAM for implementing their own studies as well as being able to use the results of others, tailoring those results to the agency's needs and circumstances. Additionally and very much by design, there are many steps in STREAM that would be common to agencies, suggesting that a concerted collaboration on these common steps would benefit many.

The question also remains how STREAM might be implemented, not only within an agency but more generally. In this final chapter the research team considers how this might occur by offering two (not at all mutually exclusive) paths to wider adoption and application of STREAM. The first the research team calls the "top-down" approach that would require establishing formal institutions for collaboration. The second, grassroots or "bottom-up" approach would, by its nature, be less formalized institutionally and so would follow a more path-dependent and variable process for achieving similar ends. However, the effort required to initiate this process would be less challenging. Both paths could help individual agencies with tough technology choices in the future.

Cooperative Technology Board/Panel Approach

The STREAM process has potential for division of labor (i.e., some of the steps must be conducted entirely or in part by the agencies weighing the technological alternatives while other steps lend themselves to collaboration). Indeed, it is hard to imagine all but the largest of DOTs and MPOs having the resources and organization to fully implement STREAM in all particulars for each technology choice they face. Few could or would do so.

Instead of an agency-by-agency implementation of STREAM, the research team imagined a partnership between a structure (hereafter, the "Board/panel" as described below) constituted to carry out some of the steps on a collaborative basis and to then pass along their findings in standardized format to individual agencies which then determine the relevance for their own situations and the decisions they face. The research team outlines below one approach for framing institutions such as the Board and the processes they use as well as those to be followed by transportation agencies.

The research team envisioned the collaborative effort carried on outside the individual DOTs to have both fixed and temporary institutional components. Specifically, the "Board" element would serve as a body for ongoing oversight, coordination, and task definition. It would have permanent standing with periodic rotation of membership. Its members would include both those who have senior experience in the policy realm of transportation at either the federal or state levels and those who have had considerable experience with transportation technology efforts.[46] It, in turn, would cause more specific working group "panels" to be formed to focus on specific functional areas of general interest identified by the Board.

There would be four distinct phases in carrying out the STREAM process as an ongoing endeavor. These phases are defined by four specific decision points. The work flow and specification of the necessary decisions, and decision authorities, would be as follows:

Phase I. The Board, either on its own or based on requests from DOTs, considers the following question with respect to a specific activity or transportation agency function: "Could the use of new technology improve the current state of practice?" The question is pitched in deliberately broad terms. The Board is a higher level body whose deliberations, while not theoretical in nature, should be expansive in considering all aspects of transportation agency missions and activities.

[46] There may be members who combine both policy and technology expertise. We are suggesting, however, that having sole experience in only one and not the other need not bar an individual from membership.

This is the body that initiates and largely carries forward the Frame step of the STREAM process.

If their conclusion is that there is no current need or that a reasonable prospect for improved function through use of technology is lacking, the process ends for this round although the final determination may be to schedule a future time for reviewing this decision based on information received in the interim.[47]

Phase II. If the answer from the Phase I decision point is instead "yes, there is potential room for improvement," the Board and staff then begin the first stages of the Identify step in the STREAM process. Here the question to be answered is, "What current or prospective technologies would aid efforts to improve the specified activity?" This is an initial assessment carried out by relying on the technical specialists on the Board and its staff or engaging consultants from the outside. The initial assessment focuses on existing and potential technologies and if these warrant more detailed investigation. If so, Phase III is begun. If the determination is no, detailed investigation is not warranted, the question would be tabled for a year and then reviewed at that later date.[48]

Phase III. If the Board has determined that there is sufficient reason to suppose the answers to the first two questions are yes, Phase III begins with a qualitatively different thrust. Specifically, the Board empanels and provides a charge to a working group, hereafter referred to as a "panel." While the Board is a permanent oversight body, a panel has only a limited life and tasking. It is composed of practitioners and experts in either the technology involved or the area of transportation agency functions being examined. It is intended that its members be more focused on the working level than in the case of the Board. This being said, a panel takes the initial higher level findings of the Board as only a starting point rather than a firm limitation on their own efforts to identify potentially applicable technologies. They would, in fact, begin their own deliberations at the first STREAM step, that of Framing.

The function of a panel is to complete the Identify step begun in Phase II as well as to complete the Characterize step and to establish the framework, metrics, and database required for the Compare step in STREAM. It does so by examining existing literature and results from trials, carrying out quantitative analyses reported in terms of metrics based on potential agency mission outcomes, and ultimately produces an analytical report which includes a compendium of the substantive data on which it deliberated, a framework for comparison and assessment of alternative technological approaches, including possible hybrid or mixed approaches, and the initial findings from its work. This analysis may be based on generic DOT characterizations.[49]

The goal of the phases to this point, and indeed of the STREAM framework itself, is to place the evaluation of technologies and the assessment of their suitability for meeting transportation agency needs in a unified context that considers the full range of issues that must be addressed. As stated before, a partial goal is to make these considerations explicit so that knowledge inputs can be assessed within a unified framework that also suggests next steps for appropriate agency action based on the totality of this knowledge. It is an approach consciously constructed to change many aspects of current practice; there are currently various demonstrations and trials of potential technological applications but the information gained cannot be easily shared or generalized, nor is it necessarily put in a form that directly feeds into agency-level decision processes to follow up.

Phase IV. If the conclusion provided to the Board is that there appear to be insufficient reasons to push forward with one or more technological solutions at this time, the full findings of the panel are retained by the Board for future reference in its own deliberations. If the findings are that certain technologies are worthy of the attention of DOTs and other transportation agencies that participate in the collaborative effort, the results (including most especially the bases and data for conducting the Compare step) are passed along to the member agencies. It is at this level where the final step of STREAM, Decide, is performed. However, it is most likely that the individual agency will first want to review and modify the panel's work on the Characterize and Compare steps. They now have a highly developed starting point for doing so to achieve the greatest value while conserving agency resources.

The essence of this institutional approach is that the Board/panel could be engaged in the generalizable aspects of the first four STREAM steps. Individual agencies would necessarily play an increasingly prominent role in the final three. This breakdown is shown in Table 5-1. The overlap, Characterize and Compare, would be where "handoff" occurs between the

[47] This, like all such deliberative decisions, is susceptible to varying degrees of Type II error bias—finding no cause for action when one, in fact, does exist. Unlike a medical situation where such an error may prove injurious or even fatal to the life of a patient, in this setting the consequences would be less dire. Accumulating evidence of adverse consequences and advances in technological capabilities as well as accumulating evidence on these advances will most likely combine to provide a truer appreciation to the Board when the specific activity area is taken up once more for deliberation and scrutiny.

[48] Once again, there is a possibility of too myopic a view at this stage leading to a false negative. The automatic 1-year review should serve to limit the consequences of this determination.

[49] In the case of bridge monitoring and assessment, the situation of groups of DOTs may be characterized by climatological region or number of bridges under jurisdiction to name just two such characteristics. The snow and ice removal STREAM application in Appendix B provides an example of how the typology-of-agencies approach could be applied.

Table 5-1. Overview of agency and assessment board roles in STREAM process.

STREAM Step	Board/Panel	Agency
Frame	Defines functions for which alternative technologies are being considered and agency goals being addressed.	Review and adapt
Identify	Develops survey and timelines of potential technology applications to agency functions.	Review and adapt
Characterize	Identifies appropriate technology bundles. Characterizes technologies quantitatively. Identifies and recommends opportunities for research to funding agencies. The findings of that research will inform future rounds of this process (e.g., the identify step). Identifies how technologies in the future may shape the function itself. Suggests "anticipatory" steps and thinking to the agency. Future rounds of the board may use the "new" nature of the function in the identification and assessment process.	Characterizes technology bundles quantitatively within the local agency context based on Board/panel output
Compare	Uses quantitative assessments performed in previous step to examine tradeoffs.	Evaluates tradeoffs for technology bundles within local context
Decide	Provides guidance on basis for individual agency decision.	Determines whether to monitor, shape, or adopt a technology application

Board's efforts and agencies' work. The work of the Board can be embodied in the form of technology application-specific guidelines for agencies to use, keyed to agency functions. The guidelines would be updated at set intervals, determined in part by changes in the development of technology applications and in part by changes in perception of transportation agency functions.

Systematizing assessment in this manner plays a role in shaping technology by providing a feedback loop to future rounds of this process. The research team believes those undertaking a STREAM evaluation will arrive at an enhanced understanding of technologies, applications, nature and roles of agency functions, and the state of current research. This in itself can have an effect in shaping those technologies that will appear in the longer term (e.g., by highlighting required research and also anticipating some of the requirements and issues that would arise from various identifiable barriers for the prospective adopting agencies). A portion of the output of a STREAM process might be on research needs and recommendations to FHWA, NCHRP, and other funding bodies concerning the most pressing needs. The results of one round of STREAM could also inform future rounds undertaken (e.g., 5 years from now when technologies have matured and the results of current research are known).

Agency-led Approach

The Board/panel model for implementing STREAM presupposes the existence of a formal body that starts the STREAM process and conducts the initial steps. The process is then handed off after an initial iteration of the Compare step by the panel. The results are shared by the Board with individual transportation agencies who would then refine them to account for local conditions and concerns, beginning with the Characterize step. Under this model, the question becomes who assumes ownership and what institutional structure and auspices lead to founding the Board mechanism. This implementation model presupposes the need to answer that question.

There is a second way to view the issue of implementation. This is to note that not all DOTs are created equal; some transportation agencies are notable for carrying out a good deal of research effort intended to provide input to their own transportation technology adoption decisions while others have more limited means for doing so. The research team has noted some of the shortcomings in conveying the results of many such research efforts even for internal agency use. These also then necessitate other agencies to duplicate the research while yet others find it difficult to do product evaluations of this type or even to make use of what the leading agencies have done. If such agencies adopted the STREAM approach, the results could then be made more standard and so more accessible and usable to others willing to adopt this approach. Many DOTs and even MPOs have product assessment committees or similarly tasked bodies. This fact and the asymmetry between agencies could provide a basis for implementing STREAM from the bottom up rather than the top down.

Today, if a DOT wants to better understand the choices available for improving outcomes from performing function '*X*' or whether they should consider adopting technology '*Y*,' they search for available studies that cover the field broadly. In doing so they can well find several hundred such studies—or none. How can they decide which ones they should actually examine? Search is difficult and drawing appropriate inferences and conclusions even harder. Which are likely to prove of value in conveying usable information that is also relevant for their own circumstances?

If such agencies could have access to studies by other states conducted by applying STREAM principles and formats and if such studies could be identified as such or even made available in a central repository, both their results and the STREAM steps themselves could be made to flow more easily into existing patterns of effort. In particular, this bottom-up approach would considerably reduce the necessity for some type of central oversight body, at least in the initial stages of the STREAM process adoption into practice. Rather than be a problem of direction and coordination (with the need to deal with issues of jurisdiction and authority) this approach would be more one of crowd-sourcing at the transportation agency level.

This approach could change the game qualitatively. The challenge would be less one of assigning organizational ownership of STREAM at a high level; rather, dissemination would occur by convincing a few individual state DOTs to accept the STREAM approach for their own studies and letting them begin to build a body of such work. If the utility of such an approach in addressing the problems of technology decision-making and dissemination of knowledge becomes clear, there might be an accelerating diffusion effect. This could lead to standardization *de facto* rather than *de jure*.

It is not clear that even under this second strategy a role for some type of oversight Board would be entirely eliminated. At first glance, the agency-driven or bottom-up approach would seem not to require any formal agenda setting from a broad perspective; however, the most important step in STREAM is the initial Frame step. The bottom-up approach is more "market" driven—individual agencies will conduct studies of interest to them. These will then also be of use to other agencies in other states. To accept this fully is to also accept the assumption that there will be no "market failures," that attention and resources will be devoted to examining possible technology applications in support of functions that are, indeed, of importance and wide interest. This may, indeed, prove to be the case. But there might still be value in having a method to address such matters collectively.

A potential hybrid approach, occurring in two stages, might be useful. Initially, STREAM might be recommended for adoption and support by individual DOTs to employ in studies they will undertake. Once momentum builds, it might then become clearer why a joint agenda setting approach might be beneficial. This, in turn, might make such an approach more tractable by, on the one hand, making clearer the "value proposition" in accepting and following the STREAM path while, on the other, easing some of the institutional issues that might otherwise be difficult to resolve in the absence of first having concrete experience with STREAM.

APPENDIX A

Technology Assessment, Adoption, and Implementation by Transportation Agencies

This appendix provides a more detailed overview of the case studies performed under the direction of Dr. Elizabeth Deakin and Karen Trapenberg Frick of the University of California Transportation Research Center.[50] The four technology applications treated in case studies included

- ITS,
- Pavement technology and infrastructure,
- Context-sensitive design, and
- Integrated transportation-land use modeling.

Case Studies of Technology Adoption in Transportation

Table A-1 provides an overview of the interviews conducted for these case studies. Interviewees included representatives of state DOTs, MPOs, industry, local and federal government, and leading faculty experts across the United States.

ITS

ITS refers to an array of technologies with potential to contribute to many areas of transportation: planning and forecasting, design, construction, service delivery, operations and management, and marketing. In broad terms, ITS encompasses information and communication technology applications that could improve transport safety, security, reliability, environmental performance, and customer convenience. Examples of ITS applications include advanced traffic signal systems, electronic pricing devices, real-time transit information, vehicle performance monitoring devices, location information systems, and automated driving technologies.

[50] The studies have not been formally published at the time of this writing. Details may be obtained by contacting the University of California, Berkeley researchers directly.

Researchers at the University of California previously conducted a detailed literature review and extensive interviews to assess factors affecting ITS implementation as a "mainstream" transportation planning activity (Deakin, 2006.) This work builds on and updates that study.

The study of ITS barriers focused particularly on the many non-technical barriers:

- Difficulty assessing the performance of ITS applications,
- Lack of market pull and of motivating studies,
- Lack of market assessment and implementation planning efforts,
- Insufficient staff or inadequate skill-mix,
- Difficulty establishing intra- and interagency partnerships,
- Difficulty keeping pace with technological advancements, and
- Lack of funding.

Asked to identify the top barriers to faster and more widespread implementation of ITS technologies, interviewees widely agreed on several recurring factors.

One of the key concerns revealed in an earlier study of ITS barriers (Deakin et al., 2006) was that proponents of ITS often had unrealistic expectations of system performance or impact and benefits were overstated. Interviewees from this study noted that agencies had taken a more realistic view of ITS in recent years.

Concerns remain, however, about how the costs and benefits of ITS are evaluated and by whom. Several interviewees noted that ITS cost-benefit analyses and evaluations are often done by the same individuals who developed or implemented the technology, either at the agency or at supporting firms, suggesting there may be a lack of objectivity in assessing the costs and benefits.

Additionally, much of the success of ITS depends on the market environment, public perception, an agency's human capital resources, and other non-technical factors. Elected

Table A-1. Case study interviews by organizational type, topic, and location.

Interviews by topic:	Federal Agency	State Agency	MPO	City, County, Special Dist.	Elected Officials	Consultants, Private Sector	University Researcher	Totals
ITS	7	5	5	6	5	3	6	37
CSS	8	5	5	8	6	2	6	40
Models	6	5	6	8	5	5	6	41
Pavement	2	8	1	3	0	3	4	21
Totals by organization type	23	23	17	25	16	13	22	139
Interview locations	DC, CA, MA	CA, FL, MA, WI	CA, FL, TX	CA, FL, TX, MA, MD, NY, OH, VA, WA, WI	CA, DC, FL, MA, NH, NY	CA, DC, MA, NY, WA, TX	CA, FL, GA, MA, MN, OR, TX	

Note: Some interviews covered more than one topic

officials commented that there was not much evidence of a constituency for the changes [in practice towards implementing ITS], and while they were willing to help create one if there were clear benefits to the public or important user groups, the technology advocates often do not make it clear how an individual, or an industry such as trucking [for technologies like, roadway sensors and on-board information systems] would benefit from the changes being proposed. A lack of market pull exacerbates these challenges. One interviewee commented, "The public isn't asking for most of this stuff, so decisionmakers see it as optional and in the current economic climate, it won't get funded."

One MPO staff member noted that, at one point, the state and local agencies that the MPO worked with had hopes of selling their traffic and transit data derived from sensors, GPS, and so forth. Now, the data are posted on line and made available for free for direct consumer use or development of third-party applications. In her view, this approach has greatly accelerated implementation of ITS information systems, though she added that it was "a bit humbling" for agencies to have to accept that their data did not have much value in the marketplace.

One possibility raised in several of the interviews was that implementation of smart highway technologies could be accelerated if there were more markets for the data and noted that one possible internal and external market is for regional and statewide planning. Collecting traffic volume and speed data is easy with currently available ITS technologies, and collecting origin-destination data is also feasible and has been demonstrated in several projects. However, current implementations often fall short of providing the data that planners would need.

Decisionmakers in public agencies also expressed a certain degree of frustration with their technical advisors, reporting that they sometimes have difficulty understanding proposals because the technical staff uses jargon and abbreviations to discuss their proposals.

Despite the importance of market assessment and implementation planning, much ITS work continues to focus on technology development. In some instances, research has been directed to broader questions of costs and benefits in the context of existing and emerging markets, organizational capacities, and institutional relationships. However, interviewees raised additional concerns about this work, noting that it is often undertaken by engineers and technologists, rather than social scientists. Interviewees suggested methodological and other shortcomings in their cost-benefit analyses in these areas. As one consultant noted, "The technology developers are advocates, but not necessarily effective ones, because they are not expert in market assessments, strategic positioning, and other factors that, in addition to technology itself, are needed for success."

There was near-unanimous agreement that many DOTs were having difficulty with ITS implementation, for several reasons. Partnerships are needed to implement and partnerships necessitate a change in agency culture, including less hierarchical decision-making. In the experts' view, separate ITS units and ITS implementation plans—an approach taken by several agencies—can foster strategic thinking about ITS technology development but may hinder ITS incorporation into ongoing plans, programs, and funding streams. As noted earlier, there was near-unanimous agreement that ITS deployment requires coordination between agencies and with developers and other groups. Stronger partnerships with local government and other state agencies developing mutually beneficial and multi-purpose applications were recommended.

The need for staff with new skills was identified as a barrier, if agencies chose to proceed independently rather than contracting for services. In particular, many ITS technologies require extensive knowledge of computer science and electrical engineering sensor technology—disciplinary expertise not currently common in transportation agencies.

Conflicting objectives sometimes get in the way of ITS applications. For example, transportation agency staff noted consumer and provider interest in cell phone apps that would notify drivers of fog, stopped traffic ahead, parking availability at their destination, and more. But concerns about distracted driving are deterring publicly supported applications. Making data available on websites for independent product development rather than providing the apps directly has been an increasingly common response.

Standards pose impediments to adopting ITS because they cannot keep up with the pace of technology development and become restrictive. As one interviewee noted, "Standards are designed to provide for consistent products with a known performance, and don't leave any room for the nonstandard, even if it's better." Relatedly, slow business processes were another issue raised by several, who commented that by the time a purchase order wended its way through their purchasing department or a contract was negotiated and signed, it was often necessary to revise the details because the technology had changed or the services being sought were no longer available. One interviewee noted, "If technology is changing every three months, it doesn't work to have contracts or procurement processes that take six months." Some further argued that the private sector should be left to implement ITS applications such as traveler information systems, because the technologies for providing it were changing too rapidly for government agencies to be able to take the lead.

Respondents urged that future ITS work should pay more attention to legal and institutional issues and provide a clearer sense of "next steps." A demonstration—proof of concept—may be successfully implemented but what to do next remains unclear. ITS deployment is further hampered because many systems are not yet ready for low-risk implementation and there is reluctance in public agencies to experiment with unproven technologies using public funds.

Agencies also face financial constraints in implementing ITS. Efforts have been made to continue the deployment of ITS, but the reduction of earmarked federal and state funds for ITS projects was identified by many agency staff members as limiting implementation. "When funds [restricted to use for ITS] were available, the research team could add at least some technology to projects. Without those funds, ITS looks like an optional extra, and it is first to be cut when project costs are high," one state DOT official put it.

At the same time, senior managers noted that ITS was being introduced and improved as opportunities presented themselves. "New buses are equipped with GPS, new traffic signals are 'smart,' new traffic management information systems connect to regional public information centers and cell phone apps," pointed out one manager, a viewpoint echoed by many. "We are implementing ITS when we replace equipment. We cannot afford to do it any other way," said another.

Transit agency staff members echoed the ideas that ITS technologies were being implemented as equipment was being replaced, that funding limitations meant that service-enhancing technologies took a lower priority than maintaining existing services, and that private-sector initiatives with agency cooperation were likely the better strategy for many agencies than the reverse.

CSSs

CSS refers to an innovation in transportation system design and process that combines street design, multimodal operations, landscaping, and streetscape investments, coordinated with land uses along the street being remedied. AASHTO and FHWA offer the following definition:

> Context-sensitive solutions (CSS) is a collaborative, interdisciplinary approach that involves all stakeholders in providing a transportation facility that fits its setting. It is an approach that leads to preserving and enhancing scenic, aesthetic, historic, community, and environmental resources, while improving or maintaining safety, mobility, and infrastructure conditions (AASHTO/FHWA, 2007).

CSS evolved over several decades as ideas drawn from experiences with traffic-calming, traffic mitigation, and promotion of transit non-motorized modal concepts were integrated.

CSS is in part a reaction to frustrations over stringent design standards. Before ISTEA, roads paid for with federal funds were required to meet guidelines set forth in the AASHTO "Green Book" or obtain design exceptions from the FHWA, a process many viewed as arduous, time consuming, and somewhat arbitrary. Many states had similar design regulations and similar mandates for compliance unless a design exception request was granted.

Design standards were intended to create safe, efficient facilities, and transportation engineers were trained to design by the book to ensure compliance with the standards. Yet many other transportation engineers, along with landscape architects and urban planners, chafed at the "one size fits all" character of the design rules, which for the most part paid little attention to context. They argued that well-trained professionals could assess the safety and suitability of designs and produce better products that were more in keeping with their surroundings. Yet litigation when designs veered from the guidebooks reinforced many transportation engineers' concerns about seeking design exceptions.

Responding to the urgings of the critics, Congress added provisions to ISTEA, signed into law in 1991, that gave states the option to adopt alternative design, safety and construction standards for roads not on the designated National Highway System. The National Highway System Act of 1995 extended the option of alternative design standards to NHS highways other than Interstate highways. Responding to these new authorizations, the FHWA issued guidance for CSS in 1997. Several additional design manuals and guidance documents on best practices in CSS followed.

Interviewees noted that a handful of states and cities are widely regarded as leaders in implementing CSS, but individual examples of good context-sensitive design can be found all over the United States. However, many U.S. practitioners (and several of those interviewed specifically for this study) find that a focus on CSS remains an exception rather than a rule. In their view, many areas have adopted policies allowing design exceptions to proceed somewhat more readily than in the past, but the designs are still exceptions. Some also think that good design remains elusive and few areas have been able to implement CSS successfully as a general policy (examples are for specific links or small stretches, not for the overall planning and design practice).

The researchers interviewed both supporters and skeptics of CSS to understand the reasons for the uneven adoption of CSS. Interviews revealed several barriers:

- Controversial and confusing policies and standards,
- Lack of persuasive performance assessment,
- Conflicting mission goals,
- Agency culture and inertia,
- Interagency disagreements,
- Insufficient leadership, and
- Conflict with local public interests.

Interviewees largely agreed that part of the problem CSS proposals face is that CSS policy has, for the most part, been an additional layer rather than a revision: previous policies and design standards are still in place. However, supporters and skeptics offered different interpretations of this conclusion. For CSS supporters, the layering of policies—rather than revision—indicates a failure to change organizational culture and practices to reflect a new and more progressive approach to street design. They believe this undermines the intent of the policy to reduce the need for design exceptions. They further believe the policy should have led to a broad rebalancing of the weight given to mobility versus access as a function of context. CSS skeptics, however, see a narrow interpretation of CSS policies as appropriate. In their view, "normal" standards are best practice and CSS policies accommodate special circumstances under which exceptions to design standards might be allowed, together with an explication of how such acceptable design exceptions might be produced.

CSS proponents and opponents seemed to have conflicting mission goals and priorities and to interpret performance assessments of projects differently. For example, CSS proponents believed that lane widths could be safely reduced, that narrowing road width would in general improve safety, that parking spaces could be designed for the average vehicle rather than the largest, and that bike lanes could be fit in by reducing travel lanes. Skeptics worried that these changes would lead to more delays, more conflicts, and more crashes, and saw lane narrowing as an action to be taken only when there was no other choice. CSS proponents also argued that level of service standards should be relaxed or transformed into multimodal performance measures in urban areas. For the skeptics, the likely results—increases in motor vehicle delay and congestion—were viewed as unacceptable. The researchers found these sharply differing viewpoints within and between departments in the same agency and between state and local governments.

The researchers also found cultural differences within agencies as well as inertia. Younger staff members are more likely to be comfortable with CSS than their older counterparts. One senior staff member at a state DOT commented that CSS policies "were certainly not consistent with [his] many years of education and practice." Another commented that CSS policy seemed to him to be a "fad" that had caught the attention of a previous executive; he added, "[Executives] come and go." This staff member saw CSS as something that had dubious value overall, because in his view, with the street redesigns that CSS espouses for urban areas, traffic delays would be certain but increases in biking, walking, and transit use were likely to be modest at best. Another senior engineer commented that the CSS guidelines were optional and their application needed to be limited to cases where they could be applied using excess capacity.

In contrast, younger engineers had been introduced to traffic-calming in undergraduate or graduate classes. They were sympathetic to the idea that land use needed to be considered in selecting street designs and traffic controls; thought it was their responsibility to create good opportunities for walking, biking and transit; and believed that environmental considerations and the preferences of local residents and businesses needed to be weighed heavily in developing a street design and traffic operations plan. In this regard, the views of the younger generation of traffic engineers were much more closely aligned with those of the planners and landscape architects interviewed, who were almost unanimous in their support for CSS.

These differences also contributed to interagency conflict. City staff trying to manage multi-use arterials, especially ones that pass through residential areas or shopping districts, were frustrated with what they saw as foot-dragging by opponents to the CSS policy. In one case, city planners had redesigned a major bus route and shopping street to be more multimodal and community-oriented. The state DOT was reluctant to issue the design exception because it feared that the level of service on the street would significantly worsen. The city developed a detailed traffic micro-simulation model to confirm the findings of the simpler modeling, which showed that traffic could be accommodated with little additional delay. One of the city transportation executives noted, "Smaller or less affluent cities would not be able to do this and would probably have given up."

One elected official saw interdepartmental and interagency conflicts as a failure of leadership, arguing that top executives in these agencies "should clarify expectations, insist on change, reward successes, and see the new policy implemented throughout organization, "not just added as a new requirement on top of the older ones."

Other researchers commented that it is not always recalcitrant public agency staff members who oppose CSS; sometimes it is motorists and merchants who believe their success depends on easy motor vehicle access. Several agency staffers shared problems they had faced when angry residents, workers, and merchants found out about a street redesign project only after its implementation was underway—despite strong and continuous outreach efforts, including design charrettes, public information meetings, and information packets sent to all local addresses. While the staff acknowledged that this problem was not unique to CSS but was encountered in many planning projects, they noted that traffic management issues are often among the most contested in their cities, and CSS had been a lightning rod for controversy in several states and cities.

Advanced Transportation and Land Use Models [51]

Travel demand modeling is a core tool of transportation planning. Travel demand models were first developed in the 1940s and 1950s as a new technology for metropolitan transportation planning. The models were used to study patterns of demand for travel in cities and metropolitan regions and to estimate the resulting demand for highways and, in some cases, for transit.

In the many decades since, transportation modeling has become institutionalized in transportation agencies and reinforced through legislation. For example, the Clean Air Act Amendments of 1990 tightened certain transportation-air quality requirements, including those for demonstrating that transportation plans conform to air quality planning requirements. The passage of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) renewed emphasis on the metropolitan transportation planning process. ISTEA strengthened the role of MPOs by allocating funding to them and gave more flexibility and more decision authority to the local elected officials comprising their boards. At the same time, ISTEA reinforced the Clean Air Act (CAA) mandate for more tightly coordinated transportation and air quality planning.

MPOs faced the threat of losing funds if they failed to show, through regional modeling, that their transportation plans and programs would neither exacerbate air pollution problems nor delay attainment of national ambient air quality improvements. As a result, many MPOs took a hard look at their travel demand models and found them wanting. Together with federal agencies, the MPOs sponsored an investigation of the state of the art and the state of practice in transportation and air quality planning (Harvey and Deakin, 1992 a) and also sponsored a manual on best practices for transportation-air quality modeling (Harvey and Deakin, 1992 b). Both documents aimed to help MPOs identify acceptable methods as well as to point out paths to more substantial modeling improvements. In addition, USDOT initiated in 1993 the Travel Model Improvement Program (TMIP), initially established as a partnership with the Department of Energy and the Los Alamos National Laboratory and later evolving into a multifaceted center for training, information, and peer exchanges. From the Los Alamos partnership came the TRansportation ANalysis SIMulation System (TRANSIMS), an advanced travel modeling technology, as well as several demonstration projects on traffic micro-simulation and activity modeling. Also during this period, interest in formal land use modeling made a comeback among academics, and advances were made in the modeling of land developer decisions, household and business location choices, and the interactions of these choices with transportation systems. (See Anas, 1994, Abraham and Hunt, 1999; Waddell, 2002; Hunt and Abraham, 2003, for U.S. and Canadian examples of advanced models.)

These efforts spurred many advances in transportation modeling. There was a growing recognition that travel demand is derived from the scheduling of activities dispersed over space and that modeling individual trips rather than travel was losing important information and likely introducing grave error, which led to the development of activity models. (See Bhatt and Koppelman, 2003, for a history of the intellectual development of activity models.) Representation of a daily schedule of activities and the resulting travel "tours" rather than individual trips became the new modeling paradigm for many researchers. Others made advances in the statistical estimation approaches used in modeling, aiming to reduce biases and increase theoretical robustness and flexibility. Still others moved forward on disaggregate models using individuals and households as the units of analysis rather than population aggregates.

Despite these efforts and continuing progress in developing advanced models, practice is widely criticized for failing to

[51] The history of modeling in this section draws in part upon work by Newmark and Deakin, 2011 (forthcoming). Interview findings and quotations are taken in part from work done for a study of analysis methods for transportation greenhouse gas reduction, Deakin 2011 (forthcoming).

adopt advances from research. Rodier quoted experts who "used words such as 'dismal,' 'primitive,' 'disappointing,' and 'deficient' to describe the state of [modeling] practice." The 2007 TRB *Special Report 288: Metropolitan Travel Forecasting* commented that "Every 10 years or so there begins a cycle of research, innovation, resolve to put innovation into practice, and eventual failure to effect any appreciable change in how travel forecasting is practiced."

The researchers scanned modeling practice and found that many of the larger MPOs have embarked on the implementation of activity-based models in the last 5 years, and a few have also aimed to integrate these models with models of the regional economy and/or location and land use. However, the researchers also found that not a single state or regional agency had discarded its trip-based models and fully replaced them with activity-based models. Many of the MPOs are using a version of their trip-based models to do routine analyses and running their newer activity-based models for comparison purposes or, as one modeler put it, to see whether it gives different results. Likewise, the researchers found that land use and location models are not run routinely, even in areas that have them.

The 2007 TRB report identified several barriers to travel demand model innovation, among them budget limitations, fear of legal challenges in conformity analyses (which must track transportation system performance over time), and the pressures of day-to-day work. For some agencies these factors led them to decide not to take on activity-based models at this time (see, e.g., VDOT, 2009). For others it led to the use of the more familiar trip-based models for day-to-day work, with the activity-based models being used for special studies.

The review confirmed these barriers and suggested others:

- Uncertainty about performance and added value;
- Uncertainty about technical soundness;
- Gaps between research, practitioner, and policymaker needs;
- Significant technical requirements; and
- New skill mixes and inadequate staffing.

A significant concern among practicing modelers is whether activity-based models, integrated transportation-land use models, and other advances really provide any practical improvement over trip-based models. Academics, consultants, and modeling staff from the largest MPOs agreed that activity-based models and integrated land use-transportation models were the state of the art, with stronger theoretical grounding and higher potential for accurately modeling individual and household behavior. However, the practitioners even at these large MPOs were not entirely convinced that the new models had produced better results than their previous models and noted that the complexity of the models made them more difficult and time consuming to use, making their cost-effectiveness an issue.

Practitioners also had concerns about the technical validity of models. They argued that the activity-based modelers made many large and untested assumptions, for example, that a 1- or 2-day travel and activity diary would provide enough data for more sophisticated modeling. However, empirical evidence sufficient to test complex models is extremely hard to obtain; many variables can affect measured activity and travel patterns, including population growth rates and socioeconomic characteristics of the population, employment rates and total jobs, factor prices (e.g., price of gasoline for transportation, price of utilities for housing choice), and much more. Indeed, analysts often have to resort to additional modeling to understand the factors that led to observed outcomes. The lack of transparency into the performance of modeling innovations is thus a major issue.

There also appears to be a gap between needs and benefits perceived by academics and by practitioners. Academics argued that activity models are an improvement because their structure accords with far more reasonable behavioral assumptions than those embedded in four-step models. In addition, they argued, advanced models allow more rigorous investigation of many currently salient policies, e.g., the effects of congestion pricing on time of travel. Practitioners agreed, but expressed concern that the models need to produce regularly needed information (e.g., reasonably accurate forecasts of travel volumes, mode shares, and origin-destination patterns), as well and not just that they are theoretically sound or able to examine innovative but infrequently considered policy options such as pricing. As one practitioner put it, "I understand that if we had congestion pricing, people might reschedule certain activities to avoid peak tolls and that models that assume they must travel in the peak period will therefore overstate pricing's effectiveness. But for [my agency] that is a research question, not a practical question [because] we aren't planning to implement congestion pricing. That is not enough justification to wholesale change our practice."

Some also questioned whether advanced modeling was the right place to make investments. Federal and state officials questioned whether a transition to activity-based models would be effective for the smaller MPOs. MPO staff working on regional strategic planning and investment programming, activities that require consensus building, questioned the importance of models. As one senior official put it, "The models are useful to the extent that they offer insights, but we don't let the model results determine decisions." Elected officials also thought that models (and modelers) were too often hard to understand and sometimes were focused on details that did not matter so much to decisionmakers and oblivious to other issues that do matter to the elected.

Others argued for entirely different approaches to the development and use of models. One proposal was that researchers should be funded to develop and use models to better understand travel behavior, accumulating research results to allow generalizations, and then the results rather than the models would be used as input in formulating policies and plans based on collaborative planning. In this approach, modeling would be largely a research tool rather than a tool of practice, but research would better inform practice. Another proposal was to develop advanced models as research tools and to do periodic regional studies with them, but to develop transparent, easy-to-use, sketch planning methods that reflected the knowledge gained from these regional studies when doing everyday planning.

The data requirements for developing and maintaining the models are also an issue, and both practitioners and model developers acknowledge that available data sources may not be up to the task. For example, advanced models often call for parcel-level land use data as well as multi-day activity surveys and link-by-link and lane-by-lane network data. Many practitioners find such data requirements to be daunting. The costs of the data are problematic as are concerns about quality.

In addition, some agency staff were concerned that they did not have the expertise to collect and maintain the complex databases and would have to either contract for ongoing or repeated consulting services, hire new staff, or develop new in-house skills. For agencies that prefer to do much of their data and modeling work in house, the prospect of having to contract for assistance is not attractive; at the same time, many of the staffers the researchers talked with believed there was "no bandwidth left to take on new tasks."

Pavement Technologies

Pavement serves nearly all modes of surface transportation: automobiles, buses, bicyclists, and pedestrians all depend on smooth pavements to travel in comfort and safety. It is an essential component of the national surface transportation system and over $100 billion is spent annually in the United States on pavement (Fleming 2011).

Most pavements are designed to last for 20 years (AASHTO 1998). However, pavement lifespan can be shortened in several ways: exposure to heavier than planned traffic volumes, high truck and heavy-duty vehicle shares of traffic, extreme weather, and extreme geologic conditions.

Accelerated deterioration has both safety and cost implications. Pavements in disrepair are hazardous to motor vehicles, bicycles, and pedestrians. Early repair requirements also stress transportation agencies' already stretched budgets, and agencies can face funding shortages for paving programs. Yet allowing pavements to continue to deteriorate can lead to higher long run costs from substructure repair or rebuilding.

The high petroleum content of many pavements (both in the materials used and in the production process) has meant that pavement costs have increased with, and been volatile because of, the price of oil.

Pavement design and choice of materials also have environmental and health consequences. Some pavement materials and designs are more noise and water polluting, affecting both humans and wildlife. Pavement production workers are exposed to fumes, particulate matter, and high temperatures. Manufacturing worker hazards are comparable with constant exposure to cement dust that causes eye, skin, and respiratory irritation (OSHA, 2004).

Pavement has direct influences on the surrounding environment, including stormwater runoff, which leads to flooding and water pollution, and heat runoff, which causes thermal shock. Additionally, most energy used to produce transportation construction materials comes from the production of pavement materials, and cement and asphalt production in particular is the largest source of industrial process-related CO_2 emissions in the United States (Kalra et al., 2012).

There is great opportunity to address safety, cost, system preservation, and a host of environmental concerns with pavement innovations. As described in the next sections, much research has been dedicated to addressing these needs, but barriers to their adoption can be significant.

The researchers reviewed examples of pavement technologies that enhance agencies' abilities to manage pavement across their service area and technologies that improve the design of and materials used in pavements.

Accurate estimates of pavement performance are crucial for maintaining pavement. Transportation agencies can use pavement management systems to integrate and analyze data about pavement condition and develop programs that effectively schedule pavement maintenance, construction, and other activities. This can reduce costs associated with delayed pavement repairs and reconstruction.[52]

NCHRP is developing a national mechanistic-empirical pavement design guide to improve pavement performance prediction. FHWA notes

> "[The guide] offers procedures for evaluating existing pavements and recommendations for rehabilitation treatments, drainage, and foundation improvements. In addition, the new guide incorporates procedures for performing traffic analyses, includes options for calibrating to local conditions, and incorporates measures for design reliability. Engineers can use the guide to analyze common causes of pavement distress, including fatigue, rutting, and thermal cracking in asphalt pavements, and cracking and faulting in concrete pavements" (FHWA 2004).

[52] In the case of Washington State, pavement quality increased from 50% of the pavement in good condition in 1970 to 94% in 2005 largely due to the use of the DOT's pavement management system and state support to fund and implement projects at their lowest costs in the pavement's lifecycle (FHWA, 2008a).

Innovations in pavement design and materials, include

- Superpave, a system for designing pavements,
- Warm-mix asphalt,
- Pavements made of recycled materials,
- Permeable pavements,
- Cool pavements, and
- Self-healing pavement.

The Superpave system was developed in the 1980s to address two major concerns in asphalt pavement: rutting and low-temperature surface cracking. The Illinois Asphalt Pavement Association describes Superpave:

> Superpave is a comprehensive system for the design of paving mixes that are tailored to the unique performance requirements dictated by the traffic, environment (climate), and structural section at a pavement site. It enhances pavement performance through the selection and combination of the most suitable asphalt binder and aggregate. (IAPA)

As such, Superpave may produce cost savings and increase pavement lifetime.

Asphalt production typically occurs on site. It is very oil and labor intensive and requires very high mixing temperatures. This has cost, environment, and worker health impacts. Introduced in 2002 from Europe, warm-mix asphalt (WMA) helps address these concerns. WMA is a general term for asphalt technologies that reduce the mixing temperatures of regular hot-mix asphalt by 50 to 100 degrees Fahrenheit. Research shows that WMA is less expensive than HMA because of the reduced amounts of crude oil required. WMA also stretches the construction season, which can reduce project costs. WMA has furthermore shown improved performance on the road. FHWA has reported that WMA can improve field compaction, which can facilitate longer haul distances (FHWA 2008b).

Pavements built with recycled materials are becoming a growing priority. Recycled materials may reduce life-cycle cost, landfill space, and fuel consumption and may reduce other environmental impacts (e.g., greenhouse gas emissions). Applying recycled materials for rehabilitation and new construction projects has been considered a priority for FHWA.

Permeable pavements allow water runoff to percolate through the pavement and into groundwater sheds. Permeable pavements are ideal for low-volume applications such as parking lots; however, care must be taken to ensure that the water runoff does not have significant levels of contaminants that then are channeled into other water resources.

Cool pavements reflect solar radiation to reduce ambient temperatures, which can be particularly important in urban areas. Other benefits of cool pavements include reduced stormwater runoff, lower tire noise (due to porous material absorption), and improved local comfort (with reduced temperatures) (U.S. EPA, a).

Self-healing pavement has additives mixed into the asphalt or concrete that help seal cracks once they are formed. Originating in Europe, research efforts in the United States have included self-healing polymers and self-healing cement mixers.

Several barriers make it difficult for transportation agencies to effectively respond to technologies such as these. Barriers include

- Financial constraints,
- Federal restrictions on proprietary materials,
- Low-bid contracting practices,
- Constrained construction time, and
- Internal and industry inertia.

Limited funding sources and rising capital costs pose significant barriers to technology adoption. State and local agency interviewees expressed frustration in maintaining the quality of their roads with reduced budgets. All of the interviewees remarked on this growing problem of fiscal constraint, both for maintaining existing pavement as well as developing innovations.

Low-bid contracting practices are also problematic. Transportation agencies often outsource construction and rehabilitation to third-party contractors. Subject to project budget limitations, agencies select the lowest bids, which tend to not include total service life costs. This places the focus on immediate up-front costs without incorporating longer costs of the total service life of the pavement. Although some innovations reduce costs (e.g., WMA), others may increase the cost of pavement projects significantly. Complications from the low-bid practice may deter the implementation of newer innovations that have higher initial costs but might result in lower total costs (Caltrans, 2007).

Federal restrictions on proprietary materials pose additional barriers. As of 2006, FHWA "prohibits the expenditure of federal-aid funds on a federal-aid highway project 'for any premium or royalty on any patented or proprietary material, specification, or process'" (FHWA 23 CFR 635.411). One interviewee interpreted this restriction as preventing the use of specialized materials, even if they are most appropriate for the project. Another interviewee stated that it hindered but did not necessarily prevent use: "Technically, the restriction doesn't prevent the use—if patented products are proposed, additional economic and engineering analysis is required to confirm the need of the proprietary product, so it doesn't prevent but limits the use."

Certain pavement materials cannot be laid in cold temperatures and can limit off-peak construction. For states with particularly cold winters, construction season is limited from March to September, concentrating user delay.

Finally, although innovations may yield benefits to agency staff, the public, or both, agency staff may resist incorporating new practices to their jobs. Interviewees spoke of the difficulty of transferring knowledge of innovations that may be more technically preferable but more complex than original practices. Also, the industry itself is seen as resistant to change. One interviewee summarized the prevailing perspective of the industry as "if new, then no." High fragmentation between some state DOT headquarters and field offices also was cited as a barrier for innovation distribution where headquarters staff need to "convince" the many districts to implement a new technique or material.

Summary of Barriers

A synthesis of the four case studies suggests a set of common barriers as shown in Table A-2. This set is not intended to be exhaustive or conclusive, but to highlight the range of technological and institutional challenges with which agencies contend in their efforts to respond to technology.

Some barriers to technology assessment and adoption have to do with the technology itself.

- **Technology Uncertainty.** The performance of technology may be inherently uncertain (e.g., because the technology is not yet proven or has complex interactions with the transportation system that are difficult to anticipate and assess). This makes it difficult for agencies to weight the costs, benefits, and effects of technologies.
  Example from Case Studies: The technical validity of advanced transportation and land use models was a key concern of practitioners.
- **Other Technical Barriers.** There may be barriers inherent in a technology.
  Example from Case Studies: The use of several pavement innovations is limited by very cold winter climate in some regions.

Many other barriers are institutional (i.e., an agency's own organization, culture, capacity, and resources may stand in the way of its engaging fruitfully in processes to identify, assess, shape, and adopt innovative technologies).

- **Performance Assessment.** Agencies (or their partners) may not have adequate skills, experience, or resources in accurately assessing the costs, benefits, and outcomes of technology adoption. They may also have insufficient objectivity in evaluating a technology.
  Example from Case Studies: Many interviewees expressed concerns that the developers of ITS applications also evaluate their performance and may not be objective evaluators.
- **Standards, Rules, and Regulations.** Agencies may adhere to technical standards, rules, and regulations that limit or hinder their ability to adopt technology. For example, although adhering to technical standards can encourage consistency, predictability, and assess ability; standards may hinder the adoption of innovations that are rapidly evolving and for which the development and adoption of standards cannot keep pace.
  Example from Case Studies: Confusion about the role of different standards and regulations hinders the adoption of CSS.
- **Internal Organization and Culture.** The steeply hierarchical organizational structures often found in transportation agencies may make it difficult to bring together the correct mix of decisionmakers, technologists, managers, and other stakeholders. Projects may stall because their technology assessments were not fully communicated to decisionmakers and agency staff. Agencies may not have a culture of innovation. Personnel may not have resources with which to be innovative or may not be rewarded for taking risks.
  Example from Case Studies: Reviews suggest that there may be significant inertia and conflicting values among staff that hinders the adoption of CSS.
- **Inadequate Skill-Mix.** Agencies may not have the required technical knowledge or the human resources to successfully assess and adopt technology.
  Example from Case Studies: Interviewees expressed significant concerns that agencies may not have technical expertise to evaluate or implement certain ITS projects.
- **Technical Information.** The information about a technology may have shortcomings (e.g., if it is poorly communicated).
  Example from Case Studies: Decisionmakers in ITS expressed frustration at the use of technical jargon in communicating about projects.

Other barriers are created by the larger political, economic, legal, and social context in which agencies operate and can particularly affect the ability of agencies to assess and adopt technologies.

- **Investment, Legal Requirements, and Markets.** Uncertain or high deployment and maintenance costs, restrictions on funding, and unfavorable market conditions may make it difficult for agencies to secure or use resources to successfully adopt technologies. Public agency contracting procedures such as stringent bidding requirements or inefficient bid/award rules may make it difficult for agencies to employ the best organizations and devices.
  Example from Case Studies: The emphasis on low-bid practices has hindered agencies from using advanced pavements that may have lower life-cycle costs than other materials.

Table A-2. Barriers identified in case studies.

Barrier	ITS	CSS	Transportation/ Land Use Models	Pavements
Technology Uncertainty			• Validity of models and assumptions	
Other Technical Barriers			• Data availability and reliability	• Climates limit implementation of materials
Performance Assessment	• Lack of objective assessments • Lack of or methodological shortcomings in assessments in broader social, economic, and legal context	• Controversy and over forecasting of impacts of CSS project	• Uncertainty about need and value added • Lack of observability of model performance	
Standards, Rules, and Regulations	• Rapid change makes standards restrictive	• Unclear relationship between existing and new standards	• Low-bid practices prevent adoption of technologies with lower life-cycle costs	
Internal Organization and Culture	• Conflicting mission goals • Separate ITS units may hinder implementation • Slow contracting processes • Reluctance to take risks with public funds	• Conflicting mission goals • Inertia towards using CSS and conflicting internal culture • Insufficient leadership		• Cultural resistance to new methods and processes
Inadequate Skill-Mix	• Need for new skills		• Need for new skills • Heavy existing work loads	
Technical Information	• Use of jargon			
Investments, Legal Requirements, and Markets	• Insufficient attention to legal issues • Cutbacks on funds earmarked for ITS • Implementation paced by technology and system replacement cycles		• Fear of legal challenges in conformity analyses • Budget limitations	• Low-bid practices prevent adoption of technologies with lower life-cycle costs • Restrictions on use of funds for proprietary materials and processes • Limited sources of funding and rising capital costs

(continued)

Table A-2. (Continued).

Barrier	ITS	CSS	Transportation/ Land Use Models	Pavements
Multi-Party Coordination	• Partnerships across agencies and with private sector necessary but difficult	• Need for cross-agency partnership • Conflict between policy goals of elected officials and agency mission goals • Differences in attitude about CSS between staff across agencies • Perceived "foot-dragging" in cross-agency approvals for projects	• Conflict between policy goals of elected officials and agency mission goals	• Fragmentation between DOT headquarters and field offices • Headquarters staff need to “convince” districts to implement new technique or material
External Acceptance	• Difficulty assessing market value and acceptance • Difficulty convincing users of value	• Conflict with local stakeholder interests		

- **Multi-Party Coordination.** Deploying almost any technology requires consensus from many parties, and there may not be established processes to build consensus or resolve stalemates, particularly when agencies and organizations have conflicting policy objectives.
  Example from Case Studies: ITS projects often require but are hindered by coordination between transportation agencies, local governments, private companies, and public groups.
- **External Acceptance.** The success of technology also depends on consumer preferences, which may not be aligned with technological offerings because of alternative preferences or cultural and social norms that work against a particular technology application. Also, users may not be familiar with or educated about particular technologies or misunderstand their risks and benefits. These barriers can arise at various times during project development, from the initial inception of an idea to deployment.
  Example from Case Studies: CSS projects faced difficulty in implementing street redesign projects because of dissatisfaction from local business owners, neighborhoods, and other stakeholders, despite strong outreach efforts.

Response to Barriers

What can be done about these barriers, if transportation agencies decide it is important to remove them? In addition to more resources (e.g., more funding for implementation and technical training for staff), some of the strategies identified in the literature and in the case studies include

- Development of a legal, institutional, and political environment that is willing and able to run trials, carry out test projects, and learn from them, coupled with an ability to accept failure of test products or processes as a cost of innovation rather than treat failure as a punishable offense.
- Strategic planning for innovations, including identifying opportunities, constraints, competing options, likely market shares, costs and benefits, returns on investment, and potential partners.
- Strategic assessment of agency capacity for development or adoption of the innovation. This includes determining who has authority, what they can do, when/how fast they can move, where they have jurisdiction, why they would be motivated to act, how they can move forward (i.e., assessment of compatibility of the innovation and its development and implementation process with the agency’s resources, capabilities, values, and priorities).
- Internal management of change: look for potential internal conflicts as a result of moving forward, in order to clarify expectations and set clear priorities (eliminate conflicts or provide decision rules and a timeline for decisions when there are different values and approaches).
- If an agency is interested but cannot move on its own because of institutional constraints or priorities, looking

for partners who can – or finding other ways to provide support (e.g., helping to fund research and development carried out by others) with more flexibility.

- Recognizing different partner roles (e.g., as sources of innovation, developers of innovation, independent evaluators of innovation).
- Use of pilots, test markets, and demonstration projects to explore options at relatively low cost.
- Consultation with the product or process users to assess the market, identify potential problems, identify user-led innovations, and adjust products in a cycle of learning and improvement. Use of external reviewers, committees of peers, and other peer review to help make sure decisions are rational and high quality.
- Adopt enhanced contracting methods. This includes performance specifications and longer warranties in contractor performance contracts that demand levels of performance for a certain number of years and penalize contractors if those specifications are not met. It also includes the use of design-bid-maintain projects that allow the contractors the flexibility to design their perceived best bid for a certain project.
- The federal restriction for projects using federal funding on not allowing patented materials (FHWA 23 CFR 635.411) can be improved to reduce the required analysis needed to support use of such materials.
- Ongoing outreach and marketing in identifying the importance of smooth streets can increase the awareness of the cost and importance of pavement projects.
- Incentive programs to encourage innovation also could be pursued, particularly with respect to research, best practices, and lessons learned abroad. In addition to removing any barriers that may hinder innovative products from entering the marketplace, government has incentivized contractors and agencies in using certain innovations that have proven effectiveness.

APPENDIX B

STREAM Applied to Snow Removal and Ice Control Technology

Over 70 percent of the nation's roads are located in snowy regions, which receive more than five inches (or 13 cm) average snowfall annually. Nearly 70 percent of the U.S. population lives in these snowy regions. Snow and ice reduce pavement friction and vehicle maneuverability, causing slower speeds, reduced roadway capacity, and increased crash risk. Average arterial speeds decline by 30 to 40 percent on snowy or slushy pavement. Freeway speeds are reduced by 3 to 13 percent in light snow and by 5 to 40 percent in heavy snow. Heavy snow and sleet can also reduce visibility. Lanes and roads are obstructed by snow accumulation, which reduces capacity and increases travel time delay.

Each year, 24 percent of weather-related vehicle crashes occur on snowy, slushy or icy pavement and 15 percent happen during snowfall or sleet. Over 1,300 people are killed and more than 116,800 people are injured in vehicle crashes on snowy, slushy or icy pavement annually. Every year, nearly 900 people are killed and nearly 76,000 people are injured in vehicle crashes during snowfall or sleet. Snow and ice increase road maintenance costs. Winter road maintenance accounts for roughly 20 percent of state DOT maintenance budgets. State and local agencies spend more than 2.3 billion dollars on snow and ice control operations annually. Each year, these road agencies also spend millions of dollars to repair infrastructure damage caused by snow and ice[53].

Frame

Winter operations include plowing, sanding, and salting—the traditional methods for snow removal and ice control. Although agencies are gradually shifting from reactive methods to more proactive strategies, the three classical methods remain a mainstay. Although the traditional methods are relatively cheap and easy to use, they tend to be less efficient and less effective than emerging technologies while having larger adverse effects on the environment, infrastructure, and vehicles. Therefore, states could adopt new technologies to better meet their goals while avoiding the disadvantages of traditional methods. Major inputs to the STREAM analysis of snow removal and ice control are as follows:

- Functions: snow removal and ice control
- Goals: preservation, safety, mobility, sustainability
- Objectives (metrics)
  - Preservation: less corrosion—less corrosive effect of winter maintenance chemicals on pavements and steel structures
  - Mobility: less congestion and closure—shorter travel time and faster speed
  - Safety: better de-icing and anti-icing—fewer crashes due to higher road friction and better maneuverability
  - Sustainability: less environmental damage—reduced detrimental effects on air and water quality, soil, and vegetation

Winter Management Strategies and the Status Quo

DOTs must meet their preservation, mobility, safety, and sustainability goals while contending with winter storms. Furthermore, all state DOTs are facing increasing demand for higher level of service (LOS[54]), especially during inclement weather, more environmental considerations, and ever tighter winter operation budgets (Rochelle, 2010). Traditional methods such as salting, sanding, and plowing are being challenged because

- Salts based on chlorides have corrosive (*low preservation*) and environmentally detrimental (*low sustainability*) characteristics;

[53] Road Weather Management Program, Federal Highway Administration (http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm)

[54] LOS, in the context of roadway snow and ice control operations, is a set of operational guidelines and procedures that establish the timing, type, and frequency of treatments. The maintenance actions are directed toward achieving specific pavement condition goals for various highway sections (Blackburn, Amsler Sr and Bauer, 2004).

- Sand has poor performance characteristics and produces particulate matter which leads to low LOS (*low mobility and safety*) and causes health problems; and
- Plowing slows traffic (*low mobility*) and creates problems with dispatching and routing decisions.

DOTs may choose to adopt new technologies that are more environmentally friendly and less corrosive while maintaining high LOS and optimizing the use of pre-existing materials and equipment. For example, thermal methods (e.g., bridge deck heating systems) are emerging because they have no negative effects on environment and transportation infrastructures while improving traffic flow and reducing car crashes during inclement weather. In addition, when acetate-based chemicals are used as an anti-icing agent, they have less detrimental effects on environment and infrastructures than chloride-based chemicals. As such, by introducing emerging technologies, state DOTs can attain their goals in an efficient and effective manner.

Most winter management strategies used by most state DOTs are mechanical removal with or without friction enhancements and de-icing[55] and anti-icing[56] with chemicals or other methods. While these strategies can be used individually, they are more often used in combination with one another (Blackburn et al., 2004). Among those strategies, anti-icing is relatively new and emerging in snow-belt states due to its efficiency and effectiveness with the advancement of information technology and more reliable weather forecasting.

> In 1996 maintenance managers with the Idaho DOT began an anti-icing program on a 29-mile (47-kilometer) section of US Route 12. This highway segment is located in a deep canyon and is highly prone to snowfall and pavement frost (i.e., black ice) due to sharp curves and shaded areas. An anti-icing chemical is applied to road surfaces as an alternative to spreading high quantities of abrasives. Abrasives are thrown to the roadside by passing vehicles and only improve roadway traction temporarily. . . . Mobility, productivity, and safety enhancements resulted from the anti-icing treatment strategy. Mobility was improved, because a single application of magnesium chloride was typically effective at improving traction for 3 to 7 days—depending on precipitation, pavement temperature, and humidity. Faster clearing of snow and ice reduced operation costs and enhanced productivity. Safety improvements were realized by reducing the frequency of wintertime crashes (Idaho DOT).

Most sources agree that, for anti-icing, the new technologies bring high LOS and cost saving while meeting DOT missions. Despite this, most transportation agencies continue to use traditional methods to maintain highways and bridges in winter. Some states are shifting their approaches for removing snow and controlling ice from reactive (i.e., plowing with chemical follow-up and abrasives *after a storm*) to more proactive strategies (i.e., treatments to prevent or weaken the bond between the pavement and snow *prior to a storm*), but these states still depend heavily on traditional methods.

In particular, when choosing winter maintenance chemicals, most states still execute de-icing practices with solid chemicals—primarily, sodium chloride (NaCl) and magnesium chloride ($MgCl_2$)—rather than anti-icing with liquid chemical products (Rochelle, 2010). According to Rochelle, one common reason is that it is believed that anti-icing chemicals will be washed away during wet snow events or during storms in which rain turns into snow. Another is because forecasting algorithms have not been extensively implemented into their winter maintenance practices. This suggests the possibility for improvement by shifts to newer anti-icing methods with developing advanced information technology (IT), more accurate weather forecasting, and more refined decision systems.

Some chemicals can be used for de-icing as a solid and for anti-icing practices as a liquid. Common table salt (NaCl) can be used for de-icing as rock salt and for anti-icing as salt brine and this is true for others as well. They may have both less impact on the environment and infrastructures but more positive influence on mobility and safety when they are used for anti-icing as opposed to de-icing purposes. As shown in Idaho DOT's practice, liquid $MgCl_2$ was used for anti-icing and attained the DOT's goals better than granular $MgCl_2$ as a deicer.

Factors Driving a Shift in Approach

When selecting winter management strategies, many states have begun to consider the following factors: LOS, cost, infrastructure and environmental impacts, equipment, and weather. This has led several to conclude that there are limitations in using traditional methods. Some states have enacted legislation for reducing the use of salt and the use of alternative, agricultural-based products[57] (ABP) in addition to acetates. Many studies cite the disadvantages of traditional methods, in particular salt usage:

> One concern regarding reactive maintenance practices is the increased potential for accidents and injuries due to poor road conditions while maintenance crews are being deployed. Another problem with reactive practices is the quantity of materials and labor hours needed to maintain the desired LOS for winter roadways (O'Keefe and Shi, 2006).

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[55] De-icing breaks the bond between snow/ice and the pavement by chemical and mechanical means *after a storm*.

[56] Anti-icing requires timely application of winter maintenance chemicals *before the onset of a storm* to weaken or prevent the bond between compacted snow and the pavement surface from forming so as to improve removal efforts.

[57] Byproducts from the agricultural industry are often used as additives to inorganic (e.g., chloride-based) winter maintenance chemicals. Some ag-based products are produced by the fermentation and processing of cane or beet sugar syrup, corn barley, or other carbohydrates and milk (Fay and Shi, 2012).

> The widespread use of rock salt (sodium chloride) to remove snow and ice and facilitate a 'bare pavement' LOS has provided for the increased safety of motorists for some time. However, de-icing salt use has some detrimental side effects. The damage to the ecosystem from chloride ions has been documented, along with the corrosive effects to metals. Consequently, frequent repair and rehabilitation of bridges has resulted (Kahl, 2002).

Traditional methods often lead to poor efficiency and low effectiveness of plowing, i.e., LOS:

> In contrast to anti-icing operations, traditional snow and ice control practice is to wait until the snow accumulates on the pavement before beginning to plow and treat the highway with chemicals or abrasives. A consequence of traditional practice is formation of a compacted snow layer tightly bonded to the pavement surface. A subsequent de-icing of the pavement is then necessary and usually requires a large quantity of chemical to work its way through the snow pack to reach the pavement and destroy or weaken the bond. Although requiring less information and training than for anti-icing, de-icing may provide less safety as a result of the inherent delay (Kahl, 2002).

Another concern is corrosion-related issues when using salt as a deicer:

> A survey of 200 concrete highway bridges carried out by Maunsell & Partners found that many of the bridges had reinforcement corrosion because of the high chloride content in the concrete caused by the use of salting for winter maintenance. The study confirmed that leakage through bridge joints occurred frequently. Consequently, areas of the abutments, piers, and deck soffits became stained and contaminated with chloride. Other areas were affected by spray from passing vehicles (Burtwell, 2004).
>
> Chlorides in de-icing salts can significantly increase concrete scaling, possibly due to increased osmotic pressure in addition to expansion of freezing water and/or when dissolved salts recrystallize in the concrete pores (Kahl, 2002).

Finally, environmental problems resulting from salt usage are significant:

> Already at an early stage, it was recognized that the use of salt had not only the desired effect of improved traffic safety and accessibility but also several negative impacts. Numerous investigations of impacts on vegetation, soil, and groundwater have been presented, and the matter is still of great concern in North America, Europe, and Japan (Gustafsson and Blomqvist, 2004).
>
> The salts, NaCl, $CaCl_2$, and $MgCl_2$, leave residues of chloride ions that can be swept up in storm water runoff or snowmelt and carried into adjacent drainage ditches to be discharged into downstream surface waters. It is these de-icing compounds that are the focus of the most intense environmental scrutiny. Chloride concentrations from roadway de-icing can be substantial. Although natural background concentrations in water may be only a few parts per million, roadway runoff during de-icing operations has been measured as high as 18,000 mg/l. Resulting chloride concentrations in the environment also can be significant. Values measured in lakes can vary from 15 to 300 mg/l in rural settings to 2,000 to 5,000 mg/l in urban impoundments. Streams have been documented to carry concentrations as high as 4,300 mg/l. These values become important because of the relatively low thresholds at which chlorides can do harm to freshwater aquatic species (Davis, 2004).

Identify

Snow Removal and Ice Control Technologies

Three categories of technologies are available (Rochelle, 2010):

- **Traditional methods:** mechanical plowing, de-icing (salting), and sanding;
- **Proactive approach:** anti-icing; and
- **Emerging technologies:** heated bridge deck, pre-wetting, fixed automated spray technology (FAST), surface overlay, information technology, improved removal equipment.

This three-part breakdown presents a neater division than exists in practice. Some chemicals are used as both a deicer and an anti-icer, and technological innovations are being made that cross categories so the latter are not mutually exclusive. Thus, it is desirable to look at all three categories in an integrated manner. Incremental innovations as well as revolutionary innovations need to be considered.

Table B-1, which shows various technologies employed in winter operations, provides a list of technologies ranging from maintenance management systems and plows to IT and thermal methods. Table B-1 also shows frequency of use based on a survey conducted by the two studies cited in the table. The research team divided these technologies into two categories: Category I contains primary technologies which have direct impact on snow removal and ice control; Category II contains secondary or peripheral technologies which have indirect impact. For the purpose of this case study, the research team put more emphasis on Category I technologies than Category II. Table B-2 shows a wide range of available chemicals for de-icing or anti-icing.

The first two categories—traditional methods and proactive approach—represent the current state of practice used by most states. Examples are as follows:

- **Mechanical plowing** (Ketcham et al., 1996)—Most states use the same basic type of equipment including, dump trucks with plows, rotary plows, and loaders. Some common types of plows are one-way front plows, reversible plows, deformable mold board plows, underbody plows, and side-wing plows. Some plows can be shifted from side to side using hydraulics, allowing the plow to extend to the side by 9 to 12 feet.
- **Chemicals used for de-icing and anti-icing** (Rochelle, 2010)—NaCl is the most common because it is abundant

Table B-1. Technologies employed in winter operations.

Category I	Ranking by Frequency	Specific Technology
Plow Configuration	1 (53/54)	Front plows
	2 (29/54)	Underbody plows
	3 (18/54)	Wing plows
	4 (9/54)	Rear plows
Plow Blades (Types)	1 (47/51)	Carbide
	2 (24/51)	Underbody blade
	3 (19/51)	Wear plates
	4 (9/51)	Double/triple edge
	4 (9/51)	14+ ft
	6 (4/51)	Rubber
	7 (2/51)	Triple-blade
	7 (2/51)	Tow blade
	7 (2/51)	Carbide with steel backer
	9 (1/51)	Steel
De-icing & Anti-icing	1 (50/54)	Anti-icing with liquids
	2 (47/54)	De-icing with solids
	3 (38/54)	De-icing with liquids
	4 (22/54)	Anti-icing with solids
	5	Other—Pre-wet system
Application Methods	1 (50/52)	Spinner applications with solids
	2 (32/52)	Stream method with liquids
	3 (28/52)	Spray method with liquids
	4 (12/52)	Gravity Feed
	5 (9/52)	Zero Velocity
	6 (4/52)	Advanced Placement
Thermal Methods (Pavement Heating Methods)	N/A	Electrically conductive concrete
		Electrical resistive heating
		Geothermal heat pumps
		Infrared heating
		Microwave and radio frequency power
		Solar and wind power

Category II	Ranking by Frequency	Specific Technology
Maintenance Management System (MMS)	1 (12/29)	GPS / Automatic Vehicle Location (AVL)
	2 (7/29)	TAPER logs
	3 (2/29)	Work Management System (WMS)
	4 (1/29)	Resource Management System (RMS)
	5	Other—Timesheets, manual and vehicle reports, crew information cards
Information Technology	1 (43/48)	Road Weather Information System (RWIS)
	2 (26/48)	GPS
	2 (26/48)	AVL
	4 (24/48)	Maintenance Decision Support System (MDSS)
	5	Other—Free web-based information provided by the National Oceanic and Atmospheric Administration (NOAA), Full Mobile Data Computing
Windshield Wipers	1 (47/51)	Standard equipment
	2 (8/51)	Hot Shot
	3 (6/51)	SlapMe
	4 (4/51)	Clear Fast
Add on Vehicle Accessories and Training	1 (26/40)	Specialized lighting packages
	2 (11/40)	Back-up cameras
	2 (11/40)	Vehicle airfoils
	4 (9/40)	Driver simulator training
	5 (8/40)	Vehicle deflectors
	6 (7/40)	Vehicle moldboards
	7 (14/40)	Other
Vehicle Sensors	1 (48/48)	Pavement temperature sensors
	2 (39/48)	Air temperature sensors

Note: In the column of “Ranking by Frequency” the number in parentheses means the number of survey respondents.
Sources: Veneziano et al., 2010; and Zhang and Peterson, 2009

Table B-2. Chemicals employed in winter operations.

Chemicals Listed	Abbreviation	Ranking by Frequency
Sodium Chloride (solid)	NaCl (s)	1 (20/24)
Abrasives (sand)	Sand	2 (17/24)
Magnesium Chloride	$MgCl_2$	3 (14/24)
Agricultural-based Product	ABP	4 (12/24)
Calcium Chloride	$CaCl_2$	5 (11/24)
Potassium Acetate	KAc	6 (6/24)
Sodium Chloride (liquid brine)	NaCl (l)	7 (4/24)
Sodium Chloride & Abrasives	NaCl & Sand	8 (3/24)
Clearlane®	NaCl, $MgCl_2$	8 (3/24)
IceSlicer®	NaCl, KCl, $MgCl_2$	8 (3/24)
Calcium Magnesium Acetate	CMA	11 (2/24)
Sodium Acetate	Nac	11 (2/24)
Potassium Formate	Kform	13 (1/24)

Note 1: In the column of "Ranking by Frequency" the number in parentheses means the number of survey respondents
Note 2: ABP included Ice B'Gone® (n=2), Magic by Caliber® (n=1), beet and/or corn based (n=3), unspecified ABP as inhibitor mixed with $MgCl_2$ (n=2), unspecified ABP as inhibitor mixed with $CaCl_2$ and NaCl (l) (n=1), or an unspecified small amount of ABP listed generally as inhibitor (n=3), and Geomelt® (n=1)
Source: Fay et al., 2008

and inexpensive while performing relatively well. $CaCl_2$ and $MgCl_2$ perform better than NaCl in colder conditions, but they lead to higher cost and possibly greater impacts on infrastructure. Acetates are less expensive and less corrosive to metals. One example is CMA and another is KAc which is good for bridge decks because of its much less corrosiveness. ABPs are an additive to other chemicals to improve performance and reduce corrosion but they have higher costs.

- **Sanding** (Blackburn et al., 2004)—Sanding and use of abrasives is used to enhance friction on a snow or ice surface, include sand, cinders, ash, tailings, and crushed stone.

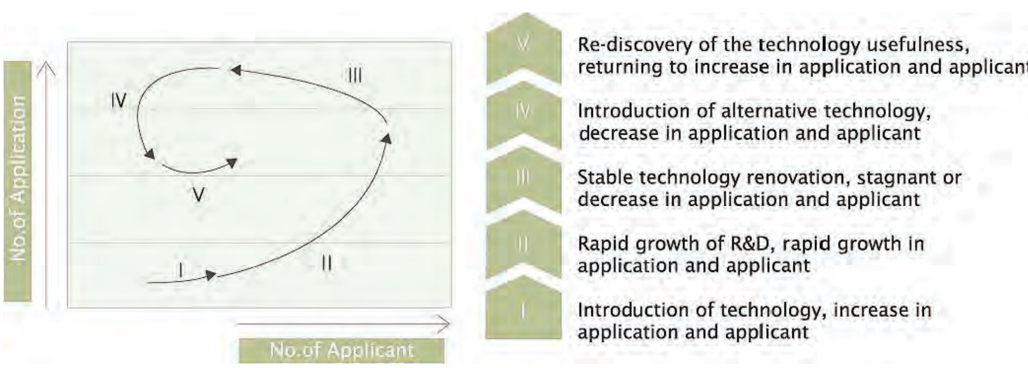
The last category—emerging technologies—includes incremental improvements from the first two categories along with innovations for which such technologies are being attempted by a few states but are not yet widespread. Examples of such technologies are as follows:

- **Thermal methods,** including heated road and bridge deck (Rochelle, 2010; Zhang and Peterson, 2009)—Local heating of road segments segregates the ice-substrate interface and allows ice to be removed with little effort. There are three types of technologies: (1) hydronic (heated fluid is pumped through tubing embedded in pavement); (2) heat pipe (a working fluid contained in steel pipes vaporizes and condenses resulting in a passive transfer of heat); and (3) electric (heat is generated by electrical resistance cables buried in the pavement near the surface). The heat pipe type is perceived as having lower cost and causes less damage to infrastructure durability than the hydronic or electrical types. In addition to these three primary methods, there are also infrared heating, microwave and radio frequency power—both of which can be mounted on a truck or on bridge side structures with their beams directed toward snow and ice—and solar and wind power as a supplement for electricity generation.
- **Pre-wetting** (Shi, 2010) and (Blackburn et al., 2004)—Pre-wetting is the addition of a liquid chemical to an abrasive or solid chemical before it is applied to the road. The pre-wetting of solids is performed either at the stockpile or at the spreader. Pre-wetting has been shown to increase the performance of solid chemicals or abrasives on the roadway surface and their longevity, thereby reducing the amount of materials required. Most commercially available liquid ice control chemicals can be used for pre-wetting of solid ice control chemicals, abrasives, and abrasive/solid chemical mixtures. The primary function of the liquid in pre-wetting is to provide the water necessary to start the brine generation process for the solid chemicals. When used on abrasives, pre-wetting helps abrasives adhere to the ice surface and provides some ice control chemical to the roadway that may at some point improve LOS.
- **Fixed Automated Spray Technology (FAST)** (Zhang and Peterson, 2009)—FAST uses active and passive sensors embedded in the road surface to predict surface temperature and activate the spray system. The system continuously monitors conditions on the structure, based on the detection of critical threshold parameters, and sprays the chemical just in advance of icing conditions. Road sensors can be either passive or active. Passive sensors are tuned for the type of de-icing chemical used in order to determine the proper freezing-point depression. Active sensors can accurately measure the freezing point independent of the type of chemicals being used. As of 2003, 23 states either have FAST systems or are planning to install them.

- **Surface overlay** (Rochelle, 2010)—Special bonded surface overlays set anti-icing chemicals in place and gradually release them onto the surface. This method is primarily used for bridges against frost and ice formation. For example, the Wisconsin DOT applied a thin layer of epoxy covered with a layer of absorptive aggregate to a bridge in Wisconsin. Alaska and Nebraska also attempted to use rubber asphaltic mixes and a conductive concrete overlay for breaking ice and preventing ice formation, respectively.
- **Information technology** (Rochelle, 2010)—ITS approaches are closely related to snow removal and ice control in that ITS approaches can assist winter management personnel in making informed decisions. Of many information technologies, the following four technologies pertain to snow removal and ice control: (1) MDSS (maintenance decision support system) which provides objective guidance to winter control decisions concerning appropriate strategies; (2) RWIS networks which provide relevant road information through non-invasive road temperature and condition sensors; (3) weather observation technology which uses passenger vehicles as weather probes by having automobile manufacturers equip cars with on-board units and receivers, and collects data such as windshield wiper state or outside air temperature and transmits the data to a national communication station; and (4) GIS (global information systems) and AI (artificial intelligence) which prioritize snowplowing routes and improve snowplowing time and personnel dispatch.
- **Equipment,** including snow-blowing vehicles and blade geometry (Rochelle, 2010)—This applies to equipment containing various advanced technologies ranging from specialized vehicles to specific parts. Specialized vehicles include AVL, which consists of on-board computer systems, pavement-sensing devices, multiple material distribution systems, increased horsepower, automated activity reporting, and a friction measuring device; and HMCV (highway maintenance concept vehicle) which applies a precise amount of material at a given time and uses a friction meter to adjust the chemical rate. Specific parts include high-speed environmental plow, which is equipped with flexible cutting edges, and blade geometry with a plow angle of 55 degrees rather than the typical 90 degrees.
- **Advanced chemicals for de-icing or anti-icing** (Kahl, 2002)—Advanced chemicals perform better and are environmentally friendly and less corrosive than conventional anti-icing and de-icing materials. For example, the Michigan DOT used them and consequently could provide the required high LOS (i.e., bare pavements) quicker, while reducing the chemical application rate and inhibiting the corrosive effect of chloride ions.

Maturity of Alternative Technologies

To determine the maturity of state-of-the-art snow removal and ice control technologies, the research team analyzed relevant patent data. Technological maturity frequently follows the general model of patenting activity shown in Figure B-1. On the x-y plane (where the x axis = the number of applicants and the y axis = the number of patent applications), technological maturity shows a spiral shape throughout the stages from the introduction of technology to rapid growth to



A general model for patterns in patenting activity can be established to understand the stages of development of a particular technology. On the introduction of a new technology, only applicants are involved in patenting in the field and only few applications are filed. Following this growth period, the technology enters a development period, during which the technology develops rapidly as a result of active competition between numerous applicants, who together file many applications. As research and development continues, the growth in the number of applications stagnates or declines as does the number of applicants. This period can be termed a “maturity period.” As new technologies or even entirely new technology paradigms emerge, a period of decline begins for the original technology, at which point the number of applications and applicants in that field declines strongly. It is possible for a revival of interest to occur in the original technology, if a new application can be found for it, leading to resurgence in the number of applications and applicants (WIPO, 2009).

Figure B-1. General model of patenting activity (technological maturity).

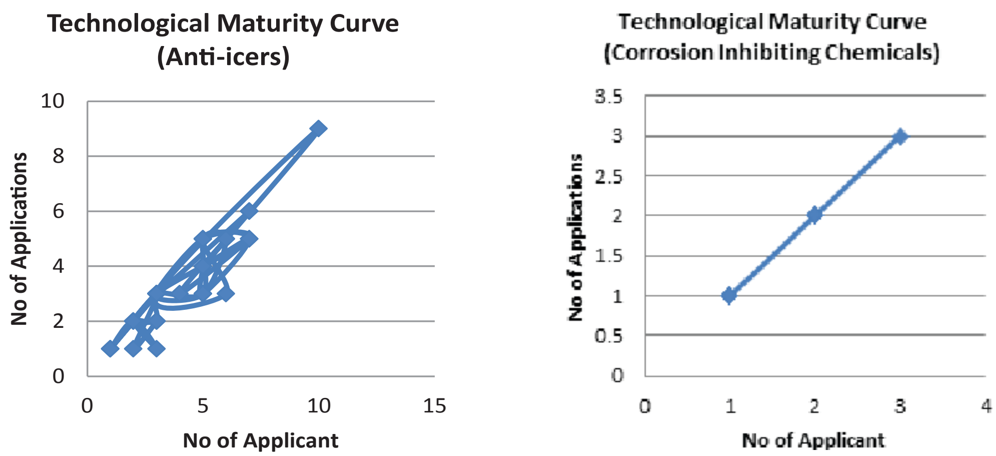


Figure B-2. Technological maturity of anti-icers and corrosion-inhibiting chemicals.

maturity and then the introduction of alternative technology to the re-discovery of technology.

Figure B-2 provides two examples of anti-icers and corrosion-inhibiting chemicals. When compared to Figure B-1, both graphs show these two technologies are still at the stage of technology introduction (Stage I) or at the beginning of rapid growth (Stage II). In other words, these two technologies are not fully mature yet and need more time and more R&D efforts to enter the stable stage. In addition to these two technologies, the maturity of other technologies, such as pre-wetting, thermal method, RWIS and blade geometry, are presented in Appendix E. It seems that all these technologies are at Stage I or II, except for blade-related technologies which are at Stage III (Stable technology renovation).

Characterize

In this phase, characteristics of both state-of-the-practice and state-of-the-art technologies were described with exemplary practices of some DOTs. For each technology, its performance, corrosive and environmental impacts, and cost were roughly characterized according to parameters relevant to transportation agency decision-making. Also, based on the anti-icing strategy as a successful case, the drivers or barriers to technology adoption were evaluated in the organizational terms. In order to consider technological aspects of new, advanced technology adoption, the concept of technological monopolization was introduced using the Concentration Ratio and Herfindahl Index. Characteristics are as follows:

- **Mechanical plowing** (Rochelle, 2010)—Mechanical plowing is regarded as the most important and widespread technique. Its innovations come with advances in snowplow technology, in particular snow blade geometry and the mechanics of scraping snow and ice, which reduce the amount of energy needed to remove snow and ice. Some studies show that fairly minor changes in the cutting edge geometry provide substantially improved ice cutting. For example, preferred blade geometry and serrated blades outperform conventional blades, and trucks with underbody plow blades showed performance that improved on that from front-mounted blades.
- **Chemicals used for de-icing and anti-icing**
  - **De-icing** (Fischel, 2001)—De-icing is suitable for most weather, locations, and traffic conditions. It also allows for higher traffic speed and volume, reduces the need for abrasives (thus improving air quality), and saves on fuel consumption compared to plowing alone.
  - **Anti-icing** (Rochelle, 2010)—Anti-icing uses smaller volumes of chemical to achieve effective results, but is limited by lack of established dispersal rates, laboratory studies to verify field studies, and an understanding of the science associated with anti-icing principles.
- **Abrasives** (Nixon and Williams, 2001)—Because they do not lower the freezing point of water, abrasives are not used for de-icing or anti-icing operations. Even though the Montana DOT uses abrasives in its winter maintenance operations, it says that "abrasives are costly to purchase, store, use and clean up. Additionally, they are poor in performance, have a short beneficial life, and are hard on the environment as well as human health, and cause wear to pavement markings." Due to these concerns, snow and ice control operations in Montana are shifting from abrasives to the use of winter maintenance chemicals to maintain desired levels of service.

Table B-3 summarizes the main materials in use in the de-icing and anti-icing activities of agencies. Table B-4 provides further information on widely perceived advantages and disadvantages.

Table B-3. Summary characteristics of current winter maintenance materials.

		Abrasive	Sodium Chloride (NaCl)	Calcium Chloride ($CaCl_2$)	Magnesium Chloride ($MgCl_2$)	Calcium Magnesium Acetate (CMA)	Potassium Acetate (KAc)
Performance	Eutectic Temp.[58]	NA	-21°C @23%	-51°C @29.8%	-33°C @21.6%	-27°C @32.5%	-60°C @49%
	General	<11°C	Effectively depresses the freeze point of water	Effective at low temperatures; melts ice faster than NaCl	Effective at low temperatures; melts ice faster than NaCl	Effective as a liquid anti-icer; melts longer than NaCl	Effective as a liquid anti-icer; effective at low temperatures
Corrosion Impacts	Highway Structures and Vehicles	Non-corrosive	Corrosive	Moderately corrosive	Moderately corrosive	Non-corrosive	Non-corrosive
	Asphalt Concrete	Non-corrosive	Slightly corrosive	Slightly corrosive	Slightly corrosive	Moderately corrosive	Moderately corrosive
Environmental Impacts	Air Quality	Fine particulate material increase in air pollution	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives	Net decrease in air pollution from reduced use of abrasives
	Vegetation	Can smother roadside vegetation causing mortality	Inhibits water and nutrient uptake; vegetation damage and mortality	Inhibits water and nutrient uptake; vegetation damage and mortality	Inhibits water and nutrient uptake; vegetation damage and mortality	Potential mortality from oxygen depletion in soil	Potential mortality from oxygen depletion in soil
	Soil	Little effect on soil expected	Increases salinity; decreases soil stability and permeability	Increases salinity; improves soil structure	Increases salinity; improves soil structure and permeability	Potential oxygen depletion from breakdown of acetate; improves soil structure	Potential oxygen depletion from breakdown of acetate
	Surface/Ground Water	Increases turbidity; inhibits photosynthesis in aquatic plants	Potential increase in water salinity; slight increase in metals	Potential increase in water salinity; slight increase in metals	Potential increase in water salinity; slight increase in metals	Potential oxygen depletion	Potential oxygen depletion
Cost	Initial	Low cost	Low cost	Relatively low cost	Relatively low cost	High cost	High cost
	Associated	High cost	High cost	High cost	High cost	Low cost	Low cost

Source: Fischel, 2001

In the Identify step, several new, advanced technologies were introduced. In particular, information technology and equipment have plentiful, heterogeneous sets of sub-technologies. In this case study, however, the research team selected advanced RWISs and changes in blade geometry for discussion and did not more fully explore the other potential innovations and technologies.

Thermal Method—Pavement temperature in winter has a significant influence on highway maintenance and safety issues concerned with snow and ice management (Adams et al., 2004).

Conductive concrete overlay (Tuan and Yehia, 2004)—Unlike conventional concrete, conductive concrete is a cementitious admixture containing electrically conductive components to attain stable and high electrical conductivity. Due to its electrical resistance and impedance, a thin conductive concrete

[58] The eutectic temperature is the lowest temperature at which ice melts.

Table B-4. Advantages and disadvantages of state-of-the-practice technologies.

Ice Control Materials	LOS	Advantages	Disadvantages
Abrasives	Low	They can provide at least some measure of traction enhancement when it is too cold for chemicals to work effectively. They are suitable for use on unpaved roads and on thick snow pack or ice surfaces that are too thick for chemicals to penetrate.	When mixed with enough ice control chemical, abrasives will support anti-icing and de-icing strategies; however, this is very inefficient and costly as the abrasives for the most part are "going along for the ride" while the chemical portion of the mix is doing the "work."
Solid Chemicals	High	They support both anti-icing and de-icing strategies. When anti-icing, they are most effective when applied early in a winter weather event, before ice or pavement bond has a chance to develop. Some snow, ice, or water on the pavement will minimize bouncing and scattering of the chemicals.	They may be used as a pretreatment, but only when applied at traffic speeds under about 30 mph and traffic volumes under 100 vehicles/hr.
Liquid Chemicals	High	They support anti-icing and limited de-icing strategies. They are particularly well suited to pretreating for anticipated frost, icing, or black ice situations. Here, the water evaporates, and the residual dry chemical is relatively immune to dispersal by traffic. Liquid chemicals are also used to pretreat roadways before a general snow or ice event. This is an effective way to initiate the anti-icing strategy. At pavement temperatures higher than about 28°F, liquid chemicals are a very effective treatment for thin ice in the absence of precipitation. The ice-melting process in this situation is almost immediate.	They are not well suited to general de-icing operations as they have little ability to penetrate thick snow and ice. They may be used for limited de-icing if the treatment is immediately followed by an application of solid chemicals or the process is reversed. Liquid chemicals are probably not a good choice at pavement temperatures below about 20°F. Liquid chemicals, as a within-winter weather event treatment, should be limited to lower moisture content events, pavement temperatures above 20°F, and cycle times less than about 1.5 h. This will minimize the risk of ice/pavement bond formation. It is not advisable, however, to use liquid chemical during moderate or heavy snow, sleet, and freezing rain events.

Source: Blackburn et al., 2004

overlay can generate enough heat to prevent ice formation on a bridge deck when connected to a power source. The Nebraska Department of Roads (DOR) examined this method with the University of Nebraska and Western Michigan University and obtained data showing that an average of 500 W/m^2 (46 W/ft^2) was generated by the conductive concrete to raise the slab temperature about 9°C (16°F) above the ambient temperature. It proved that the conductive concrete overlay had the potential to become the most cost-effective bridge deck de-icing method.

Pre-wetting (Burtwell, 2004)—With the Transportation Research Laboratory (TRL) Limited, the UK Highways Agency and the National Salt Spreading Research Group (NSSRG) evaluated the applicability and costs of introducing pre-wetted salt compared with dry salts. Salt is most effective if it can form a solution with the moisture on the road surface. If this moisture has already frozen before the salt is applied, the salt is much less effective in combating the slippery conditions. For this reason, dry salt is wetted and, usually, pre-wetting agents such as NaCl or $CaCl_2$ brine are used. Special vehicles and equipment are needed to process pre-wetted salts: vehicles with a traditional hopper for the dry de-icing agent and integral tanks for the storage of brine; and a saturator station to produce the brine solution.

Information technology—Advanced RWIS—RWIS consists of a network of weather stations, forecasting services, and the supporting infrastructure (Ballard, 2004). Given that it refers to the entire system used to obtain and send data, RWIS is making innovations both in hardware and software.

- Hardware (Hoffman et al., 2009)—RWIS stations have progressed from being expensively and permanently mounted along the roadside (even on an existing sign post or overhead mast) to being electrically powered and collecting data from a puck embedded in the road. The Utah DOT made a special point to show the team examples of its newer RWIS stations, which are portable, lightweight, solar- or wind-powered, and video-camera equipped. Furthermore, the Colorado DOT pointed out that new technology can now gather surface condition information noninvasively from the roadside and is able to provide a useful measurement of slipperiness (i.e., friction).

- Software (Boselly, 2004)—Since the late 1980s, some RWISs such as Weather Traveller Information Web and Real-time Road became operational. However, they were not enough to provide key forecast information needed by decision-makers. In this vein, the Washington DOT developed a new capability for maintenance operations decision-making, named ARROWS (Automated Real-time ROad Weather System), with the University of Washington. ARROWS takes numerical weather prediction and pavement condition outputs and presents the forecast information in a format for easy use and understanding by maintenance personnel. To do that, ARROWS requires the high-resolution modeled output, the integration of other weather information sources, and developing the presentation format.

Equipment—Blade geometry—Cutting edges (Hoffman et al., 2009)—The type of plow cutting edge varies from state to state, mostly based on temperature, weather conditions, and whether the agency is dealing with solid ice, snow, or slush. Blades are made of regular rolled steel, hardened steel, serrated steel, carbide steel inserted in steel, rubber blades, and carbide steel inserted in rubber. The most popular configuration is the standard single blade per plow configuration; however, experimentation is being done with double- and triple-blade configurations. While snow- and ice-removal agencies are interested in the experiences of others, they tend to do their own in-house experimenting and to base purchasing selections on their own research. Much depends on their organization's own unique culture and their own weather and traffic conditions. Driving forces include extending life (thus reducing frequency of replacement), reducing vibration, minimizing damage due to obstructions on the surface, reducing noise, and balancing pressure to reduce chemical usage versus willingness to achieve goals using more chemicals. Perhaps equally important is the operator's degree of interest and willingness to try or use something new. Today's industry is responsive to user agencies in providing options to cover varying needs and conditions.

Advanced chemicals for de-icing or anti-icing:

- Agriculture-based products (ABP): Research in recent years shows that adding various organic compounds to common winter maintenance chemicals can significantly decrease the freezing point (Koefod, 2008). Nixon suggests that ABP can be combined with winter maintenance materials to act as corrosion inhibitors and increase melting capacity (Nixon and Williams, 2001). ABP have low eutectic and effective temperatures and are relatively benign to the environment and highway infrastructure.
- Corrosion-inhibiting chemicals: Corrosion-inhibited deicer products must prove to be at least 70% less corrosive than NaCl to be qualified for the PNS[59] (Pacific Northwest Snowfighters) specification for corrosion[60] (Fay et al., 2008).

Drivers or Barriers to New Technology Adoption

According to the case study presentation arranged by TRB, it is said that anti-icing was one example of a successful distribution of new, advanced technology in the transportation area (even though it is not yet a complete success in that some states still are not practicing anti-icing). The research team therefore examined the critical factors affecting distribution (i.e., the drivers or barriers to technology adoption) in the specific areas of snow removal and ice control. These include

- **Number of Initial Participants.** Twelve states were involved in the anti-icing program from the start. There were enough personnel in several agencies to know the "language" and to try the new method.
- **Attitude toward Failures.** When practicing the anti-icing program, early failures were accepted as part of the learning process.
- **Knowledge Sharing.** Experience of anti-icing practices was collected into a manual that is readily available and includes clear guidelines. In particular, the manual was freely available on line and had some user-oriented charts that gave recommended practice in most conditions likely to prevail during winter weather.
- **Communication.** The lead states team focused on communication. Even team members who were not themselves technical staff played a significant role in communication.

[59] PNS is the association of state members of Washington, Oregon, Montana, Idaho, Colorado, and British Columbia, whose mission is to strive to serve the traveling public by evaluating and establishing specifications for products used in winter maintenance that emphasize safety, environmental preservation, infrastructure protection, cost-effectiveness and performance. PNS developed specifications for chemical products which must pass a series of tests for chemical, frictional, toxicological, and corrosion; meet environmental and health standards; and be at least 70% less corrosive than road salt.

[60] One of PNS's functions is to develop anti-icing chemical specifications that all member organizations utilize. The PNS specification for corrosion is that a corrosion-inhibited anti-icing chemical must be at least 70% less corrosive to a given type of metal than sodium chloride is corrosive to that same type of metal. This reduced level of corrosion is determined by a laboratory test. Generally, the lab test consists of immersing and removing separate metal washers in a sodium chloride solution and a corrosion-inhibited chemical solution. Over a 72-hour period, the metal samples are immersed for 50 minutes and removed from the solution for 10 minutes. This immersion and removal process is done hourly for the 72-hour period. After the test period is complete, the metal samples are weighed. If the metal sample exposed to corrosion-inhibited chemicals has at least 70% less weight loss compared with the weight loss of the metal sample exposed to the sodium chloride solution, the corrosion-inhibited chemical meets the PNS specification (Baroga, 2004).

Table B-5. Concentration ratio and Herfindahl-Herschman index.

	Heated Road	Pre-wetting	RWIS	Blade Geometry	Advanced Chemicals	
					Environmentally friendly	Corrosion-inhibiting
CR3	24	100	30	11	57	36
HHI	202	5000	300	47	1950	528

- **Conservation of Momentum.** When the lead states effort came to its conclusion, the SICOP[61] (Snow and Ice Pooled Fund Cooperative Program) was present and able to take over. Dissemination costs money, and SICOP provided (via the states) the conduit for that money to keep flowing.

Technological Monopolization

In addition to organizational issues affecting new technology adoption as discussed in the previous section, technology applications themselves also generate drivers or barriers to broader employment of new, advanced technology. One such technology-specific factor is the degree of monopolization in presenting applications of a technology to the market. As economic theory shows, a monopoly results in a smaller number of products at higher price when compared to a competitive market. A monopoly would therefore incline a vendor to impose a high price on selling or licensing their technologies.[62] This situation is enabled by strong and/or numerous patents.

Agency officials may be more reluctant to commit to a technology application for which there is only one vendor compared to a situation where there are multiple vendors (thus giving the potential adopting agency more market power). To look at the degree of technological monopolization in the area of snow removal and ice control, the research team analyzed patent data again and computed two indicators—Concentration Ratio (CRn) and Herfindahl-Herschman Index (HHI)—to determine how intensely patents in specific technologies are concentrated in a handful of companies and to compare them across technologies.

When examining the maturity of technologies in areas of snow removal and ice control before, the research team found these technologies are in the initial phase of development. This often means there are a few relevant companies. Table B-5, which gives the market share of the three largest firms (CR3) and HHI,[63] shows that pre-wetting technology is intensively concentrated and dominated by one company. Environmentally friendly chemicals are moderately concentrated and other technologies have low levels of concentration. Pre-wetting and environmentally friendly chemicals, therefore, have a certain level of limitation in vendor choice and proprietary relations. Regardless of organizational issues, in this case technology itself might pose a sizable hurdle for adopting new, advanced technology due to the difficulty of technology transfer and implementation and subsequent low accessibility and availability.

Compare

In this phase, the research team created metrics with both normative and natural units in order to evaluate likely outcomes stemming from each candidate technology. On the basis of given assumptions and initial conditions, the research team sorted out five technology packages: use of either $CaCl_2$ or KAc, delivery of each by vehicle or FAST, and the thermal method—and compared them with respect to created metrics and cost to adopt. When creating metrics, the research team considered four primary DOT mission goals: preservation, safety, mobility, and sustainability. When conducting cost analysis, the research team included not only the easy-to-quantify part (e.g., installation and material costs) but also the hard-to-quantify part (e.g., the cost of corrosion and environment and the benefit from reduced travel time and crashes). The former are used to provide input to the STREAM Decide step. The latter will be used as a check on the benefit metrics discussed immediately below.

Creating Appropriate Metrics

In order to compare technologies, the research team needed to (1) sort out candidates from various available and emerging

[61] SICOP has the task of demonstrating the effectiveness of the new technology (and other new tech) rather than creating new research. It is a pooled fund study that requests about $2,000 from each state every 2 or 3 years for ongoing expenses and solicits additional funds for specific projects (such as the soon-to-be-released computer-based training in RWIS and anti-icing). SICOP communicates via their website (www.sicop.net or http://www.transportation.org/Default.aspx?SiteID=88) and the snow and ice listserv.

[62] The degree of monopoly rents the vendor chooses to extract may be modified by the time frame within which it is willing to operate. We speak now only of pure theory.

[63] A small index indicates a competitive industry with no dominant players. HHI scores above 2,500 suggest a high degree of concentration.

technologies to be compared; (2) set up standards and create metrics to judge; (3) assess the range of possible outcomes from the use of each candidate technology; and (4) judge likely outcomes according to created metrics.

Given that snow removal and ice control strategy depends on several conditions (e.g., LOS and weather), candidate technologies are limited according to those conditions. For example, air or road temperature puts a limitation on the availability of chemicals because of their eutectic temperatures. In a region with sensitive vegetation or national monuments, chloride chemicals are excluded from the list of candidate technologies.

When creating metrics, the research team needed to consider DOT goals (e.g., preservation, safety, mobility, and sustainability). Then, the research team could think of other metrics as well. For example, using NaCl as a reference point, the following paragraph suggests some idea of how to compare alternatives (For example, it contains information about cost, the ease of application, the LOS, corrosive effects, and environmental impacts.)

> Rock salt is used extensively because it is inexpensive, easy to spread, and effective in keeping pavements safe in the winter. Damage to vegetation, soil, water quality, vehicles, and infrastructure is the known negative impact of rock salt, although most deicers have some of these environmental impacts (Burtwell, 2004).

Potential outcomes of each candidate technology could be estimated through literature review, laboratory and field experiments, and users' perception based on their experience and expertise. In this vein, Fay et al. (2008) shows user perception on performance of winter chemicals (see Figures B-3 and B-4).

Finally, the research team matched likely outcomes with the metrics and evaluated them. The research team needed to consider various aspects—not only DOTs' goals but also of other metrics such as costs across candidate technologies.

Among the current-use and state-of-the-art technologies discussed in the Identify step, several appeared likely candidates for consideration under the assumptions and initial conditions presumed in the scenario. Blackburn et al. (2004) suggests the following conditions when selecting appropriate technologies (Blackburn et al., 2004):

- **Climate conditions:** frequency of snow and ice events (low/moderate/high), severity of winter pavement exposure (mild/moderate/severe), wintertime precipitation (type/rate), urban influence (small/medium/large/industrial), water influence (minor/river/lake/ocean), elevation/large-scale topography (plain/rolling/mountainous)
- **Weather conditions:** rain (light/moderate/heavy/freezing), sleet (light/moderate/heavy), snow (light/moderate/heavy/blowing; powder/ordinary/wet or heavy)
- **Site conditions:** area type (urban/suburban/rural), special highway segment area (hills/curves/grades/intersections/bridges/sags/ramps/crosslopes/weaving areas/narrowings/roadway widenings/elevated roadways/pavement surface types/tangents), shadings from solar influence (forest or vegetation/buildings or structures/cuts), pavement condi-

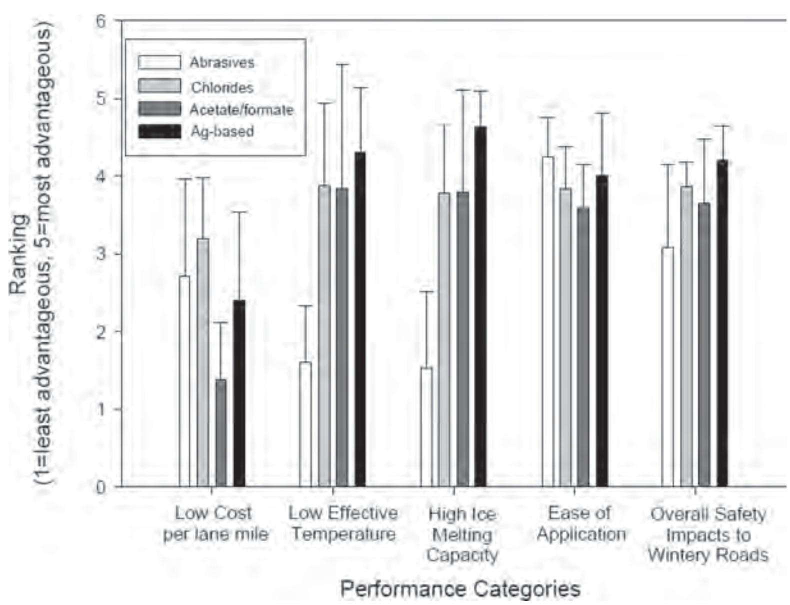
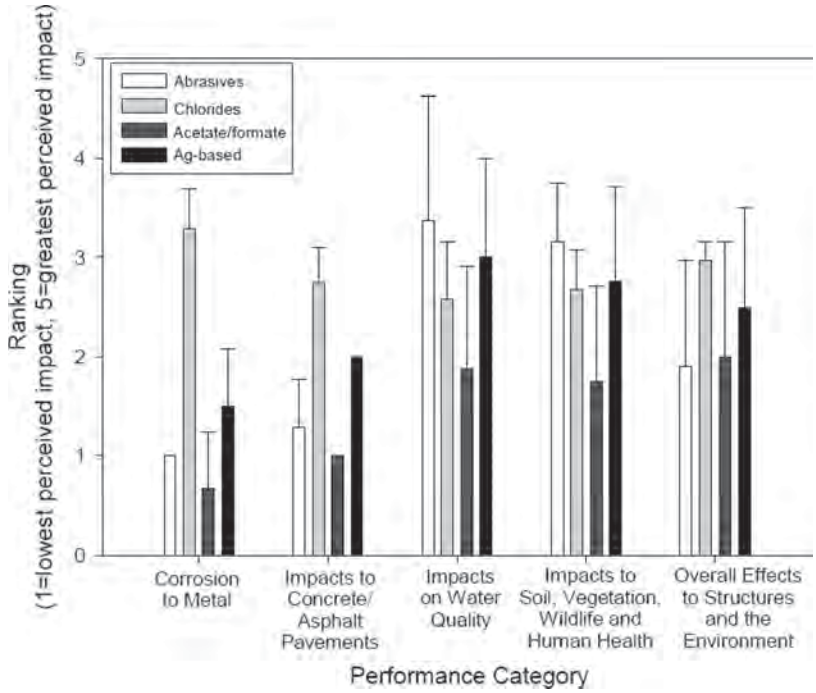


Figure B-3. User perception on positive performance.



Source: Fay et al., 2008

Figure B-4. User perception on negative performance.

tions (temperature/ice and pavement bond/frost or thin ice/slush, loose snow, packed snow, thick ice)

- **Traffic conditions:** traffic volume (very low/low/medium/high/very high), commercial vehicle mix (low/moderate/high), vehicle speeds (low/moderate/high)

Definition of Metrics

In the most general case, the research team developed a metric for each of the mission objectives: safety, preservation, mobility, and sustainability. If these were true outcome metrics, each would be measured in its natural units, e.g., "safety" in terms of car crashes (or relative risk), "preservation" in terms of maintenance of road and bridge condition (or relative corrosion), "mobility" in terms of travel time (or relative speed), and "sustainability" in terms of environmental impact (or relative detrimental effects on air, soil, water, etc.). The effect of each technology alternative on each of these outcomes would have a distribution that depends on how the technology is implemented and used, as well as the specific characteristics of weather, site, and traffic.

Winter maintenance is subject to environmental conditions as well as methods or strategies in use as shown in Figure B-5. Although input factors are homogeneous, outputs or outcomes may be heterogeneous. In this vein, the research team used output[64] or outcome[65] measures for the metrics rather than input[66] measurements.

Metric for Safety and Mobility

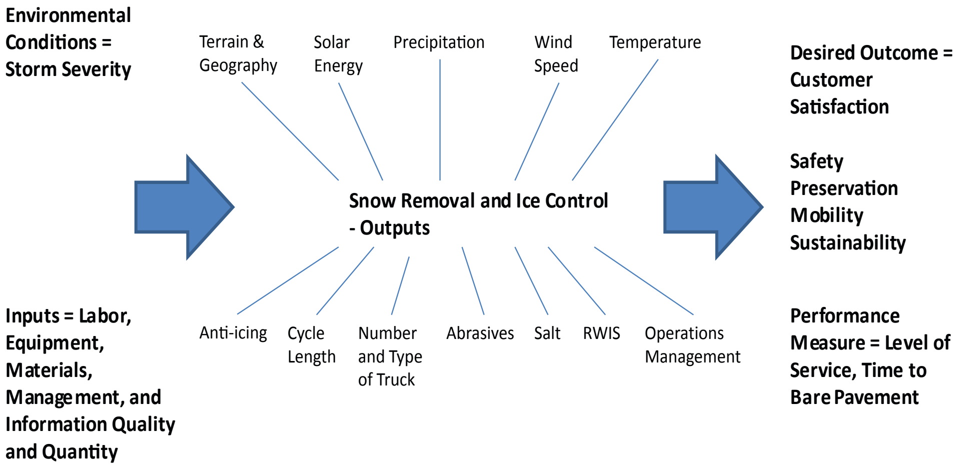
For the example of snow removal and ice control, the research team defined a single metric for "safety" and "mobility" in terms of how well each candidate technology can attain the desired LOS. When defining LOS goals, Blackburn et al. suggest pavement snow and ice conditions (PSICs) (Blackburn, Amsler Sr., and Bauer, 2004). For each "Condition State," the Manual recommends different feasible actions, as shown in Table B-6. Higher LOS are associated with "better" PSICs and more rapid achievement of "better" or "bare" pavement conditions.

Given that PSICs include several measures related to "safety" and "mobility," the research team based the overall metric on them and sought to make an assessment that would

[64] Output measures quantify physical outputs from the resources that are used in units of work of winter operations. Output specifications primarily deal with defining methods of performing the work and the associated accomplishments (Maze, 2007).

[65] Outcome measures reflect the end result of winter maintenance during and after a storm event, usually as perceived by the motorist (Maze, 2007).

[66] Input measurements are used to quantify the resources spent on snow and ice control or winter maintenance operations, typically applied to equipment, material, and labor used for winter operations (Maze, 2007).



Source: Maze, 2007

Figure B-5. Relationship between inputs, outputs, and outcomes in snow removal and ice control.

incorporate the following measures that might actually be available to a transportation agency (Maze, 2007):

- Measure: Degree of clear pavement
  – Approach: Manual observation
  – Approach: Camera-assisted observation
- Measure: Traffic flow
  – Approach: Detectors providing information on speed, volume, and occupancy
  – Approach: Road closure
- Measure: Crash risk
  – Approach: Friction (or slipperiness)
  – Approach: Reported crashes

Table B-6 shows that road surface conditions are associated with the friction coefficient which has direct bearing on both "safety" (relative risk) and "mobility" (relative speed). The research team used those values as the natural unit for the purpose of comparison. According to a Swedish study, for example, sanding could produce an increase in the friction coefficient of around 0.1 from a baseline level of around 0.2–0.3 and, consequently, cause travel speed to be increased on average by 2.4 km/h. It is known that sanding generally could reduce the number of accidents by 62% at a 5% significance level. In terms of PSICs as shown in Table B-6, sanding could change the road surface conditions to Condition 3 from Condition 4.

Based on these PSICs, the research team could then define the following metric for "safety" and "mobility" in terms of normative units. These, in turn, could be obtained through either a Delphi technique or a survey of relevant professionals:

- Metric Value 1 – Inability to attain Conditions 1, 2, 3, and 4;
- Metric Value 2 – Ability to attain Condition 4, but not Conditions 1, 2, and 3;
- Metric Value 3 – Ability to attain Condition 3, but not Conditions 1 and 2;
- Metric Value 4 – Ability to attain Conditions 1 or 2.

Table B-7 shows both normative and natural units in order to compare candidate technologies.

Metric for Preservation and Sustainability

Because the effects on "preservation" and "sustainability" of snow removal and ice control primarily result from (1) corrosion and (2) dispersal and runoff of winter maintenance chemicals (with chlorides) which lead to structure (including bridge) deterioration and the contamination of air, water, and soil, the research team defined a single metric for "preservation" and "sustainability." The problem is that these detrimental effects are highly variable depending on location, the type of chemicals, application rate, and so on. For example, chemicals applied to a bridge adjacent to the sea might have no actual influence on the environment. On the other hand, chemicals applied to a road and then splashed off to a roadside where chemical-sensitive vegetation and wildlife grow might have a significant adverse effect.

The transport of salt from the road to the roadside environment is the main environmental concern of winter maintenance. The basic mechanisms determining the salt exposure are salt dose to the road, road conditions, traffic characteristics (type, intensity, and speed), and meteorological parameters, such as wind (Gustafsson and Blomqvist, 2004). In addition, there are several categories of adverse effects from spills (Burkett and Gurr, 2004):

- Soils and groundwater: increase in calcium, magnesium, phosphorous, and soil organic matter

Table B-6. Description of PSICs.

Road surface conditions		(Friction coefficient)	Safety: Relative risk	Mobility: Relative speed
Condition 1	All snow and ice is prevented from bonding and accumulating on the road surface. Bare/wet pavement surface is maintained at all times. Traffic does not experience weather-related delays other than those associated with wet pavement surfaces, reduced visibility, incidents, and "normal" congestion.	(0.7 – 0.9)	1.0	1.0
Condition 2	Bare/wet pavement surface is the general condition. There are occasional areas having snow or ice accumulations resulting from drifting, sheltering, cold spots, frozen melt-water, etc. Prudent speed reduction and general minor delays are associated with traversing those areas.	(0.4 – 0.7)	1.3	0.9
Condition 3	Accumulations of loose snow or slush ranging up to 2 in. are found on the pavement surface. Packed and bonded snow and ice are not present. There are some moderate delays due to a general speed reduction. However, the roads are passable at all times.	(0.3 – 0.4)	1.5	0.7
Condition 4	The pavement surface has continuous stretches of packed snow with or without loose snow on top of the packed snow or ice. Wheel tracks may range from bare/wet to having up to 1.5 in. of slush or unpacked snow. On multilane highways, only one lane will exhibit these pavement surface conditions. The use of snow tires is recommended to the public. There is a reduction in traveling speed and moderate delays due to reduced capacity. However, the roads are passable.	(0.1 – 0.3)	2.5	0.4
Condition 5	The pavement surface is completely covered with packed snow and ice that has been treated with abrasives or abrasive/chemical mixtures. There may be loose snow of up to 2 in. on top of the packed surface. The use of snow tires is required. Chains and/or four-wheel drive may also be required. Traveling speed is significantly reduced and there are general moderate delays with some incidental severe delays.	(smaller than 0.1)	4.4	0.3
Condition 6	The pavement surface is covered with a significant buildup of packed snow and ice that has not been treated with abrasives or abrasives/chemical mixtures. There may be 2 in. of loose or wind-transported snow on top of the packed surface due to high snowfall rate and/or wind. There may be deep ruts in the packed snow and ice that may have been treated with chemicals, abrasives, or abrasives/chemical mixtures. The use of snow tires is the minimum requirement. Chains and snow tire equipped four-wheel drive are required in these circumstances. Travelers experience severe delays and low travel speeds due to reduced visibility, unplowed loose, or wind-compacted snow, or ruts in the packed snow and ice.	(smaller than 0.1)	Greater than 4.4	0.1
Condition 7	The road is temporarily closed. This may be the result of severe weather (low visibility, etc.) or road conditions (drifting, excessive unplowed snow, avalanche potential or actuality, glare ice, accidents, vehicles stuck on the road, etc.).			0

Sources: Blackburn et al., 2004; and Elvik and Hoye, 2009

Table B-7. Metrics table for safety and mobility.

PSIC	Normative Unit	Natural Unit	
		Safety	Mobility
1	4	1.0	1.0
2		0.77	0.9
3	3	0.67	0.7
4	2	0.4	0.4
5	1	0.23	0.3
6		0.15	0.1
7		0.05	0

Note: The natural unit of "safety" is the inverse of "relative risk" while that of "mobility" equals "relative speed."

- Terrestrial vegetation: potential damage by airborne contaminants
- Streams: depletion of dissolved oxygen (DO), water quality concern
- Air quality: fine particulate material

For the normative unit, the research team created metrics based on output or outcome of environmental and corrosive effects with four different scales for measurement in both corrosive and environmental terms:

- Metric Value 1 – serious effect;
- Metric Value 2 – moderate effect;
- Metric Value 3 – small effect;
- Metric Value 4 – no/little effect.

In creating this metric the research team considered winter operation strategies' environmental effect on all four subjects—air, vegetation, soil, and water—and then used the average value of the effect on these four categories.

Based on the natural units in Table B-8 and the normative metric above, the research team created Table B-9, which compares candidate technologies.

Metric for POSI

The research team based the metric for "POSI" on the severity of the barriers to implementation (e.g., the inertia of DOTs to avoid changing from the current methods of plowing, sanding, and salting; difficulties associated with approvals, acquisition, training, and other necessary actions to enable the use of the alternative technologies; and concerns about its use, for example, uncertainties about the cost and technical viability of the new method, as well as its possible demands on management and training resources.)

Based on Table B-10, the research team in Table B-11 defined the following metric for "POSI."

Comparison of Current Methods and Technology Alternatives

Assumptions

To consider several conditions when comparing candidate technologies, the research team assumed that the PSICs accurately and fully reflect the conditions of climate and weather. Furthermore, through the initial conditions, the research team took the conditions of site and traffic into account.

Another important assumption was about the frequency and regularity of snowfall and inclement conditions. More northern states expect snow during winter and thus prepare for winter storms; however, some states with less severe winters may also anticipate snow at irregular intervals. To account for this intermittency of snow, the research team assumed that each state behaves in the economic manner. In other words, that states are rational and try to optimize winter operations as appropriate. This posture is then reflected in their winter strategies,

Table B-8. Comparative corrosion rates and relative corrosiveness for selected chemicals.

Chemical	Corrosion Rate (mils per year)	Relative Corrosiveness
Calcium Chloride	63.53	1.2
Sodium Chloride (rock salt)	52.94	1
Magnesium Chloride	17.44	0.33
Distilled Water / Potassium Acetate (KAc)	5.29	0.1
Calcium Magnesium Acetate (CMA)	4.16	0.08

Source: WSDOT and Minnesota Corn Processors

Table B-9. Metrics table for preservation and sustainability.

Detrimental Impact	Normative Unit	Natural Unit	
		Preservation	Sustainability
No/Little	4	Smaller than 0.1	4
Small	3	0.1 – 0.5	3
Moderate	2	0.5 – 1	2
Serious	1	Greater than 1	1

Note: The natural unit of "preservation" follows "relative corrosiveness." The research team used the same value in "sustainability" across normative and natural units.

Table B-10. Sources of impediments that reduce POSI.

Category of Impediments	Specific Barriers Affecting POSI
Technology	Unfamiliarity with core or applied technology
	Uncertainty concerning actual performance
	Additional implementation requirements (training, standards, etc.)
Agency Process or Institutions	Need for new or conflict with existing regulations & standards
	Non-fungibility of funding for required expenditures
	Extended or problematic approval processes
External to Agency	Inertia of existing processes and methods
	Insufficient political or public acceptance
	Lacking presence of necessary vendor or support base

Table B-11. Metric table for POSI.

POSI Score Level	Conditions for Achieving POSI Score Level
4	Number of Major Concerns = 0
3	Does not meet criteria for POSI score level of 1, 2, or 4
2	Number of Show Stoppers = 1 or Number of Major Concern > 2
1	Number of Show Stoppers > 1

primarily de-icing and anti-icing. Based on that, the research team assumed that snow-belt states execute anti-icing practices while non-snowy region states employ de-icing practices. This seemed reasonable in as much as anti-icing requires a large prior investment. To take effective measures before snow storm events, anti-icing requires more expensive chemicals (e.g., liquid chemicals), information technology (e.g., RWIS and MDSS), relevant equipment, and appropriate training. Thus, it would be economically optimal for less severe region states to prepare for intermittent snow storms with de-icing strategies.

Initial Conditions

For comparison purposes, the research team set up the following initial conditions:

- Climate and weather conditions: *Snow-belt States.* The research team assumed PSIC = 2 before snow storms and expected PSIC = 4 after snow storms without anti-icing. The aim was to attain PSIC = 2 through winter operations.
  - Anti-icing: Because this area belongs to snow-belt states, in particular the Northeast, the Midwest or Alaska, the research team assumed that this area adopts anti-icing strategies.
  - Low temperature: The research team assumed that these states want to make certain that they can operate their de-icing and anti-icing missions effectively at any temperatures above the very low temperature of −40°F and so this became the planning scenario. This would limit the availability of candidate technologies in part because of chemicals' eutectic temperature. For example as Figure B-6 shows, at such low temperatures only $CaCl_2$ and KAc are appropriate for application.
- Site conditions: Bridge
  - Various available technologies: Bridges are of interest for the present purpose because they permit a greater variety of technologies to be compared than with roads. In addition to chemicals, for example, the research team could test thermal methods (pavement heating technologies), FAST, and so forth.
- Traffic conditions: Highway—For conditions, the research team drew on the data shown in Table B-12 from the I-35W bridge over the Mississippi in Minnesota where anti-icing strategies were employed in 2000 (Johnson, 2001).
  - Traffic volume: AADT[67] = 140,000 vehicles with the number of commercial vehicles = 5,000.

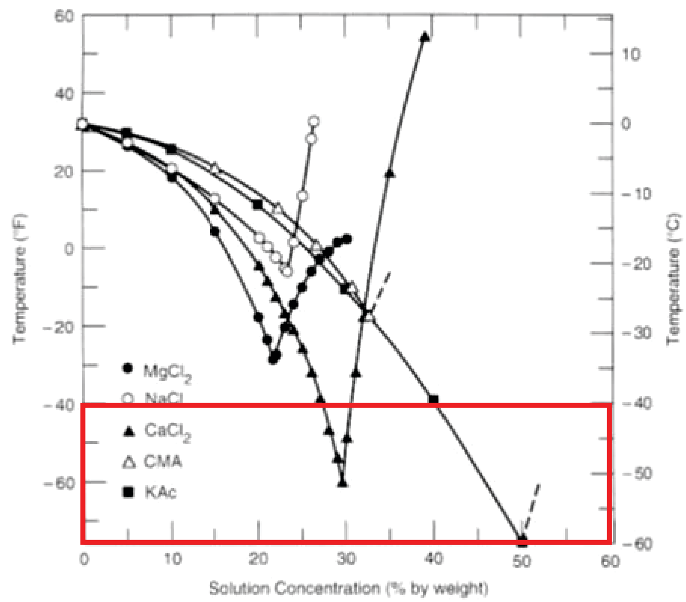


Figure B-6. Eutetic temperature and concentration of chemicals.

[67] AADT = annual average daily traffic

Table B-12. Comparison of crash data for I-35W bridge before and after treatment.

Non-dry surface crash before and after employing the anti-icing system			
Description	Unit	Before	After
damage			
Fatal	crashes	0	0
Injury Type A only	crashes	0	0
Injury Type B only	crashes	2	0
Injury Type C only	crashes	8	5
Property Damage only	crashes	21	4
daily traffic	vehicles	140000	
auto	vehicles	135000	
truck	vehicles	5000	

Note: "Before" = 1996-1997 winter season; "After"= 2000-2001 winter season.

– Number of car accidents: the number of crashes related to human and property damages dropped from 31 (during winter season of 1996-1997) to 9 (during 2000-2001).

Candidate Technologies to be Compared

The research team examined five different technology bundles for this demonstration. Four of the bundles were variations based on combinations of chemical type ($CaCl_2$ or KAc) and application method (vehicle or FAST). The fifth technology alternative was the thermal method, described above.

Drawing on the description of the metrics discussed above and a review of the relevant literature, the research team assessed and compared the candidates in Table B-13 (and Figure B-7) based on normative units and Table B-14 (and Figure B-8) based on natural units. It is worth noting that in a full STREAM analysis of this agency activity, the research team would include a richer set of both technology bundles and of alternative sources of inputs from expert sources thus most likely generating a range of assessments that would be treated in the same manner as the bridge deck monitoring and evaluation assessment presented above.

There did not seem to be much difference between the two approaches to constructing a metric for comparison. The order of preference between technology bundles remained the same between the two views and the absolute magnitude of this ordering remained largely the same, with one exception. When measured in natural units, the drawbacks for

Table B-13. Comparison of technology application bundles using normative units.

	Chemical Method				Thermal Method
	Application by Vehicle		Application by FAST		
	Calcium chloride	Potassium acetate	Calcium chloride	Potassium acetate	(e.g., thermal fluid)
Attained PSIC	3	3	3	3	2
Safety	3	3	3	3	4
Mobility	3	3	3	3	4
Corrosive effect on:					
Highway structures & vehicles	2	4	2	4	4
Asphalt concrete	3	2	3	2	4
Preservation	2.5	3	2.5	3	4
Environmental effect on:					
Air	4	4	4	4	4
Vegetation	2	3	2	3	4
Soil	2	3	2	3	4
Water	2	3	2	3	4
Sustainability	2.5	3.25	2.5	3.25	4
Probability of Successful Implementation:					
Technology	4	3	3	3	3
Agency Process or Institution	4	4	3	3	2
External to Agency	4	4	3	3	3
POSI	4	3.67	3	3	2.67

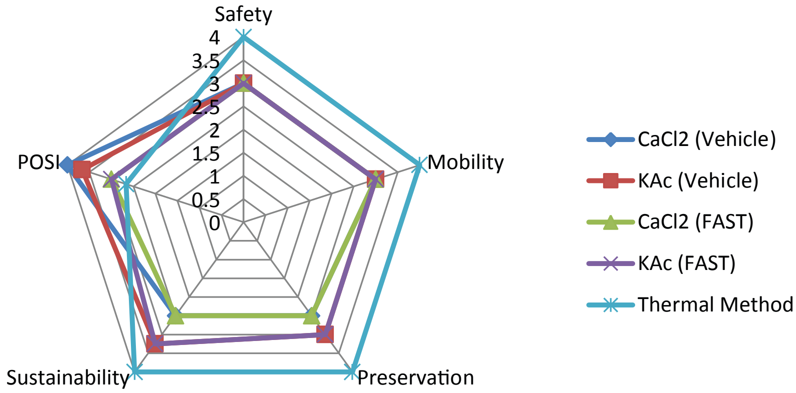


Figure B-7. Comparison of technology application bundles using normative units.

Table B-14. Comparison of technology application bundles using natural units.

	Chemical Method				Thermal Method
	Application by Vehicle		Application by FAST		
	Calcium chloride	Potassium acetate	Calcium chloride	Potassium acetate	(e.g., thermal fluid)
Attained PSIC	3	3	3	3	2
Safety	2.68	2.68	2.68	2.68	3.08
Mobility	2.8	2.8	2.8	2.8	3.6
Corrosive effect	1.2	0.1	1.2	0.1	0
Preservation	0.33	4	0.33	4	4
Environmental effect					
Sustainability	2.5	3.25	2.5	3.25	4
Probability of Successful Implementation:					
Technology	4	3	3	3	3
Agency Process or Institution	4	4	3	3	2
External to Agency	4	4	3	3	3
POSI	4	3.67	3	3	2.67

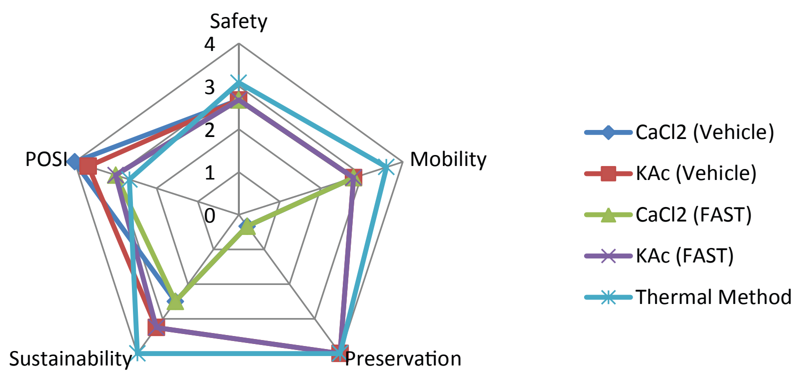


Figure B-8. Comparison of technology application bundles using natural units.

Table B-15. Costs and benefits of technologies.

Technologies	Cost		Benefit	
	Easy to quantify	Hard to quantify	Easy to quantify	Hard to quantify
Anti-icing and de-icing	Materials, labor, maintenance	Environmental and societal impacts		Fuel and travel time savings, the potential for material and labor savings
Plow blades	Equipment	Potential damages caused by changes to plowing equipment and practices	Labor and material savings	Efficiency gains, safety improvements, and added equipment versatility
RWIS	Complete site installations	Maintenance, power, and communications		Labor and material savings, improved LOS, safety improvements, lower insurance costs, and fuel savings

Source: Veneziano et al., 2010

using $CaCl_2$ as the active chemical became starker. In the normative 1 to 4 scaling, by definition there cannot be a greater than four times difference. When using natural units, however, an order of magnitude (or larger) difference becomes possible, as in this case. Both methods can convey useful information to agency decisionmakers and the use of both provides a cross-check on each other.

Cost of Current Methods and Technology Alternatives

Given that transportation, and therefore snow removal and ice control, is closely related to human lives and activities, it has a significant effect on not only DOTs in terms of preservation and sustainability but also users in terms of safety and mobility. All of these, therefore, have costs and benefits associated with them. Road users, for example, are affected by the cost of accidents (as well as the value of accidents avoided), travel time, fuel cost, corrosion damage, snow tire and equipment costs, and the loss of benefit from cancelled journeys. Road authorities face costs of re-asphalting, road markings, washing signs, increased bridge maintenance, as well as the direct costs of sanding, salting, and plowing (Elvik and Hoye, 2009).

These money values frequently consist of two parts: easy to quantify and hard to quantify. Table B-15 shows some examples in the area of snow removal and ice control. In what follows the research team considered the easy-to-quantify costs as being representative of the fixed and recurring costs actually incurred by transportation agencies. This is what the research team used when analyzing the cost of each candidate technology adoption. The hard-to-quantify costs largely represent quantifications of some of the mission goal benefits discussed above.

The data on which the calculations below are based is provided in Appendix E. The research team presents only the results of analysis here. Table B-16 shows those costs that apply directly to agencies. These include one-time initial costs such as equipment and installation and recurring costs such as materials and labor. In this scenario, it would seem that calcium chloride by vehicle is least costly compared to the use of potassium acetate and other methods for dispersal such as FAST. The thermal measure appears most costly among the five shown. Yet, if different categories of cost are more or

Table B-16. Cost calculation, transportation agency ($000s/bridge).

Cost		Chemical Method (Vehicle)		Chemical Method (FAST)		Thermal Method
		Calcium chloride	Potassium acetate	Calcium chloride	Potassium acetate	(e.g., thermal fluid)
Net Participants' Cost	Equipment	20	20	300	300	300
	Installation	5	5	300	300	400
	Lifecycle (O&M)	2	2	20	20	30
	Utility Incentive Payments	0	0	0	0	0
Cost of Operation	Materials	60	120	60	120	100
	Labor	60	60	1	1	2
Total Cost		147	207	681	741	832

Table B-17. Cost calculation, user and society perspective ($000s/bridge).

Cost		Chemical Method (Vehicle)		Chemical Method (FAST)		Thermal Method
		Calcium chloride	Potassium acetate	Calcium chloride	Potassium acetate	(e.g., thermal fluid)
Cost of Corrosion and Environment		300	120	300	120	-
Benefit of Travel Time Saving		-	-	(394)	(394)	(590)
Benefit of Reduced Crash		(756)	(756)	(756)	(756)	(869)
Total Cost		(456)	(636)	(850)	(1,030)	(1,459)

Table B-18. Net cost calculation, both parts ($000s/bridge).

Cost		Chemical Method (Vehicle)		Chemical Method (FAST)		Thermal Method
		Calcium chloride	Potassium acetate	Calcium chloride	Potassium acetate	(e.g., thermal fluid)
Total Cost		(309)	(429)	(169)	(289)	(627)

less sensitive to modification or local agency circumstances, it is important to look beyond the total shown. The use of calcium chloride in combination with FAST has the lowest operational cost followed by the thermal method which has the highest net fixed cost. If initial funding support is available from outside sources, such as the federal government, FAST or the thermal method remain viable candidates on this basis.

The calculation becomes more complicated if the research team also seeks to quantify net costs when looking at elements of cost and benefit that accrue largely to the road users and society such as corrosive and environmental effects, influence on travel time, and human and property damage from car accidents. The single cursory analysis presented in Table B-17 seems to show that the thermal method is most attractive followed by FAST, given that they bring greater benefit from travel time savings and crash reduction as well as smaller monetary damage from corrosion and to the environment compared to chemical methods by vehicle. In a fuller analysis, these costs elements would also be crafted from several input sources and from surveys of experts in order to craft ranges of possible net cost as was done in the prior bridge deck evaluation application of STREAM.

Solely for the purpose of obtaining a final cost calculation for this demonstration of STREAM, the research team now combined the two categories of cost through simple addition. The result is shown in Table B-18. Because the elements on the benefit side of the ledger in the hard-to-quantify part are of a larger magnitude than those on the cost side, and this net result is also larger than the net cost from the easy-to-quantify part, these values show a combined net benefit for each technology. By this calculation, the thermal method is the most attractive because of its huge benefit from reduced travel time and crash avoidance. The next most attractive technology is potassium acetate by vehicle. In what follows the research team, however, relied solely on the elements of agency cost to derive insights on the decision facing transportation officials.[68]

Decide

The first three steps of STREAM could be done on a collaborative basis by agencies or by an external body that would provide the information to agencies. The Compare step would also be performed on this basis but would also require a particular agency to modify it in accord with local conditions and preferences. This could certainly be done after receiving a preliminary comparative analysis. The purpose of these steps has been to provide extensive and comparable information that is also framed in the relevant terms for transportation agencies and the decisions they face. Such input or evidence is not fully actionable: there are other factors to consider. As a result, the ultimate decision rests with the individual transportation agencies themselves. The Decide step outlines the procedures that may be followed to weigh these alternatives.

What Factors to Consider

As indicated in the Compare phase, snow removal and ice control technology is dependent on several conditions. Road users care about the LOS, corrosive effect on their vehicles, and health effects. Transportation agencies are interested as well in performance, cost, and the ease of application. In both cases, weather and location are important because they play a key role in the availability of technologies. Table B-19 summarizes these considerations.

[68] Not to do so would be a case of double counting since the issue of costs and benefits from the perspective of agency missions and goals has already been rendered in the mission-specific metrics discussed above.

Table B-19. Factors to consider when deciding on appropriate technologies.

Factors to Consider		Source
Overall Strategies	Specific Chemicals	
- LOS - Cost - Infrastructure and environmental impacts - Equipment - Weather	- Performance: ability to penetrate, undercut and break the bond between the ice and the pavement, or to prevent the ice–pavement bond from forming—eutectic and effective[69] temperatures - Cost - Availability - Ease of use - Corrosion impacts - Environmental impacts - Health effects	Rochelle, 2010
- Geographical location - Intensity of precipitation - Cost	- Applicability: eutectic temperature—air and road surface temperature, concentrations of chemicals - Cost: availability of raw materials, process methods - Size of area - Geographic, economic, and environmental factors	Zhang and Peterson, 2009

Tradeoffs in Metrics

There are complex tradeoffs between metrics for preservation, safety, mobility, and sustainability. Regarding environmental issues, for example, transportation agencies are continually challenged to provide a high LOS and improve safety and mobility in a cost-effective manner while minimizing corrosion and other adverse effects to the environment (Maze, 2007). According to Maze (2007), it is desirable to adopt new, advanced technologies to attenuate tradeoff problems. But, there still exist tradeoff issues even if the magnitude of issues is relatively small as compared to traditional technologies.

The research team now used the data developed in the Compare phase, in both normative and natural units, to help weigh tradeoffs between metrics. Figure B-9 shows a series of one-on-one direct comparisons between the four summary measures in normative units the research team had developed for the four main metric categories corresponding to four main agency missions and also the POSI metric. Overall, it seems that the thermal method is superior to others largely because of its higher scores for sustainability and preservation. Yet, it turns out that CaCl (Vehicle) and KAc (Vehicle) are better technologies in terms of POSI. This is not surprising given that these come closer to the current state of practice.

Figure B-10 shows a similar set of simple comparisons for the same metrics, this time using the natural unit measures. They show similar results to those presented using the normative measures.

Such views (of which Figures B-8 and B-9 provide only some examples) can be useful in the decision-making at an agency level. But such views can also be difficult to interpret because of the large number. For this reason, it is useful to develop more integrated representations of this information. Figure B-11 is such a representation. As in the bridge deck evaluation example of STREAM, the research team presents the respective POSI scores along the x-axis, an integrated value metric consisting of an unweighted multiplication of the individual goal metrics[70] as a y-axis, and the plotted expected values.[71] The research team also shows hyperbolae representing lines of equivalent trades between the combined value metric and potential difficulty of implementation (the POSI measure). By using the aggregate value metric instead of individual metric, the research team can consider all metrics versus POSI at the same time. Figure B-10, using the normative unit measures, suggests the marked attractiveness of the thermal method, specifically when using normative units, as compared to previous matrices. The next-best technologies, although considerably less so, are those using KAc (Vehicle) and KAc (FAST). The former of these two has the virtue of possessing the highest POSI score, thus presenting less of an administrative hurdle. Yet, the difference in outcome with the thermal method might in itself be used as a means to perhaps lower some of these hurdles once the considerable value compared to other prospective and currently used approaches could be made clear.

Figure B-12 shows the same results, this time using the natural unit measures.

Tradeoffs in Cost

There are tradeoffs on the cost side as well. Table B-20 shows each technology's ranking by each part of cost.

[69] The lowest effective temperature for a deicer is defined as the temperature at which the deicer will melt a reasonable amount of ice within a reasonable amount of time.

[70] The four individual scores for safety, preservation, sustainability, and mobility could be weighted differently if an agency desired to do so.

[71] Expected value = the product of calculated total metric and POSI

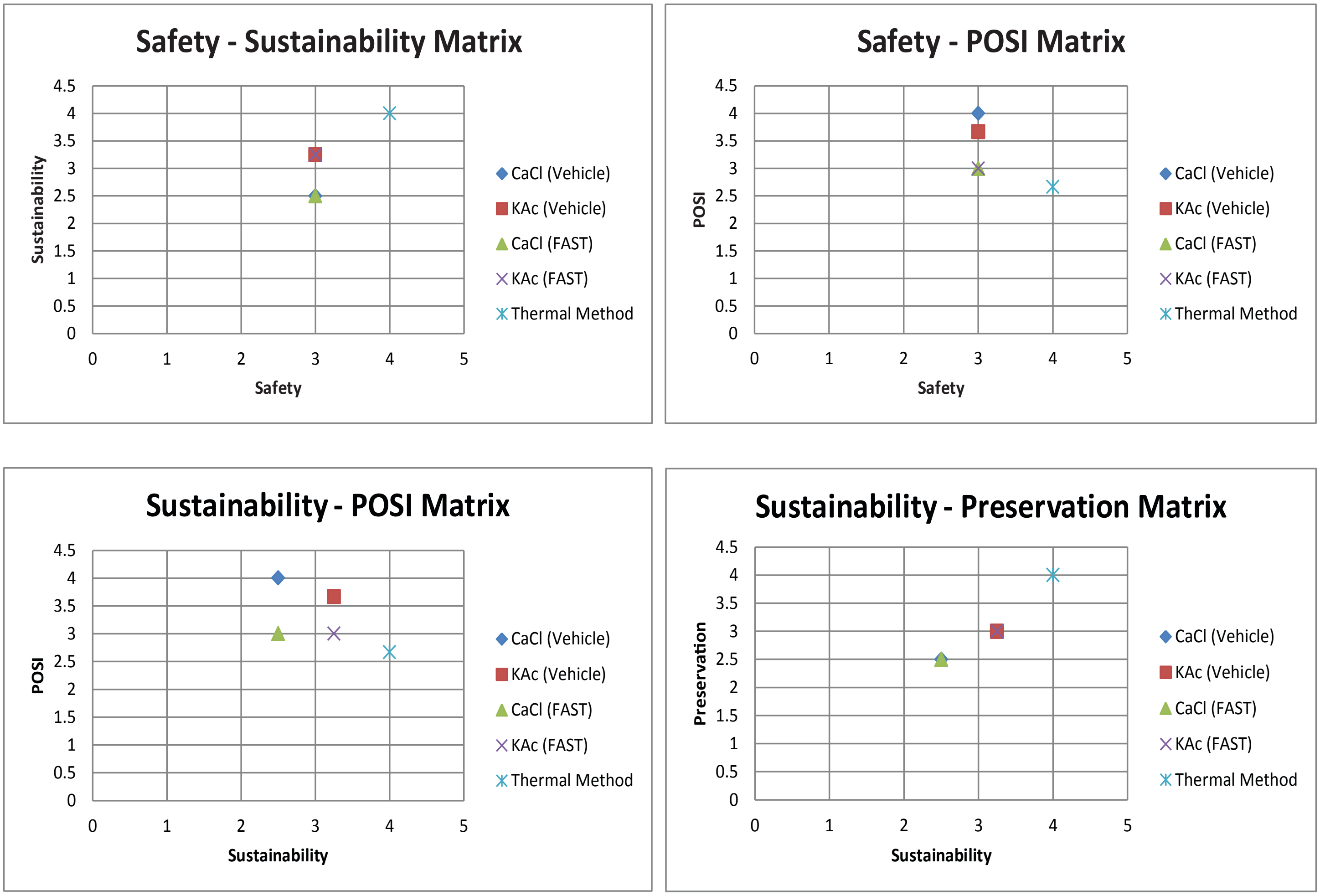


Figure B-9. Comparison of technology application bundles using normative units.

While chemical dispersal from vehicles is preferred to others in terms of initial cost (e.g., equipment and installation), the thermal method dominates the others in terms of hard-to-quantify costs (e.g., benefits from reduced travel time and crash). Interestingly, there is a totally reverse relationship between the agency-specific and road user/social costs. This highlights the importance of making clear what areas of costs are being discussed. Only in this way are fully informed decisions about tradeoffs made possible.

Overall Tradeoffs

As a way of incorporating the anticipated outcome metrics with the cost information, the research team reproduces prior figures while including notations for cost in each case. These figures show not only value metric and POSI but also cost information (see Figures B-13 and B-14).

The interpretation of these curves must necessarily be based on local agency conditions. Based solely on assumptions and initial conditions given in the Compare phase, it seems that the two preferable approaches are the thermal method and KAc dispersed by vehicles. The thermal method scores well on the mission value measures while being of approximately the same order of magnitude as the other candidates in terms of cost and POSI. The KAc/vehicle approach, on the other hand, provides less but still improved mission value with a quarter of the cost of the thermal method. Yet, if either assumptions or initial conditions change even slightly, as they are bound to do once looking at agency-specific factors, the desirable technology may well change accordingly. In particular, weather and location have critical impacts on which metric should be prioritized. Also, consideration of local (e.g., funding and traffic) will make the cost analysis more valuable to decision-makers. Thus, the ultimate decision rests with the individual transportation agencies themselves.

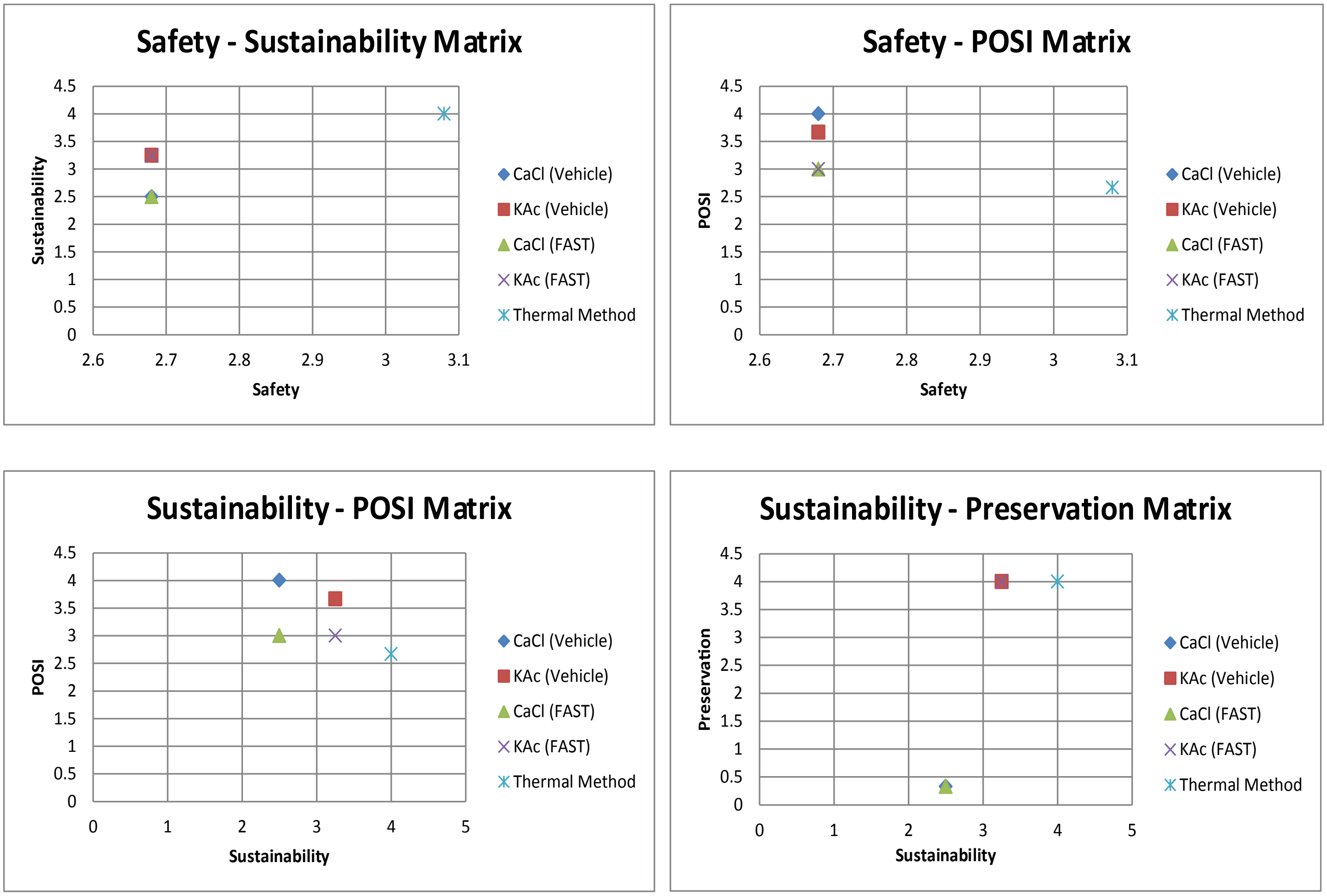


Figure B-10. Comparison of technology application bundles using natural units.

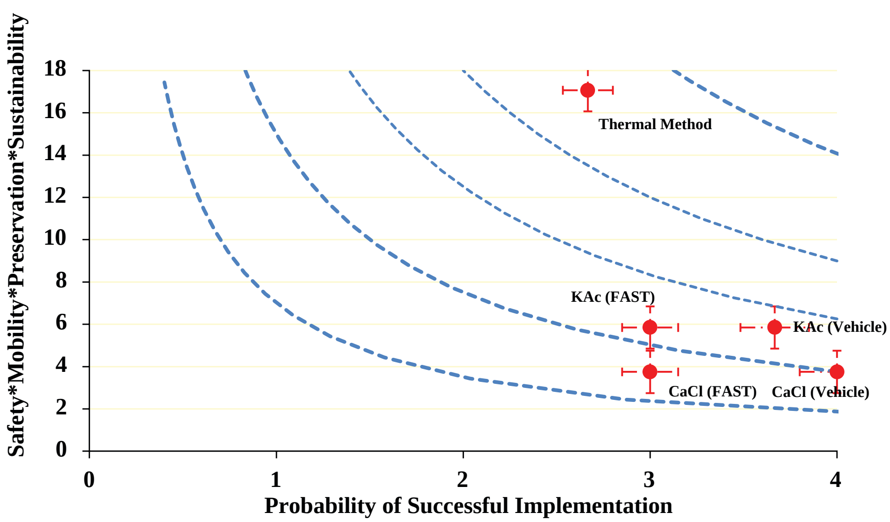


Figure B-11. Comparison of technology application bundles by integrating all summary metrics and POSI, using normative units.

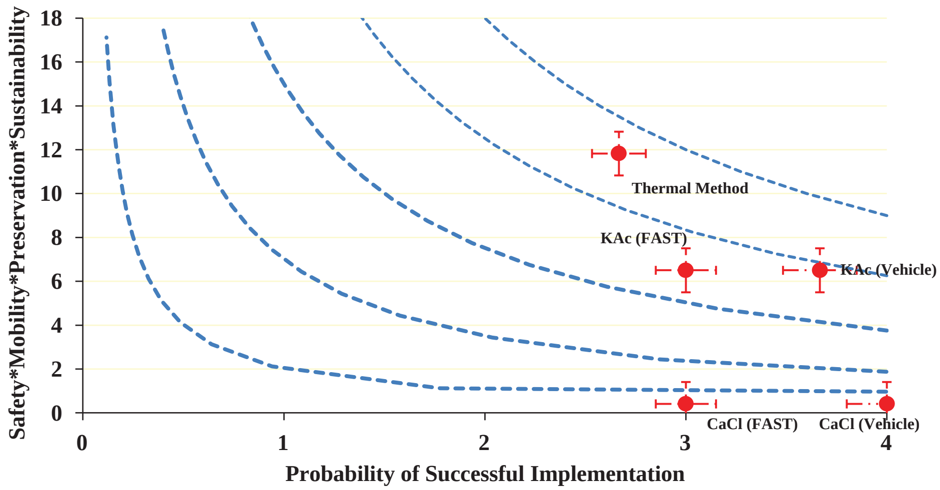


Figure B-12. Comparison of technology application bundles by integrating all summary metrics and POSI, using natural units.

Table B-20. Ranking of technologies by different categories of cost.

Cost Part		Chemical (Vehicle)		Chemical (FAST)		Thermal Method
		$CaCl_2$	KAc	$CaCl_2$	KAc	
Easy-to-Quantify	Initial Cost	1	1	2	2	3
	Recurring Cost	3	5	1	4	2
	Subtotal	1	2	3	4	5
Hard-to-Quantify		5	4	3	2	1
Both		3	2	5	4	1

Note: the numbers shown in the table are ordinal rankings with 1 being the best and 5 the worst among the five alternatives.

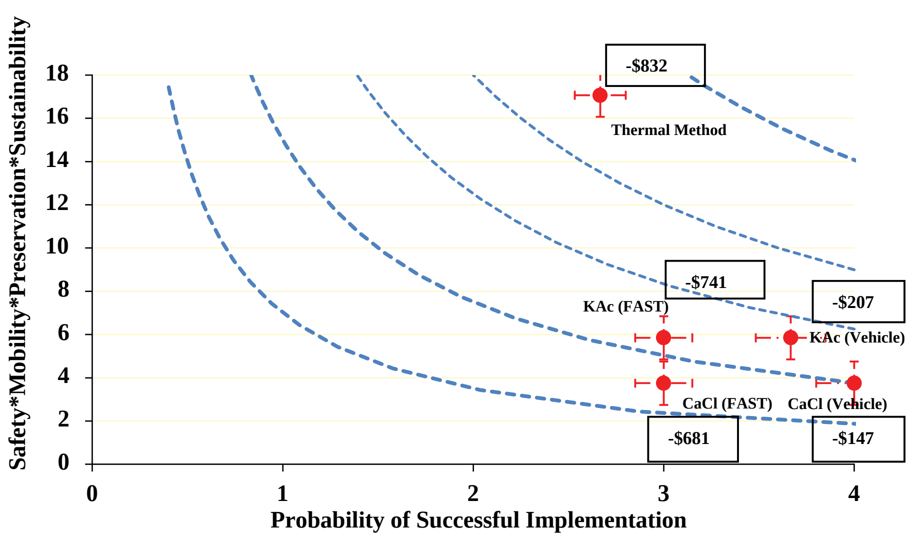


Figure B-13. Comparison of technology application bundles by integrating all summary metrics and POSI, using normative units, and including notations on agency-specific net cost ($000s/bridge).

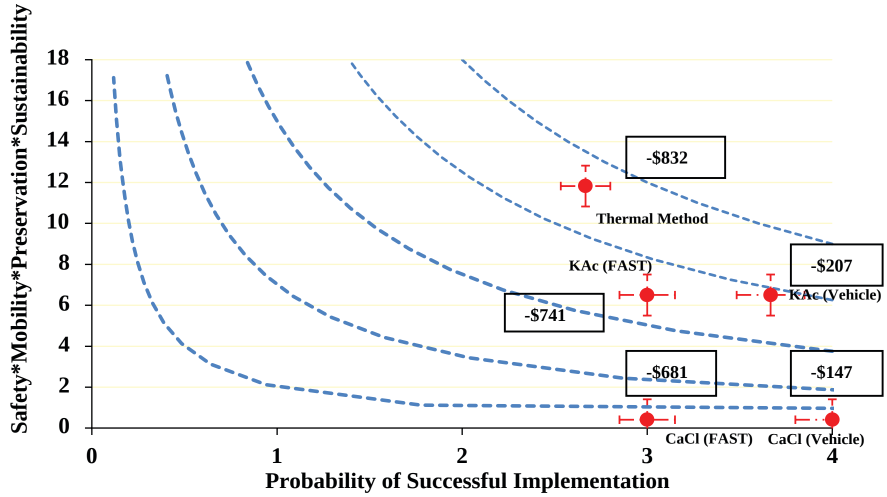


Figure B-14. Comparison of technology application bundles by integrating all summary metrics and POSI, using natural units, and including notations on agency-specific net cost ($000s/bridge).

APPENDIX C

STREAM Applied to Driver Information Systems

Population growth and urbanization have increased traffic congestion around the world. An increasing number of US highways and roads experience overwhelming traffic congestion, even though most Interstate physical and safety conditions have been improved. According to a report by the Texas Transportation Institute (TTI), based on congestion trends for 439 selected areas from 1982 to 2007, traffic congestion is costing Americans $87.2 billion (in constant 2007 dollars) in wasted time and fuel annually. Many metropolitan areas in the world including but not limited to London, Paris, Stockholm, Tokyo, and Beijing are experiencing serious traffic congestion that causes significant economic losses. (Liu, Triantis and Sarangi, 2010).

Frame

Congestion is common among some of the most economically and culturally vibrant cities in the world. However, concern is growing about the economic and environmental costs associated with congestion. Cities cannot afford to let congestion continue unmanaged because it can become a serious competitive disadvantage, hindering their capacity to continue developing and attracting new talent and new capital (de Palma and Lindsey, 2011).

The construction of new road infrastructure, an approach traditionally used to mitigate congestion, has also become a less viable solution because of social, environmental, geographic, and financial barriers. As a result, transportation agencies are exploring new ideas and methods to manage traffic. These include policies for expanding the capacity of existing roads through new control methods (e.g., ramp metering, lane control), policies for increasing the cost of private mobility (e.g., congestion pricing), and policies for providing motorists with the information they need to travel the road infrastructure more efficiently (e.g., adaptive signal systems, in-vehicle road guidance) (Emmerink and Nijkamp, 1999).

Of these emerging possibilities, development of driver information systems may be one of the most challenging and promising for transportation agencies. This novel approach could help motorists use the road infrastructure more efficiently and, as a result, reduce congestion (Kitamura et al., 1999). However, this approach also requires that transportation agencies reconsider their traditional role in providing traffic information to motorists as well as the synergies needed with other relevant parties, such as automakers, telecommunications companies, and transportation companies. Thus, transportation agencies are seeking ways to best contribute to this setting, to add real value to existing driver information systems, and to better identify and incorporate emerging technologies aligned with their goals and functions.

The options for this area of agency function can be framed in terms allowing for the STREAM approach to be applied. In terms of mobility, the research team considers that congestion problems are mitigated in a transportation system when motorists reduce their average travel times and increase their average travel speed, and, when there is an expansion of the transportation network's capacity. In terms of safety, the research team believes that the system improves once it has been possible to reduce the propensity of accidents in a transportation network, the severity of accidents, and the vehicles affected by average car collisions. Finally, in terms of sustainability, the research team considers that a transportation system improves under this dimension when motorists reduce their GHG emissions during travel.

Major inputs to the STREAM analysis of driver information systems are as follows:

- **Functions:** Provision of traffic and safety information services directly to motorists;
- **Goals:** Reduce congestion in order to contribute to three main agency goals: mobility, safety and sustainability;
- **Objectives (Metrics): Agency's objectives:**
  - Mobility:
    - Average Travel Time (hr/trip),
    - Average Speed of Vehicles (mi/hr),
    - Road Capacity (Max Vehicle/hr/lane);
    - Demand (Vehicle/hr);

- Safety:
  - Highway accidents propensity (collisions/yr/mi),
  - Severity of accidents (fatalities/collision/mi),
  - Average vehicles affected per collision (vehicles/collision/mi);
- Sustainability:
  - Average GHG emission (GHG/trip/vehicle type)

The Growing Challenges of Private Mobility

Transportation problems arising from the use of automobiles are among the most pressing issues in urban areas. Worldwide, many metropolitan areas (e.g., New York, Chicago, Los Angeles, London, Milan, Paris, Bangkok, Jakarta, and Tokyo) suffer seriously from the social and environmental problems resulting from congestion. Broadly speaking, three main types of externalities arise from congestion: (1) negative economic effects caused by the restrictions that congestion imposes on the economic activity of a region, (2) social problems related to the limited mobility of individuals and (3) negative consequences for the natural environment and the health of the population (Emmerink and Nijkamp, 1999). In most cases, these negative externalities do not outweigh the economic opportunity and comfort offered by these metropolitan areas. In fact, many cities suffering from congestion are also among the most vibrant economic and cultural centers in the world. Nevertheless, experience also shows that cities cannot afford to leave these problems untreated for long because congestion problems can significantly reduce the quality of life of their residents and the cities' capacity to attract new people and new capital. Addressing congestion is of notable strategic importance for metropolitan areas and a primary concern for travelers, transportation agencies, and transportation companies.

Various agencies have estimated the monetary costs of these externalities. For example, the European UNITE project estimated the costs of traffic congestion in the United Kingdom to be $23.7 billion/year or 1.5% of GDP (Nash et al., 2003). For France and Germany the estimates were 1.3% and 0.9% of GDP, respectively. In the United States, the TTI estimates that in 2007 congestion caused an estimated 4.2 billion hours of travel delay and 2.8 billion gallons of extra fuel consumption with a total cost of $87 billion, amounting to 0.6% of GDP (Schrank and Lomax, 2009). In fact, the average annual cost per traveler in urban areas averaged $757 (de Palma and Lindsey, 2011). Even more alarming than the magnitude of these costs is the fact that the congestion costs seem to grow at a rate faster than GDP (Emmerink and Nijkamp, 1999).

Transportation agencies can use several tools to improve traffic flows and reduce congestion. The traditional approach has been to increase the capacity of the transportation network by building new roads. However, this approach has become more difficult and costly during recent times for various reasons. First, the costs of expanding the existing road infrastructure may be too high if all aspects are taken into account; for example, the social and environmental costs of expanding road infrastructure. This has made it more difficult for new infrastructure projects to secure resources and public support for their construction. In urban areas with a high population density it can be physically impossible to enlarge the current road infrastructure. As a result, expansion of freeways or the construction of new roads is often considered to be infeasible and highly disruptive. Experience has also shown that most short-term benefits in reducing congestion from building more roads have a limited effect in urban areas because of latent transportation demand. Often, new infrastructure becomes as congested as the old just a few years after being built (Emmerink and Nijkamp, 1999).

The complications and limitations of this traditional approach have encouraged transportation agencies to explore new ideas that can increase the efficiency of the transportation networks they manage. In this regard, a set of new policy ideas has been developed which can help agencies in this matter. These have evolved from a traditional command and control planning paradigm used by transportation agencies into a more dynamic and interactive concept of transportation infrastructure that seeks to exploit and integrate the capabilities of the road infrastructure, vehicles, and motorists. These new ideas and concepts invite transportation agencies to reconsider their role in managing transportation networks and also suggest new capabilities of transportation agencies to mitigate the adverse effects of massive private mobility in metropolitan areas.

New congestion policies can be clustered into three main categories:

1. Policies focusing on **expanding the effective capacity of existing road infrastructure.** These include ramp metering, the introduction of reversible and pooling lanes, and other more progressive ideas like new automobiles that can use highway space more efficiently by driving faster and closer to each other;
2. Policies that seek to **reduce the demand for private mobility** by making it less attractive. This includes congestion pricing to decrease the attractiveness of automobiles as well as other measures (e.g., subsidizing public transportation) that can encourage motorists to adopt other modes of transportation;
3. Approaches that aim at **providing motorists with information** to use the road infrastructure more efficiently. This consists of using driver information systems to assist motorists in planning travel routes more efficiently and to adapt quickly and more effectively to the changing conditions of traffic in highways (Bovy and Van Der Zijpp, 1999).

Driver information systems have the potential for reducing congestion, smoothing traffic flows, and increasing the efficiency of transportation infrastructure. Providing motorists with better and more information about traffic conditions may decrease travel times because motorists can use this information to make better decisions about whether, when, and where to travel. Offering motorists more information may also reduce driving stress and anxiety, increase safety, and diminish environmental pollution (Shladover, 1993). However, driver information systems pose serious challenges for transportation agencies. The net benefits of driver information systems are far from clear or easy to determine. The provision of travel information to motorists may have adverse effects that could offset its benefits (i.e., information saturation, congestion transfer from one place to another, and incentives to drive more) (Kitamura et al., 1999).

Multi-actor Context of Driver Information Systems

The possibility of using driver information systems encourages transportation agencies to reconsider their role in providing traffic information to motorists and to explore new ways by which they can better manage traffic flows. Traditionally, transportation agencies have not been very active in developing driver information systems. In the past, most of these functions were carried out by private parties and traditionally the scope of using driver information systems for traffic management was quite narrow.

The new possibilities in which driver information systems can be integrated with transportation infrastructure can change substantially how transportation agencies perform these functions and help them reach important milestones in improving mobility and enhancing safety and sustainability in the transportation networks they manage.

The development and implementation of driver information systems requires the efforts and resources of several parties. Transportation agencies need to consider this carefully when analyzing how they can enhance development of these systems. In this context, the role of private information providers, as well as the role of automakers is essential. For example, the dissemination of traffic information in mobile devices (e.g., PDAs, mobile devices) is being done using the infrastructure of major telecommunication companies in the country in collaboration with companies that offer dedicated applications to process and transform traffic data into information that can be used by motorists. Many of these systems are already commercial and available to motorists today. In addition, automakers are at the forefront of the development of technologies that can integrate vehicles with the road infrastructure and with radio and wireless networks; developments in this area can also change significantly the way motorists receive information (Kitamura et al., 1999). It is clear that in this particular context, transportation agencies do not have all the resources needed to advance the development of driver information systems. On the contrary, if they choose to get involved in developing these systems, they will be expected to work along private parties in creating synergies that can enable driver information systems in wider geographical areas.

Institutional Efforts to Improve Traffic Conditions

Several projects in developed countries have been implemented to study how it might be possible to reduce congestion using new innovative approaches. The European Union is running several programs in this field, among them: Dedicated Road Infrastructure for Vehicle Safety in Europe (DRIVE) and Intelligent Vehicle Highways Systems (IVHS). The same is occurring in the United States with the Intelligent Transportation Systems (ITS) program and in Japan with the Comprehensive Automobile Control System (CACS) and Vehicle Road and Traffic Intelligence Society (VERTIS) programs. (Gordon et al., 2008)

These large institutional efforts are a clear indication of the relevance for transportation agencies of using driver information systems for mitigating congestion problems. The STREAM analysis that follows illustrates the method itself and is intended to help transportation agencies gain a strategic perspective on their roles in furthering their goals through enhanced traffic information systems.

Identify

Several technologies could change transportation agencies' ability to provide traffic and safety information services to motorists. The characteristics of these technologies vary primarily according to three features:

1. The moment at which motorists receive the information:
   - Pre-trip;
   - En route;
2. The type of communication enabled:
   - One-way communication;
   - Two-way communication (vehicle-to-vehicle, vehicle-to-infrastructure);
3. The type of transmitted information:
   - Descriptive information; and
   - Predictive information.

In addition to these features, technologies also vary in terms of maturity. In this respect, the integration of information technologies with vehicles and the road infrastructure is the main force driving new technological developments in driver information systems. Some of the concepts using IT technologies in driver information systems are already commercial applications; other are experimental concepts or state-of-the-art concepts (Watling, 1999). The great differences in relative maturities of potential applications and the rapidity of change create a climate of uncertainty that make these decisions fraught for transportation agencies.

The research team found that new developments in information technologies have increased the versatility of the technology bundles used in driver information systems. This is important for transportation agencies because these novel technology applications can serve multiple goals in terms of mobility, sustainability, and safety.

Portfolio of Technologies

An ample array of technologies can be used to provide motorists with traffic information. Table C-1 lists some of the relevant technology bundles used in driver information services and notes whether there is evidence of use in each case. In the following sections, the research team describes in more detail these technologies, paying special attention to those aspects that may affect transportation agencies' functions while discussing the different features of these technologies.

Table C-1 shows various technology applications that can be used to help driver information systems meet multiple goals. Traditionally, driver information systems have been designed to serve a single purpose. For example, traditional road signs were designed to increase road safety. They inform motorists about speed limits and possible threats in the road to help agencies achieve safety goals. However, new technology bundles, such as dynamic message signs can help transportation agencies meeting several goals at once. For instance, in addition to providing safety information to motorists, dynamic message signs can also inform motorists about the traffic conditions in the transportation network and advise them to take alternative routes to avoid congestion which helps transportation agencies to meet their mobility goals.

Discussion of how the technology bundles listed in Table C-1 and mapped in Figure C-1 can improve or change the way transportation agencies provide traffic and safety information services to motorists are discussed in this section. The different features of these technology applications guide this discussion.

The Timing of Information

Motorists can receive safety and traffic information before or during the journey. In each case, various technology applications can be used to improve the quality and usefulness of the information they receive. This is expected to enable motorists to make better decisions when planning their journeys or when adapting to unexpected events and adverse conditions in the road. This is important for transportation agencies because this information helps motorists avoid congestion by planning their journeys ahead or reducing the risks of driving by avoiding dangerous conditions in the road (e.g., unsafe weather conditions). In addition, having a more adaptive type of driver is also of interest for transportation agencies: if motorists can be given information that can help them react in more efficient and safe ways to the changing conditions of the road, this can increase the efficiency of the overall transportation network.

Television broadcast traffic pages and kiosks are technology bundles that enable motorists to access traffic information before they start their journeys. In the case of television broadcast traffic pages, motorists receive reports describing traffic conditions in main roads, possible traffic incidents (e.g., blockages or crashes), and the weather conditions. Motorists use this information to choose a particular route to their destination or by delaying their departure time. In general terms, the information provided by television broadcast traffic pages is highly qualitative and selective because drivers do not receive information in the form of metrics, but rather in the form of images and opinions of reporters. Also, drivers are given traffic information describing only a set of the roads in the transportation network, thus missing a more comprehensive description of the whole transportation network. As a result, drivers cannot tailor the information they receive to meet their specific needs (i.e., the specific roads they frequently use or alternative routes). Kiosks are different because, depending on level of sophistication, they can provide drivers with both descriptive and predictive information about their journeys. Actual formats vary, but the most sophisticated kiosks allow users to estimate their travel times and choose optimal routes. The number of motorists in a transportation system who benefit from kiosks depends on the number of existing kiosks and their locations.

Motorists can also receive traffic and safety information during their travel. Perhaps, in this area, the most relevant technology bundle used by transportation agencies is the 511 telephone information systems. The capabilities of this type of system also vary greatly. Such 511 systems range from simple telephone line systems in which drivers dial in to receive traffic information and advice during their travel, to more complex systems which combine telephone lines and internet traffic pages for traffic and safety information services. The most sophisticated 511 systems allow motorists to access detailed information of the state of the transportation network before they start their journey. The types of information they can access include incident and weather reports, traffic levels in different routes, estimated travel times, and access to video cameras in highways. In addition, these systems

Table C-1. Available technologies for driver information systems.

Technology	Evidence of Use	Type of Communication	Type of Information
Pre-trip			
Television broadcast traffic pages	Nationwide, Private Media	One-way	Descriptive
Internet traffic pages	Nationwide: Private (Google Maps) and Public (http://www.511ny.org/mapview.aspx), http://www.itsbenefits.its.dot.gov/ITS/benecost.nsf/ID/4B306AA1F6C2347C85256A6100607098?OpenDocument&Query=BApp	One-way	Descriptive/Predictive
Kiosks	Los Angeles Smart Traveller Project, http://www.itsbenefits.its.dot.gov/its/benecost.nsf/BenefitTerminators/TI+Kiosks	One-way	Descriptive
En route			
Telephone information systems (e.g., 511)	Nationwide, Federal Communications Commission (FCC), www.fhwa.dot.gov/trafficinfo/511.htm	One-way	Descriptive/Predictive
Highway Advisory Radio	Several Cities, FCC, (e.g., Sacramento, Los Angeles, New York, Baltimore)	One-way	Descriptive
Traffic Message Radio Channel	Several Cities (e.g., Total Traffic Network, http://totaltraffic.com/, The HD Digital Radio Alliance, http://www.hdradioalliance.com/)	One-way	Descriptive
Adaptive Signal Control Technology	Several States: California, New York, Florida, Texas, Oregon http://www.fhwa.dot.gov/everydaycounts/technology/adsc/casestudies.cfm	Two-way (V2I)	Descriptive
Dynamic Message Signs	Several States, including New York, California and Washington, http://ops.fhwa.dot.gov/travelinfo/dms/index.htm	One-way/ Two-way (V2I)	Descriptive
Portable Dynamic Message Signs (e.g., Automated Work Zone Information System)	Grand Canyon National Park, California, North Carolina, Los Angeles, Detroit, http://www.itsbenefits.its.dot.gov/its/benecost.nsf/BenefitTerminators/ROM+Portable+DMS	One-way	Predictive
Collision avoidance (V2V)	Experimental, US, Germany, Netherlands, http://www.itsbenefits.its.dot.gov/its/benecost.nsf/BenefitTerminators/CAS	Two-way (V2V)	Predictive
Cooperative Adaptive Cruise Control (V2V)	Southern California, http://www.itsbenefits.its.dot.gov/ITS/benecost.nsf/ID/D614703F77734198852578B80066CFCA?OpenDocument&Query=BApp	Two-way (V2V)	Predictive
In-vehicle navigation systems with GPS	Nationwide	One-way	Descriptive/Predictive
Lane departure warning systems	Alaska, http://ntl.bts.gov/lib/jpodocs/repts_te/14370_files/14370.pdf	Two-way (V2I)	Predictive
Intelligent Speed Control	Los Angeles, California, http://www.itsbenefits.its.dot.gov/ITS/benecost.nsf/ID/AA5443936A6D3A2C852577840049 0709?OpenDocument&Query=BApp	Two-way (V2I)	Predictive
Virtual Traffic Guidance System	Europe, project: AKTIV-VM, http://www.aktiv-online.org/english/aktiv-vm.html	Two-way (V2I)	Predictive

(continued on next page)

Table C-1. (Continued).

Technology	Evidence of Use	Type of Communication	Type of Information
In-vehicle vision enhancement (V2I)	Experimental, Europe, COOPERS, http://publications.lib.chalmers.se/records/fulltext/137657.pdf http://www.coopers-ip.eu/ Experimental, Erie County, New York, http://www.itsbenefits.its.dot.gov/ITS/benecost.nsf/ID/7A0A47F40911538E85256CB40057579D?OpenDocument&Query=BApp	Two-way (V2I)	Predictive
AVL Systems (Communication with Dispatch)	Experimental, Rochester, Pennsylvania; King County, Washington; Portland, Oregon; Columbus, Ohio, http://www.itsbenefits.its.dot.gov/ITS/benecost.nsf/ID/64D2E4A615027E2885257632004A5E0E?OpenDocument&Query=BApp	Two-way (V2I)	Predictive

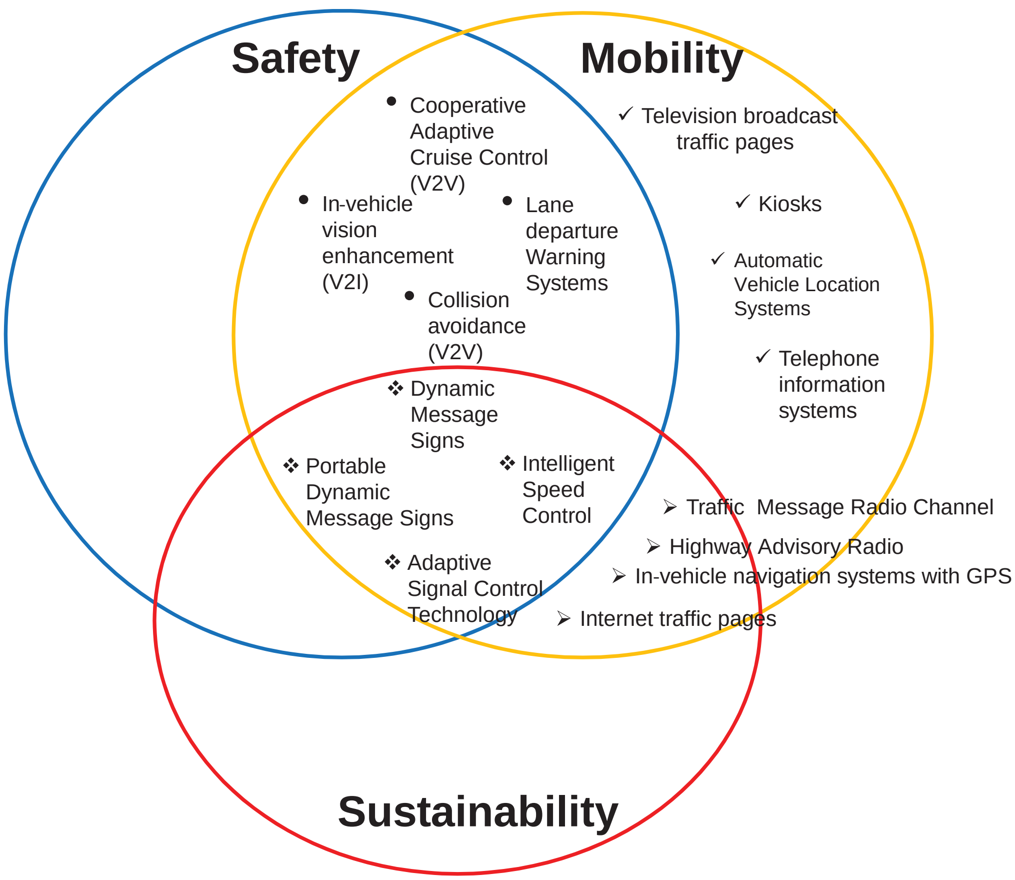


Figure C-1. Functional mapping of driver information system.

provide motorists with traffic and safety reports, as well as route selection advice while driving by calling the 511 number. The versatility of 511 systems permits motorists to tailor this vast information to meet their specific needs and develop personal heuristics that can help them in optimizing their use of the transportation network (e.g., choosing less congested routes, better scheduling their journey). Nevertheless, these systems are complex because they need to integrate different technology and information systems and because they require substantive investments in the necessary technologies for collecting and processing the information in the roads (Gordon et al., 2008).

Type of Communication

Whether driver information systems are intended to enable one-way or two-way communications is crucial for understanding the potential role of transportation agencies in the deployment of driver information systems.

Traditionally, transportation agencies have been involved in one-way communication. Transportation agencies collect and process the data they want to transmit to motorists and make it available through one or more of their communication channels (i.e., road signs, internet traffic pages, telephone systems, highway advisory radio). Agencies expect motorists to access the information and use it to assist them in their travel decisions. Under this approach, transportation agencies are usually heavily involved in collecting, processing, and disseminating traffic and safety data. Private parties are more involved in the dissemination process as in the case of private internet traffic pages and the commercialization of mobile applications for driver assistance (Geisler, 2012).

Recent technology developments have enabled two-way communications between the road infrastructure, vehicles, and motorists. These new systems permit different parties to communicate with each other for collecting and transmitting traffic and safety information. This is most evident in cooperative adaptive cruise control systems, which use vehicle-to-vehicle communication technologies, and in the case of in-vehicle vision enhancement systems which use vehicle-to-infrastructure technologies. Cooperative adaptive cruise control systems allow vehicles to share information about road conditions, such as collisions, speed limits, and recommended distance between vehicles. In this case, vehicles communicate with each other using a wireless network or hot spots in the road. These information nodes collect and monitor data being transmitted by sensors in cars (floating car data); this information is then processed and transmitted to motorists using specialized driver assistance software in vehicles (Delot and Ilarri, 2012). In-vehicle vision enhancement systems follow a similar logic, but, in this case, floating car data is not exchanged directly with vehicles. Rather, it is first transmitted to traffic management centers for processing and then sent to vehicles using road hot spots or other alternative wireless networks in highways. In this way, traffic management centers can send information to motorists about current or expected traffic road conditions. Both systems are technically complex because they need to process and analyze huge amounts of data in real time (Delot and Ilarri, 2012).

The role of transportation agencies in the deployment and management of one-way and two-way communication systems varies. In the first case, transportation agencies take part in several of the processes needed for this type of driver information system and in the construction and operation of the IT architecture needed for collecting, processing, and transmitting traffic and safety information to motorists. In the second case, the role of transportation agencies changes significantly. For example, in cooperative adaptive cruise control systems, transportation agencies do not need to invest in expanding the capabilities of their traffic management centers because in-vehicle software systems can be used for this purpose. Moreover, in schemes in which vehicles can exchange information without the support of road hot spots or other third-party networks, transportation agencies would not need to invest in deploying some components of the IT architecture needed for two-way communication systems (Geisler, 2012). This can change substantially the engagement of transportation agencies in the deployment of modern driver information systems. Depending on the actual system architecture, their role could change from developer and administrator of driver information system to regulator of driver information systems and coordinator of the main stakeholders involved in their deployment (i.e., automakers, telecommunication companies, and traffic information companies). Thus if transportation agencies want to get actively involved in the wide deployment and adoption of modern driver information systems, they will need to consider new ways in which they can create synergies with these other actors.

Type of Transmitted Information

The type of information transmitted to motorists by different types of driver information systems is also a key feature that can affect both transportation agencies' assessment of their own functions and their realization of their own mobility, safety, and sustainability goals.

Driver information systems can provide information that is descriptive or predictive (or both). The first group includes technology bundles that provide drivers with a static description of the traffic and safety conditions of the transportation network. Examples include internet traffic pages, highway advisory radio, and dynamic road signs. At their simplest, such systems provide drivers with road descriptions such as the location of congested roads, average delays due to accidents or repair work, expected weather conditions, current speed limits, and so forth. Motorists receive and process this information on their own and decide how best to use it.

Predictive information content integrates the current, empirical data with historical databases and proprietary algorithms to yield additional information. Motorists receive information that assesses how their travel plans and their journeys will be affected by the changing traffic conditions (Toledo and Beinhaker, 2006). In-vehicle navigation systems with GPS are a widespread application that informs motorists about the expected travel time of their journeys and also allows them to choose routes that can be faster or less busy at peak hours. Moreover, in-vehicle navigation systems can help drivers adjust their routes in real time and navigate in unfamiliar regions. Collision avoidance systems are another example of predictive information, but such systems are not yet widely used. Collision avoidance systems consist of vehicle sensors and processing software that inform drivers about risks that can lie ahead in the road. This can help them take preventive maneuvers to avoid a collision of their own and reduce the risks of their journeys (Toledo and Beinhaker, 2006).

Maturity of Technologies

Driver information systems are among those transportation technologies that have changed significantly owing to new technological trends in information, communications, and sensor technologies. Those systems that provide pre-trip and descriptive information and enable one-way communication are the most mature technology applications. In contrast, technologies that enable two-way communications and provide en route and predictive information are among the technologies that are either still pilot concepts or state-of-the-art applications. This is especially true for vehicle-to-vehicle and vehicle-to-infrastructure technologies. Moreover, the development of new driver information systems is an area that registers one of the highest levels of innovative activity in the transportation sector, thus increasing at an ever greater pace the ideas and concepts under development. Therefore, the list of technologies discussed in this chapter should not be viewed as exhaustive (Fan, Khattak and Shay, 2007).

The main large firms and OEMs participating in the research and development of novel driver information systems include Siemens, Honda, Toyota, Bosch, Mitsubishi, and Nissan. Worldwide, the main countries engaging in the research and development of driver information systems are the United States, Germany, and Japan. Patent analysis shows that there is no dominant firm or country in the sector which is also an indication that there is strong competition in this technological field. In addition, there is not yet a dominant technology application, which means that developing different technology platforms for novel driver information systems is still in a phase of experimentation (Wu and Lee, 2007).

Characterize

The technologies described in the Identify step will be characterized in this section. The research team will first provide a quantitative and qualitative description of these technologies focusing on a set of specific characteristics that are the most relevant for transportation agencies. These are as follows:

- Technology's effect on transportation agencies' goals (i.e., mobility, safety, and sustainability);
- Transportation Agency's Role in Adoption Process;
- Technology Adoption Barriers; and
- Technology Costs.

The research team first discusses the comparative factors used. The research team then discusses the individual driver information system considered in the STREAM analysis. The research team concludes the Characterize step with a summary table of the qualitative and quantitative descriptions of these technologies.

Overview of Characterizing Factors

Metrics

For each technology application discussed in this section, the research team will use a qualitative scale to assess its potential influence on three agency goals: mobility, safety, and sustainability. In this case study, the research team has primarily focused on both systems and outcomes at the level of the metropolitan region, rather than on a statewide basis. For the purposes of this illustration of the STREAM method, the research team provides a qualitative scale for each in which the research team aggregates several types of indicators into one measure. Full implementation of STREAM for such a complex subject would involve drawing on a range of quantitative and qualitative information sources as well as overall characterizations provided by experts familiar with different aspects of driver information system technologies.

Mobility

- **Low impact.** The technology has the potential of slightly (0–5%) reducing motorists' average travel time, of increasing motorists' average traveling speed, and of increasing the efficiency of the transportation network. The technology provides motorists with pre-trip or en route descriptive traffic information for assisting them in planning their trips or for finding alternative routes when they are in traffic;
- **Medium impact.** The technology has the potential of further reducing motorists' average travel time (5–15%), of increas-

ing motorists' average traveling speed, and of increasing the capacity of the transportation network. The technology provides motorists with pre-trip and en route descriptive traffic information for assisting them in planning their trips and in adapting to changing road conditions, which expands motorists' options to use traffic information during their trips;

- **High impact.** The technology has the potential of significantly reducing motorists' average travel time (>15%), of increasing motorists' average traveling speed, and of increasing the capacity of the transportation network. The technology provides motorists with pre-trip and en route descriptive and predictive traffic information for assisting them in planning their trips and adapting in real time to changing conditions (i.e., real-time optimal route selection).

Safety

- **Low impact.** The technology has the potential of slightly reducing (0–5%) the propensity for highway accidents, the severity of accidents, and the average number of vehicles per collision. The technology transmits descriptive pre-trip or en route safety information to motorists; this information is used for avoiding possible road threats and known vehicle collisions in the transportation network.
- **Medium impact.** The technology has the potential of further reducing (5–10%) the propensity for highway accidents, the severity of accidents, and the average number of vehicles per collision. The technology transmits descriptive pre-trip and en route safety information to motorists; this information is used to avoid and safely respond to possible road threats and known vehicle collisions in the transportation network.
- **High impact.** The technology has the potential of significantly reducing (>15%) propensity for highway accidents, the severity of accidents, and the average number of vehicles per collision. The technology transmits descriptive and predictive pre-trip and en route safety information to motorists; this information is used to avoid and safely respond to possible road threats and known and/or unexpected vehicle collisions in the transportation network.

Sustainability

- **Low impact.** The technology allows motorists to reduce the time that they spend in congested roads, but does not necessarily reduce their vehicle driven miles. This may result in a slight reduction in GHG emissions per motorist.
- **Medium impact.** The technology allows motorists to reduce their average vehicle driven miles and to increase their average travel speed. This results in a reduction in GHG emissions per motorist.
- **High impact.** The technology allows motorists to reduce their average driven miles and to increase their average travel speed considerably. This results in a significant reduction in GHG emissions per motorist.

Transportation Agencies' Role

The role that transportation agencies play in the deployment of driver information systems is largely defined by the processes in which agencies are significantly involved. As a result, for any given technology application, transportation agencies can play one or more of the following roles:

- **Data Collection.** Transportation agencies are significantly involved in construction and operation of the IT architecture and infrastructure needed for collecting traffic and safety information of the transportation networks they operate.
- **Data Management and Processing.** Transportation agencies are significantly involved in managing traffic and safety data and in processing this data into information that can be made available to motorists who use the transportation networks they operate.
- **Data Dissemination.** Transportation agencies are significantly involved in disseminating traffic and safety information among motorists who use the transportation networks they operate.

Technology Barriers

Transportation agencies wanting to implement the technologies described in this chapter may face one or more of the following barriers to successful implementation in the transportation networks they operate:

- **Technology**
  - Unfamiliarity with core or applied technology
  - Uncertainty concerning actual performance
  - Additional implementation requirements (training, standards, etc.)
- **Agency Process or Institutions**
  - Need for new or conflict with existing regulations and standards
  - Non-fungibility of funding for required expenditures
  - Extended or problematic approval processes
- **External to Agency**
  - Inertia of existing processes and methods
  - Insufficient political or public acceptance
  - Lacking precedence of necessary vendor or support base

Estimation of Costs

The US DOT has developed a costs database of different emerging technologies in the transportation sector. This includes new driver information systems. This database contains the costs concepts of different technology deployments. The costs to be incurred in each project are separated according to different component subsystems; each subsystem contains the costs of individual technology units or technology bundles needed for the deployment of new transportation technologies:

> Roadside Telecommunications (RS-TC), Roadside Detection (RS-D), Roadside Control (RS-C), Roadside Information (RS-I), Roadside Rail Crossing (R-RC), Parking Management (PM), Toll Plaza (TP), Remote Location (RM), Emergency Response Center (ER), Emergency Vehicle On-Board (EV), Information Service Provider (ISP), Transportation Management Center (TM), Transit Management Center (TR), Toll Administration (TA), Transit Vehicle On-Board (TV), Commercial Vehicle Electronic Credentialing (EC)/Administration, Commercial Vehicle Safety Information Exchange (SIE), Commercial Vehicle Electronic Screening (ES) (Preclearance), Commercial Vehicle On-Board (CV), Fleet Management Center (FM), Vehicle On-Board (VS) and Personal Devices (PD) (U.S.Department.of. Transportation, 2012).

For each technology application, the interested analyst can select the cost concepts under each of the subsystems employed in the deployment of a particular technology. For example, the implementation of dynamic message signs includes cost concepts for subsystems under Roadside Detection (RS-D), Transportation Management Center (TM), and Roadside Telecommunications (RS-TC). Although this database can be a very useful guide for estimating the costs of each technology application, a detailed cost estimation for each technology was out of the scope of this case study, so the cost estimation has been simplified by assuming that, for each technology option, the transportation agency would already have the needed equipment for collecting traffic information and transmitting this information through its information network (Roadside Telecommunications (RS-TC)) (Gordon et al., 2008). Thus, the research team will only focus on the expenses needed to upgrade such a system and in the equipment needed to disseminate traffic information to motorists. In all cases the research team assessed what the research team estimated the costs would be for deploying a system within a metropolitan region.

Characterization of Technologies

Internet Traffic Pages

Impacts. Internet traffic pages provide both descriptive and predictive traffic information to drivers. The most advanced systems provide motorists with optimal routes, traffic conditions, and travel times. This is a popular system among motorists because it is easily accessible and low cost. Modeling results indicate that individual travelers who use internet traffic pages prior to traveling would receive annual benefits of a 5.4 percent reduction in delay, a 0.5 percent reduction in crash rate, and a 1.8 percent reduction in fuel consumption (Carter et al., 2000). Based on this information, the research team estimates that internet traffic pages provide a medium mobility impact and low safety and sustainability impacts on transportation agencies' goals.

Barriers. Internet traffic pages are already mature and in recent years there has been a constant increase in the number of internet traffic pages supported by transportation agencies or by private vendors (Gordon et al., 2008). Nevertheless, the successful implementation of internet traffic pages requires highly complex integration with other technologies (e.g., video cameras, metering devices) and other information systems. This may require additional training of transportation agencies' staff or developing new protocols or standards. In addition, motorists are often not familiar with the all the possible applications of internet traffic pages.

Costs & Agencies' Role. The cost estimations presented in this chapter assume that transportation agencies have already deployed the IT infrastructure needed in roadways for the implementation of the driver information systems mentioned in this chapter. Therefore, in the following sections the research team will not consider costs incurred in Roadside Telecommunications (RS-TC), Roadside Control (RS-C), and Roadside Information (RS-I). Further work would require relaxing this assumption for estimating more accurately the costs of each driver information system.

In this case, the role of transportation agencies wanting to support the deployment of internet traffic pages may engage them in processes of data collection, data management and processing, and data dissemination. Table C-2 shows an estimate of which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

Kiosks

Impacts. Traveler information kiosks provide descriptive and predictive information to drivers before they start their journeys. Depending on the level of sophistication of these systems, kiosks inform drivers about the current traffic and safety road conditions. Motorists can only access this information in person and not remotely, reducing the potential number of motorists that can use these systems. Experience shows that users of kiosks are satisfied with the information services provided by these systems (Giuliano, 1995). Nevertheless, the research team estimates that, given the limited number of motorists that can use these systems, kiosks are expected to have a low mobility, safety, and sustainability impact in the transportation networks in which these are deployed. Several pilot programs have deployed kiosks to assist motorists in the United States in 11 metropolitan areas; however, in recent years the rate of growth of kiosk projects has stagnated (Gordon et al., 2008).

Table C-2. Cost estimates for deploying internet traffic pages.

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
ISP		
ISP Hardware	18.3	27.09
ISP Software	287.15	574.30
Map Database Software	10.45	29.27
Systems Integration	88.09	107.67
Transportation Management Center (TM)		
Hardware for Traffic Information Dissemination	2.09	2.79
Software for Traffic Information Dissemination	18.80	22.97
Integration for Traffic Information Dissemination	89.15	108.96
Total Cost	514.03	873.05
of which, Agencies' Cost	514.03	873.05

Source: U.S.DOT, 2012[72]

Barriers. The main limitations faced by traffic information kiosks include unfamiliarity with the technology among motorists as well as the lack of necessary vendor or support base. It is also not at all straightforward to demonstrate the effect of this technology in the transportation network. It seems that while there is sufficient public support for kiosks, the performance of the technology in terms of enhancing mobility is uncertain (Gordon et al., 2008).

Costs & Agencies' Role. Support for deploying kiosks may engage agencies in processes of data collection, data management and processing, and data dissemination. Table C-3 shows an estimate of which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

Telephone Information Systems

Impacts. The sophistication and capabilities of telephone information systems vary widely. 511 telephone systems range from systems that only provide pre-trip and en route traffic and safety information through telephone lines to those that integrate telephone, video, and internet capabilities into 511 driver information systems. The difference in overall impact between the most and least sophisticated 511 systems can be quite significant. Thus, based on the qualitative scale previously defined, the research team estimates that traditional telephone information services have a medium mobility impact and low safety and sustainability impacts. In contrast, the research team considers that advanced 511 telephone information services have high mobility impact and medium safety and sustainability impacts. 511 telephone information systems are becoming more popular. In 2008 these were used by 64 transportation agencies in the United States (Gordon et al., 2008).

Barriers. 511 telephone systems are already well established. However, the more recent integration of this system with other technologies, other information architectures, and other communication channels (i.e., the internet) has considerably increased the complexity of this technology, demanding further training within transportation agencies. In addition, the increasing popularity of other driver information systems has increased the competition between 511 systems and other dominant technologies.

Costs & Agencies' Role. As shown in Figure C-2, the costs of 511 systems vary according to size and level of sophistication. For example, statewide systems' costs range from $1M to $5.2M, while metropolitan 511 systems range from $1.5M to $2.3M. Given that the focus of the case study is on metropolitan areas, the research team estimates that traditional 511 telephone information systems' costs range from $1.5M to $1.8M, while integrated 511 telephone information systems' costs range from $1.8M to $2.3M (U.S.DOT, 2012). In this case, transportation agencies would need to be engaged in data collection, data managing and processing, and data dissemination.

Highway Advisory Radio

Impacts. Highway advisory radio uses low-power permanent or portable radio stations to broadcast descriptive en route traffic and safety information to motorists. The information enables motorists to adjust their trips according to

[72] The U.S. DOT Costs Database contains estimates of ITS costs that can be used for preliminary project cost estimates. The cost concepts presented in this table are the costs associated with an individual ITS element or subsystem for a particular ITS deployment. These cost estimates consider capital costs and annual operations and maintenance costs, adjusted to the year 2009 using indexes maintained by the Bureau of Labor Statistics. The titles in bold letters indicate the Costs Database section used for the estimation.

Table C-3. Cost estimates for deploying traffic kiosks.

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
Remote Location (RM)		
Informational Kiosk	10	24
Kiosk Upgrade for Interactive Usage	5	9
Kiosk Software Upgrade for Interactive Usage	10	12
Integration of Kiosk with Existing Systems	2	27
Number of units in a medium size regional transportation network: 20 kiosks	20 units	20 units
Total Cost	540	1,440
of which, Agencies' Cost	540	1,440

Source: U.S.DOT, 2012

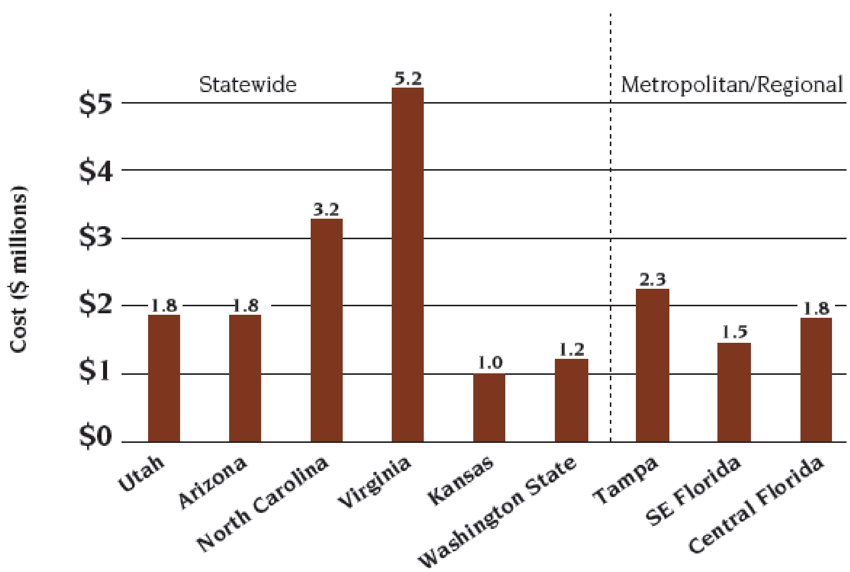
changing road, weather, and congestion conditions. Motorists that use highway advisory radio have a positive opinion of the technology. In Spokane, Washington, about one third of interviewed motorists estimated that they would consider changing routes based on the information provided in highway advisory radio systems; however, few drivers were able to identify feasible alternative routes (Gordon et al., 2008). This is an important limitation of driver information systems that provide en route information. In many cases, the opportunity to change routes has passed by the time motorists receive traffic information through highway advisory radio. Thus, considering that the information transmitted through highway advisory radio would be useful only for a fraction of drivers, the research team considers that the mobility and sustainability impact of this technology is low. However, given that highway advisory radio provides en route information that can avoid greater collision incidents, the research team estimates that this technology has a medium safety impact on the transportation network.

Barriers, Highway advisory radio is a well-established technology. Perhaps the only barriers it faces are those related to drivers being unfamiliar with the technology or the presence of other strong information systems that can provide a similar service (e.g., 511 systems, GPS, internet traffic pages).

Costs & Agencies' Role. The role of transportation agencies wanting to support the deployment of highway advisory radio systems would include data collection, data management and processing, and data dissemination. In Table C-4 the research team estimates which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

Dynamic Message Signs

Impacts. The most common media for disseminating en route information are dynamic message signs and highway



Source: Gordon et al., 2008

Figure C-2. Cost of telephone information systems.

Table C-4. Cost estimates for highway advisory radio.

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
Roadside Information (RS-I)		
Highway Advisory Radio	16	37
Highway Advisory Radio Signs	4.55	8.06
Number of units in a medium size regional transportation network: 10 signs	signsx10	signsx10
Transportation Management Center (TM)		
Software for Traffic Information Dissemination	18.80	22.77
Integration for Traffic Information Dissemination	89	109
Total Cost	413.3	582.37
of which, Agencies' Cost	413.3	582.37

Source: U.S.DOT, 2012

advisory radio. Dynamic message signs are used to disseminate en route information on freeways and arterials in approximately 86 metropolitan areas in the United States. The most common types of information transmitted through DMS are incident information, maintenance and construction information, congestion conditions and weather alerts, as well as travel time and public service announcements (Gordon, 2008). In comparison to highway advisory radio, dynamic message signs transmit traffic and safety information to a narrower set of motorists who receive relevant traffic and safety information of the conditions ahead of their journeys. Thus, the probability that a driver receives opportune information does not depend on whether or not drivers are listening to the radio before they can no longer adjust their journey. Empirical studies have shown that real-time travel traffic and safety information posted on DMS indeed influences motorists' route choice. In a survey study carried out in Houston, Texas, 85 percent of respondents indicated that they changed their route based on the information provided by DMS. Among these respondents, 66 percent said that they saved travel time as a result of the route change (Fink, 2005). Thus, the research team estimates that DMS have a medium mobility and safety impact and a low sustainability impact.

Barriers. Among the barriers that this technology faces are the uncertainty concerning its actual performance and the insufficient public acceptance of the technology. For example, even though motorists may support the implementation of this technology, impacts of this technology may vary from region to region (Fink, 2005).

Costs & Agencies' Role. The role of transportation agencies wanting to support the deployment of dynamic message signs may engage them in data collection, data management and processing, and data dissemination. In Table C-5 the research team estimates which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

Table C-5. Cost estimates for dynamic message signs.

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
Roadside Information (RS-I)		
Dynamic Message Sign (10 units for regional system)	42.7	106.6
Dynamic Message Sign Tower (2 units for regional system)	28.5	136
Number of units in a medium size regional transportation network: 10 signs	signsx10	signsx10
Number of sign towers in a medium size regional transportation network: 2 towers	towersx2	towersx2
Transportation Management Center (TM)		
Software for Traffic Information Dissemination	19	23
Integration for Traffic Information Dissemination	89	109
Total Cost	592	1,470
of which, Agencies' Cost	592	1,470

Source: U.S.DOT, 2012

Portable Dynamic Message Signs

Impacts. There is an evident overlap between the capabilities of portable dynamic message signs and the more standard fixed dynamic message signs because they are used to disseminate the same sort of traffic and safety information. However, portable dynamic message signs are a more flexible technology that enables additional capabilities which can improve traffic and safety information services. A portable dynamic message sign can be used to inform drivers about high congestion before they enter the road by moving the portable message sign to an intersection from which drivers can still opt for an alternative route. In addition, portable dynamic message signs can be moved to locations where vehicle collisions have occurred or where maintenance work is being carried out (Gordon et al., 2008). However, it is difficult to estimate whether portable dynamic message signs will have a significantly higher mobility and safety impact than traditional dynamic signs. However, the research team consider that expanding the options of drivers to avoid congested roads can increase the efficiency of the transportation network and result in a clear reduction of GHG emissions. Thus the research team estimates that portable dynamic message signs have medium mobility, safety, and sustainability impacts in the transportation network.

Barriers. In addition to the existing barriers for dynamic message signs, it can be expected that portable dynamic message signs demand further requirements (e.g., training and the development of new operational protocols).

Costs & Agencies' Role. The role of transportation agencies wanting to support the deployment of portable dynamic message signs may engage them in data collection, data management and processing, and data dissemination. In Table C-6 the research team estimates which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

Cooperative Adaptive Cruise Control (V2V)

Impacts. Recent developments in mobile technologies have led to the emergence of vehicle-to-vehicle communication networks that can be used for providing traffic and safety information to drivers. Using these communication networks, motorists can receive information from other travelers and disseminate relevant data to other vehicles within communication range. The information disseminated can be predictive or descriptive depending on the sophistication of the adaptive cruise control system being used (Delot and Ilarri, 2012). Cooperative adaptive cruise control systems can expand motorists' adaptability to changing road conditions. Drivers (or, more properly, their vehicles) can react more rapidly to vehicle collisions, reducing the damage and impact ratio of this type of incident. Such systems can also increase the frequency at which drivers receive traffic information and increase their opportunities to adapt to changing traffic conditions. Recent studies have found that cooperative adaptive cruise controls systems are most effective at improving safety when bundled with collision warning systems. In a scenario of widespread deployment, these systems also have the potential of reducing vehicle GHG emissions and increasing the effective capacity of roadways (Bose, 2001). Considering these elements, the research team estimates that this emerging technology could have high safety impacts, medium mobility impacts, and medium sustainability impacts.

Barriers. Cooperative adaptive cruise control systems are recent technologies and are still unfamiliar to motorists. This creates barriers for introduction related to motorists'

Table C-6. Cost estimates for portable dynamic message signs.

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
Roadside Information (RS-I)		
Dynamic Message Sign-Portable (10 units for regional system)	16.4	22.4
Dynamic Message Sign Tower (2 units for regional system)	28.5	136
Number of units in a medium size regional transportation network: 10 signs	signsx10	signsx10
Number of sign towers in a medium size regional transportation network: 2 towers	towersx2	towersx2
Transportation Management Center (TM)		
Software for Traffic Information Dissemination	19	23
Integration for Traffic Information Dissemination	89	109
Total Cost	329	628
of which, Agencies' Cost	329	628

Source: U.S.DOT, 2012

unfamiliarity with the technology and the uncertainty about its performance to say nothing of their willingness to use such systems if available on their vehicles. Such systems also require modifications to automobiles by the manufacturers. This involves the familiar chicken-and-egg situation in which OEMs would need to be convinced of the business case for such systems.

Costs & Agencies' Role. Transportation agencies wanting to support the deployment of cooperative adaptive cruise control technologies would only be engaged in data collection to integrate this technology with their current systems. In Table C-7 the research team estimates which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

In-Vehicle Navigation Systems with GPS

Impacts. The maturity of GPS technology and its integration with the internet, mobile devices, and PDAs have made in-vehicle navigation systems widely available for motorists. In-vehicle navigation systems provide motorists with descriptive and predictive pre-trip and en route traffic information. This is a versatile type of driver information system, depending on its level of sophistication. Using traditional GPS, motorists can find optimal routes before and during their journey while more advanced GPS can recommended proper following distance, appropriate speed limits, and receive information about vehicle collisions, weather conditions, and other possible concerns. Simulation studies estimate that in-vehicle navigation systems can improve fuel economy by 10 percent by selecting less congested routes and increase average travel speed. In addition, empirical studies estimate that wasted mileage and emissions can be reduced by 15 percent using in-vehicle navigation systems (Kamal, 2009). Another important feature of in-vehicle navigation systems is that they can be integrated with other driver information systems, such as 511 integrated telephone systems. This further expands the capabilities of these systems. Therefore, the research team considers that in-vehicle navigation systems can have high mobility and safety impacts and a medium sustainability impact in transportation networks.

Barriers. In-vehicle GPS navigation systems are a popular technology that is going through changes and is finding new application niches. Nevertheless, as with many new-to-market technologies, GPS navigation systems face deployment barriers related to motorists' unawareness of the capabilities of this technology and uncertainty concerning actual system performance.

Costs & Agencies' Role. Transportation agencies wanting to support the deployment of in-vehicle GPS navigation systems may become engaged in data collection to integrate this technology with their current systems. In Table C-8 the research team estimates which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

In-Vehicle Vision Enhancement (V2I)

Impacts. In-vehicle vision enhancement technologies provide en route traffic and safety information to motorists using vehicle-to-infrastructure communications. The IT architecture infrastructure in roadways collects traffic and safety information through various monitoring devices (e.g., cameras, sensors, and hot spots). This information

Table C-7. Cost estimates for cooperative adaptive cruise control (V2V).

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
Vehicle On-board		
Advanced Steering Control	0.3	0.4
Advanced Cruise Control	0.1	0.2
Sensors for Longitudinal Control	0.2	0.3
Communication Equipment	0.2	0.4
In-Vehicle Display	0.0 (included in vehicle)	0.1
In-Vehicle Signing System	0.1	0.3
Driver and Vehicle Safety Monitoring System	0.5	0.9
Number of private vehicles using this system in a regional transportation network: 100,000 vehicles	vehiclesx100,000	vehiclesx100,000
Transportation Management Center (TM)		
Integration for Traffic Information Dissemination	89	109
Total Cost	140,089	260,109
of which, Agencies' Costs	89	109

Source: U.S.DOT, 2012

Table C-8. Cost estimates for in-vehicle navigation systems with GPS.

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
Vehicle On-Board		
GPS/DGPS	0.1	0.1
GIS Software	0.1	0.2
Number of private vehicles using this system in a regional transportation network: 100,000 vehicles	vehiclesx100,000	vehiclesx100,000
Hard to Quantify		
Integration for Traffic Information Dissemination	89	109
Total Cost	20,089	30,109
of which, Agencies' Costs	89	109

Source: U.S.Department.of.Transportation, 2012

is then transmitted to motorists using vehicle data sensors or other wireless networks. Information that can be transmitted to drivers includes vehicle collision warnings, weather and congestion alerts, and other descriptive information to improve drivers' visibility in conditions of reduced sight distance, night driving, inadequate lighting, and snow and other unexpected weather conditions. As with other driver information systems, motorists can use this information to adapt to changing road conditions and to avoid dangerous situations. Empirical studies of similar technological concepts show that in-vehicle vision enhancement systems can be considerably effective in assisting drivers in unexpected weather conditions, increasing the safety of roadways (Kato, 2000). The research team considers that in-vehicle vision enhancement systems can have medium mobility and sustainability impacts and a high safety impact on transportation networks.

Barriers. In addition still being a young technological concept, vision enhancement barriers include those related to the challenges that transportation agencies would need to face implementing this technology in the road (e.g., additional infrastructure requirements and new regulations and standards to manage the communication interaction between vehicles with the transportation infrastructure).

Costs & Agencies' Role. Transportation agencies wanting to support the deployment of in-vehicle vision enhancement technologies may become engaged in data collection and data managing and processing. In Table C-9 the research team estimates which share of the technology implementation costs would need to be incurred by both motorists and the transportation agency and which share would need to be incurred only by the transportation agency.

Summary

Table C-10 summarizes the discussion of the Characterize step.

Compare

In this phase of the analysis, the information provided in the characterization phase is used to compare the effects of each technology application on transportation agencies' goals and

Table C-9. Cost estimates for in-vehicle vision enhancement (V2I).

Cost Concept	Lower Bound $K (2009 prices)	Upper Bound $K (2009 prices)
Vehicle On-board (VS)		
Vision Enhancement System	1.75	2.18
Communication Equipment	1.9	3.8
Software, Processor for Probe Vehicle	0.5	1.5
Number of private vehicles using this system in a regional transportation network: 100,000 vehicles	vehiclesx100,000	vehiclesx100,000
Transportation Management Center (TM)		
Software for Traffic Information Dissemination	19	23
Hardware for Traffic Information Dissemination	2	2.79
Integration for Traffic Information Dissemination	89	109
Total Cost	415,110	748,134
of which, Agencies' Costs	110	134

Source: U.S.DOT, 2012

Table C-10. Characteristics of driver information systems.

Driver information system	Characteristics					
	Impact Estimate			Costs ($K)	Transportation Agency Role	Technology Barriers
	Mobility	Safety	Sustainability			
Internet traffic pages	Low-Medium	Low	Low	514.03-872.85	Data Collection, Data Management and Processing, Data Dissemination	Insufficient public acceptance; Additional implementation requirements.
Kiosks	Low	Low	Low	540-1,440	Data Collection, Data Management and Processing, Data Dissemination	Insufficient public acceptance; Uncertainty concerning actual performance; Lacking precedence of necessary vendor or support base.
Telephone information systems	Medium	Low	Low	1,500-1,800	Data Collection, Data Management and Processing, Data Dissemination	Inertia of existing processes and methods.
Integrated telephone information systems	High	Medium	Medium	1,800-2,300	Data Collection, Data Management and Processing, Data Dissemination	Inertia of existing processes and methods; Additional implementation requirements.
Highway Advisory Radio	Low	Medium	Low	413.3-582.37	Data Collection, Data Management and Processing, Data Dissemination	Inertia of existing processes and methods.
Dynamic Message Signs	Medium	Medium	Low	592-1,470	Data Collection, Data Management and Processing, Data Dissemination	Uncertainty concerning actual performance; Insufficient public acceptance.
Portable Dynamic Message Signs	Medium -High	Medium	Medium	329-628	Data Collection, Data Management and Processing, Data Dissemination	Uncertainty concerning actual performance; Insufficient public acceptance; Additional implementation requirements.
Cooperative Adaptive Cruise Control (V2V)	Medium	High	Medium	140,000-260,000	Data Collection (partly)	Unfamiliarity with core or applied technology; Insufficient political or public acceptance; Uncertainty concerning actual performance; Extended or problematic approval processes.
In-vehicle navigation systems with GPS	High	Medium	Medium	20, 089-30,109	Data Collection	Unfamiliarity with core or applied technology; Uncertainty concerning actual performance.

(continued on next page)

Table C-10. (Continued).

Driver information system	Characteristics					
	Impact Estimate			Costs ($K)	Transportation Agency Role	Technology Barriers
	Mobility	Safety	Sustainability			
In-vehicle vision enhancement (V2I)	Medium	High	Medium	415,110-748,134	Data Collection, Data Management and Processing	Unfamiliarity with core or applied technology; Uncertainty concerning actual performance; Insufficient political or public acceptance; Additional implementation requirements; Need for new or conflict with existing regulations and standards.

functions. The research team was interested in analyzing which tradeoffs exist between the different technologies in terms that bear on agency decisions. For this, the research team translated the Characterize metrics into a set of normative measures. The research team continued to assume that the implementation of these technologies was to be compared at the regional level. Therefore, even though some of the technology applications may have a wider geographical scope, the research team did not consider this so as to compare these technologies on an equivalent basis. As discussed in greater detail below, the research team considered the total system's costs of implementing the technology, including costs incurred by the transportation agency and costs incurred by drivers (which is important from a societal and efficiency point of view). Finally, even though the research team provides a set of numerical comparative metrics in this section, the reader must consider the analysis to be essentially qualitative. The research team recommends that further STREAM analyses of this sphere of agency function relax this assumption and carry out more detailed costs and effects studies of these driver information systems in specific transportation networks.

Metrics

Mobility

The research team used a qualitative scale to define the following normative metric:

- Metric value 1: The technology has a low mobility impact in the transportation network.
- Metric value 2: The technology has a medium mobility impact in the transportation network.
- Metric value 3: The technology has a high mobility impact in the transportation network.

Safety

The research team used a qualitative scale to define the following normative metric:

- Metric value 1: The technology has a low safety impact in the transportation network.
- Metric value 2: The technology has a medium safety impact in the transportation network.
- Metric value 3: The technology has a high safety impact in the transportation network.

Sustainability

The research team used a qualitative scale to define the following normative metric:

- Metric value 1: The technology has a low sustainability impact in the transportation network.
- Metric value 2: The technology has a medium sustainability impact in the transportation network.
- Metric value 3: The technology has a high sustainability impact in the transportation network.

Technology Barriers (POSI)

- Metric value 1: The technology faces four or more of the barriers discussed in Chapter 3 for its implementation.
- Metric value 2: The technology faces three of the barriers discussed in Chapter 3 for its implementation.
- Metric value 3: The technology faces two of the barriers discussed in Chapter 3 for its implementation.
- Metric value 4: The technology faces only one of the barriers discussed in Chapter 3 for its implementation.
- Metric value 5: The technology faces none of the barriers discussed in Chapter 3 for its implementation.

Table C-11. Value-based comparison for driver information systems.

Driver information system	Mobility	Safety	Sustainability	Agency Costs	Total Costs ($M)	Technology Barriers (POSI)
Internet traffic pages	1.5	1	1	0.69	0.69	3
Kiosks	1	1	1	0.99	0.99	2
Telephone information systems	2	1	1	1.65	1.65	4
Integrated telephone information systems	3	2	2	2	2	3
Highway Advisory Radio	1	2	1	0.497	0.497	4
Dynamic Message Signs	2	2	1	1.031	1.031	3
Portable Dynamic Message Signs	2.5	2.5	2	0.478	0.478	2
Cooperative Adaptive Cruise Control (V2V)	2	3	1	0.099	200	1
In-vehicle navigation systems with GPS	3	2	2	0.099	25.09	3
In-vehicle vision enhancement (V2I)	2	3	2	0.122	582	1

Costs

For the comparison of costs, the research team used the average of the nominal values presented in Chapter 3. As in the bridge deck evaluation example, a fuller treatment would represent the ranges of current thinking about possible costs. Because the research team was modeling the decisions by transportation agencies, the costs considered were those that would be borne directly by the agency itself. For several of the technology applications discussed in this section these represent total costs as well. For others, a substantial or even preponderant share would need to be borne by private individuals and vendors such as automobile OEMs. For the present analysis, these latter were assumed to present a barrier to external acceptance in the form of resistance by the public (one of the factors in the external dimension of the POSI scale). This would then be reflected in a less favorable POSI measure which, in turn, would affect the relative standing of that technology alternative.[73]

Comparison of Technologies

Table C-11 illustrates the tradeoffs involved in implementing different driver information systems. There are strong differences among the different technologies.

[73] In a full STREAM analysis, a more quantitative tally of how much of a barrier the externally borne costs might be would be examined. There may (or may not) be less reluctance to install a $40 device than a $400 one but anything greater than zero would likely pose some challenge. Further, there is also the issue of whether the device in question would be solely devoted to the intended purpose or might be (like a mobile telephone) something that already exists that could be further repurposed to perform a traffic information function. The fundamental approach to the partitioning and treatment of costs that has been employed in this analysis would remain.

Mobility-Safety Tradeoffs

Figure C-3 shows that a considerable number of technologies have significant equivalent mobility and safety impacts. These technologies are dynamic message signs, cooperative adaptive cruise control, in-vehicle vision enhancement, in-vehicle navigation systems with GPS, integrated telephone information systems, and portable dynamic message signs. The rest of the technologies only have a marginal effect in one or both of the safety and mobility dimensions. In this grouping, the most recent technologies offer the better results in terms of safety and mobility. As mentioned in the Identify section, this may be because the newest designs of driver information systems have evolved into systems designed to serve multiple purposes.

Mobility-Cost Tradeoffs

Figure C-4 shows one estimate of the relationship between mobility and agency costs. Systems that can provide the highest mobility impact are also the most expensive (i.e., integrated telephone information systems and in-vehicle navigation systems with GPS). However, the costs incurred by transportation agencies with respect to these two technologies differ. For instance, in-vehicle navigation systems with GPS provide the same mobility benefit as integrated telephone information systems, but at a much lower cost. Nevertheless, transportation agencies should consider that, in the case of in-vehicle navigation systems with GPS, they would only need to incur a minimal share of the total system costs with the rest paid by drivers. By omitting drivers' costs, in-vehicle navigation systems with GPS become a less expensive option for transportation agencies than integrated

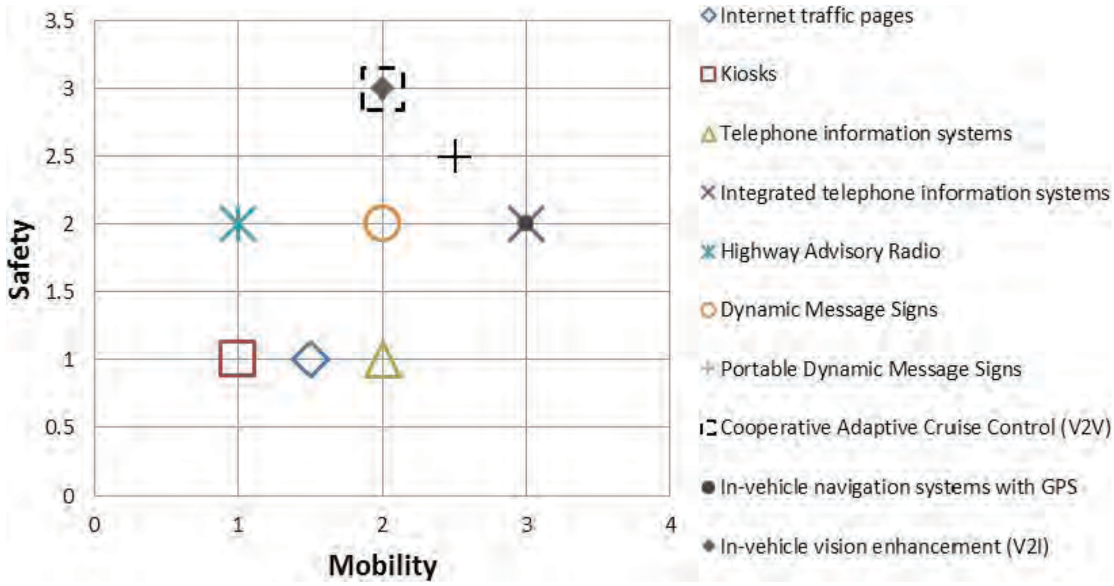


Figure C-3. Mobility and safety tradeoff.

telephone information systems. As reflected in the POSI scores, transportation agencies could opt for supporting the implementation of a technology that would be less expensive for them but that would have higher system costs but possibly less-wide public acceptance.

Mobility-Sustainability Tradeoffs

Figure C-5 shows that integrated telephone information systems and in-vehicle navigation systems provide the highest combined mobility and sustainability impact. Another good option is portable dynamic message signs, and, to a lesser extent, in-vehicle vision enhancement. The most recent and advanced driver information systems are designed to meet multiple goals. For instance, in this case, reductions in travel time and increasing travel speeds can also result in reductions to GHG emissions.

Safety-Cost Tradeoffs

Figure C-6 shows technology options that could offer superior safety effects for relatively low expected average costs. For example, portable dynamic message signs are a technology that can offer the highest safety impact at the lowest possible cost. Other technologies worth noting are highway advisory radio, dynamic message signs, and inte-

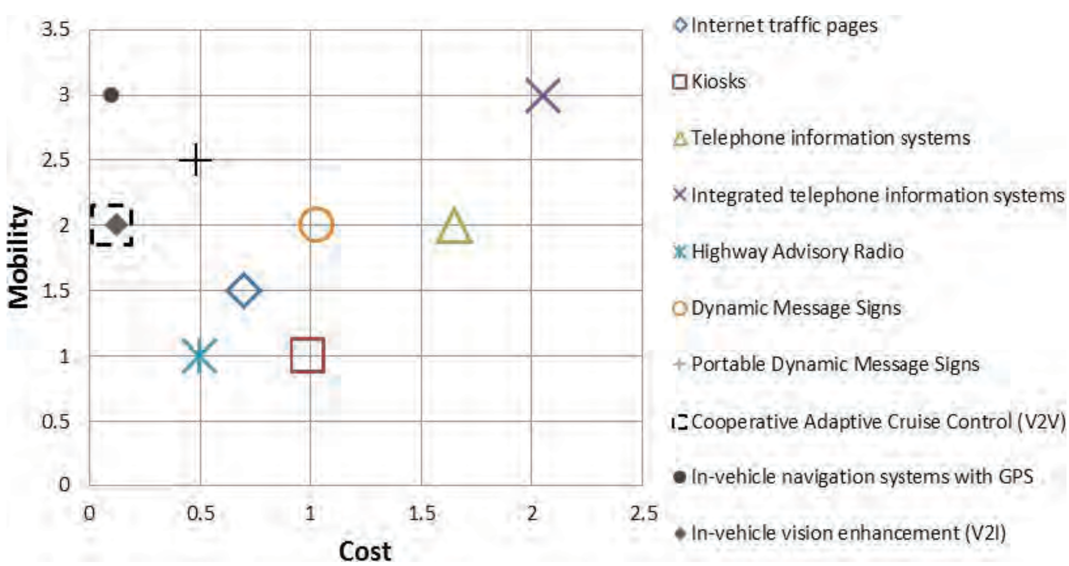


Figure C-4. Mobility and cost tradeoff.

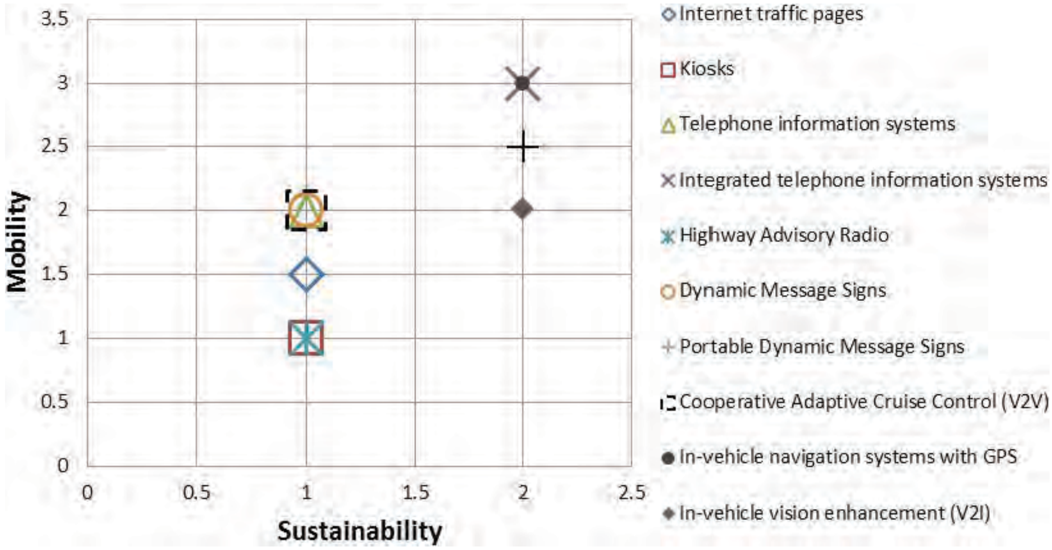


Figure C-5. Mobility and sustainability tradeoff.

grated telephone information systems. Two other technologies could offer high safety impacts at apparently low agency cost (i.e., in-vehicle navigation systems with GPS and cooperative adaptive cruise control technologies). In these cases, costs would be primarily covered by motorists and not by transportation agencies.

Comparison of Technology Alternatives

The research team compared technology alternatives in terms of an overall value metric that is the product of the metric value for mobility, safety, and sustainability. By treating each of the metric values defined as representing a distribution of random variables, the research team obtained a proxy for the total benefit in terms of agency goals of the technology alternative when implemented. This was plotted against the metric value for POSI with the two values being taken as an approximation of relative expected value among the alternatives being considered.

Figure C-7 shows this total value metric, the product of the mobility, safety, and sustainability values versus the measure of degree of implementation difficulty. Each point in the plot represents the assessment of an alternative's relative expected value (i.e., the farther from the origin, the higher this value is assumed to be) while the error bars show an estimate of the degree of uncertainty in each

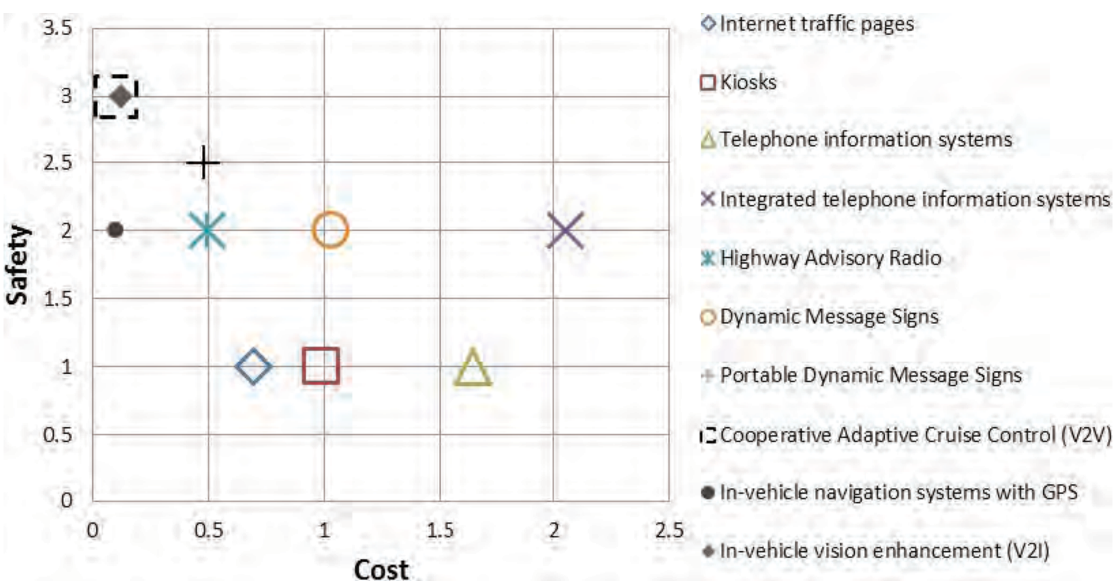


Figure C-6. Safety and cost relationship.

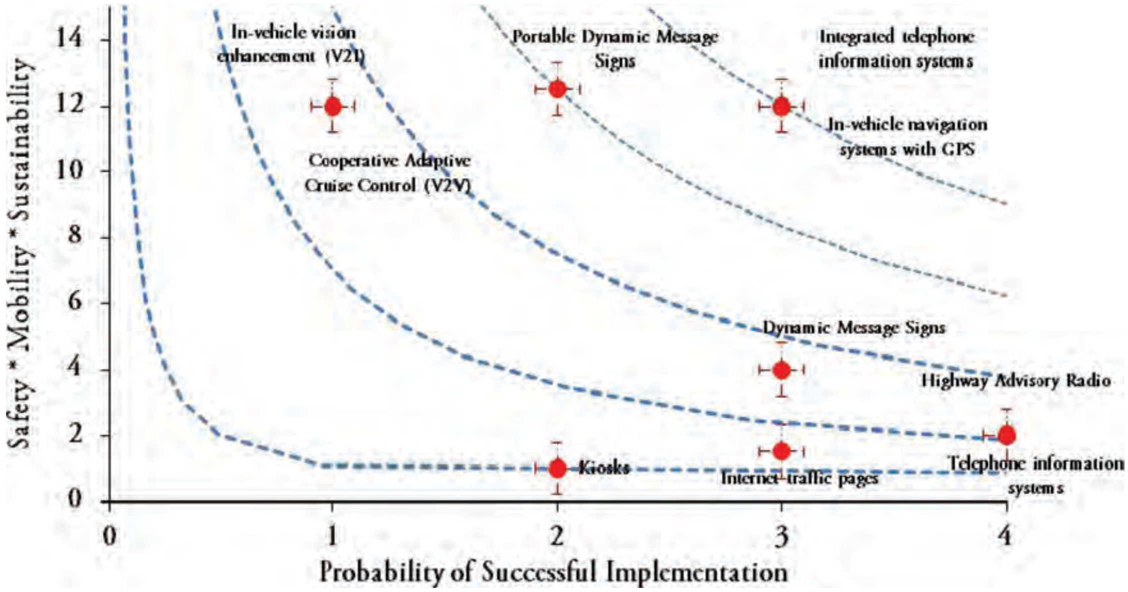


Figure C-7. Product of mobility, safety, and sustainability values compared to implementation barriers.

dimension.[74] The vertical axis represents the total mission goal value considering the three metrics of the analysis: mobility, safety and sustainability. The points further from the origin represent those technologies that offer the highest combined assessment of potential agency mission value. The horizontal axis represents the probability of successful implementation (POSI) of each technology. The points further from the origin represent technology options with the highest POSI (i.e., the fewest identified potential obstacles or barriers). The research team also plotted iso-curves that show the contours of equivalent (in relative expected value terms) tradeoffs between the presumed total agency mission benefit and the POSI metric. Movement along these curves away from the origin would imply trading some potential benefit in exchange for a higher POSI while maintaining the same expected value.

Viewing the information in this way makes it possible to present in an integrated illustration what would otherwise be a complicated set of information: the results of the metric value analyses in terms of mobility, safety and sustainability; the range of uncertainty about these values for the different technologies; the barriers to implementation identified for each alternative; and the tradeoffs between the characteristics of a group of technologies now placed on the same scale. As noted in the other STREAM case studies, other views of this same type could be generated to more fully represent in a two-dimensional format what is a multi-dimensional space.

Figure C-7 shows what may not before have been clear for such a disparate and heterogeneous set of technology alternatives—Irrespective of the technical basis for each approach or the industry sector from which it might have emerged, from the transportation agency mission (i.e., functional) perspective, the technologies form several groups. In the bottom of the graph are kiosks and internet traffic pages (which have a low expected value due to both relatively lesser potential value to improving transportation agencies' functions of providing traffic and safety information and also somewhat low POSI). Telephone information systems and highway advisory radio belong to group of technologies that may offer only marginal benefit for transportation agencies but that can be readily implemented in light of minimal barriers. This can be seen by their placement on a higher equal-value contour than the first group.

Along a yet higher contour is the group representing in-vehicle vision enhancement technologies, cooperative adaptive cruise control, and dynamic message signs. The first two offer a very high potential mission value, but the existing difficulties for their implementation give them an expected value equivalent to the less demanding alternative of dynamic message signs. In-vehicle vision enhancement requires the coordination of multiple parties (i.e., transportation agencies, car manufacturers, and motorists) for successful implementation. It is also a novel technology with uncertain expected benefits. In addition, when analyzing its combined mobility, safety, and sustainability effect, it is clear that a few other technologies present fewer implementation difficulties and similar functional returns to

[74] These uncertainties do not vary greatly in this case because of the method used to form these measures. A more detailed approach employing a survey or expert panel, for example, would yield substantial differences in uncertainty among the technology applications with the more speculative, leading edge alternatives displaying the greater uncertainty.

transportation agencies. A similar logic applies for cooperative adaptive cruise control. However, the high functional returns of these technologies should be noted. This suggests both the value of keeping technologies with different maturities in an integrated perspective as well as revisiting how the expected value of different alternatives might change as their underlying technologies mature. These assessments might also well change if there is more detailed analysis than could be provided here as well as taking into closer account the specific challenges faced by individual local or regional agencies and the environment in which they operate. What a preliminary view such as this, and the underlying analysis that supports it, does is to highlight where limited resources for assessment might be most usefully directed to support the local decisions required.

The portable dynamic message signs alternative is separated from the other groups because it is a technology alternative that offers a clear higher benefit than the technologies in the bottom of the graph; however, its relatively low POSI score remains a cause of concern for transportation agencies and reduces what would otherwise be a higher expected value. Again, given its potential benefit, it would be interesting for transportation agencies to explore ways to mitigate some of the obstacles to it. This is a technology for which transportation agencies can play the leading role in its distribution.

Finally, there are two clear "winners" in this analysis: integrated telephone information systems and in-vehicle navigation systems with GPS. They offer the same high potential functional value for transportation agencies and the same relatively high POSI. When compared to all other alternatives, these two technologies provide the highest expected value. In terms of POSI, these technologies face a similar number of implementation barriers as dynamic message signs and internet traffic pages. Both the latter have already penetrated transportation systems at significant levels, thus it is possible that existing barriers for integrated telephone information systems and in-vehicle navigation systems with GPS could be overcome as well. This would require both a closer look at those barriers and a local assessment for how serious they might be and what options might exist for surmounting them.

One thing not brought out clearly in this figure is that synergies may exist between these two leading technologies that transportation agencies could exploit. For example, there is already a tendency to incorporate in-vehicle navigation systems with GPS into internet-based mobile devices and PDAs. Therefore, in the future motorists using these navigation systems might also access integrated telephone information systems and receive traffic and weather information as well access traffic cameras and local maps. This could expand how motorists could adapt to changing road conditions and improve significantly the quality of the information that motorists use for planning their trips. It could create an additional purpose for those telephone information systems in which transportation agencies have already invested.

Decide

At this stage of the analysis, transportation agencies interested in driver information systems can use the information provided in the last four sections to decide which technologies to adopt and which technologies to monitor.

The results of this analysis are highly sensitive to the realities of transportation agencies, which are heterogeneous in terms of culture, administration, personnel, and financial capabilities. The decisions resulting from applying STREAM to the case of driver information systems would need to acknowledge this heterogeneity and not assume that what works in one region will necessarily work in another.

Generally, the analysis shows that synergies can be exploited at the technology level and at the institutional level. New driver information systems have opened new possibilities for integrating existing systems with novel applications (e.g., integrated telephone information systems and in-vehicle navigation systems with GPS). In addition it is possible that the most radical designs (e.g., in-vehicle vision enhancement and cooperative adaptive cruise control) could both yield and require synergies that transportation agencies could pursue with other relevant actors (e.g., automakers, transportation companies, and information providers) who very likely would be needed to support the distribution of these novel technologies.

APPENDIX D

Materials Supporting Bridge Deck NDE STREAM Example

Key Bridge Preservation Reports

FHWA (2008). 2008 Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance. Report to Congress.

- Chapter 2: Bridge System Characteristics
- Chapter 3: Bridge System Conditions
- Chapter 11: NHS Bridge Performance Projections
- Appendix B: Bridge Investment Analysis Method

TRB (2009). NCHRP Synthesis of Highway Practice 397: Bridge Management Systems for Transportation Agency Decision-Making. Provides an overview of how agencies make decisions about bridge investments.

Fiber-Optic Sensors

Table D-1 provides detailed information about projects using FOS.

Dispersion of Expert Opinion on NDE Bridge Deck Evaluation Technologies

Table D-2 provides an indication of the degree of uncertainty or difference of opinion these survey scores represent. For each of the three measures, the coefficient of variation has been calculated.

The standard deviation divided by the mean provides a relative weighting of dispersion. A coefficient of variation closer to one means a wider variation of values in that the standard deviation would approach the magnitude of the mean. A coefficient of variation closer to zero means that there is little variation about the mean.

Cost Assumptions

Some assumptions were used in the cost model developed by the research team. Several of these assumptions were discussed in detail during the sessions at MnDOT. Among the most important was the question of scope of application. The relatively low assumed share of bridges within the jurisdiction evaluated each year (5 percent) is based on a presumption that no technology will replace the existing statutory methods (visual and audible). Rather, instances in which further evaluation, higher reliability, or lessened impact are desired (e.g., a heavily traveled bridge in a dense urban area) would form the target group of candidates for assessment using an alternative or supplemental technology.

Report on STREAM Field Trial: Minnesota DOT

The research team's efforts to field-test STREAM to refine it and ensure its utility and practicality included a day-long workshop at the Minnesota DOT (MnDOT) in April 2012. The research team had two objectives in meeting with these representatives of the intended audience for STREAM. First, the research team sought feedback from individuals who might use STREAM, either by conducting a STREAM analysis or by using the resulting findings. Second, the research team sought to generate awareness of STREAM and explore opportunities for applying STREAM.

The research team sought a collaboration with MnDOT in particular because of close ties between the NCHRP Project Panel and MnDOT and because the case study on bridge deck evaluation—which also served as the application for the workshop exercise—drew heavily on MnDOT's efforts to assess bridge deck evaluation methods (see, for example, Gastineau et al., 2009).

The research team divided the workshop into four sessions. Sessions 1 and 2 were aimed at broadly discussing STREAM with end users and soliciting general feedback. In Sessions 3 and 4, the research team validated STREAM (using the topic of bridge deck inspection) with experts from MnDOT's bridge maintenance and related offices. The

Table D-1. Examples of bridge monitoring projects using FOS.

A total of sixteen Fabry-Perot (FP) FOS were installed on the East Bay bridge, in Hillsborough County, Florida. The bridge is a 4-span continuous reinforced concrete deck-type structure.	(Mehrani et al., 2009)
"An optical fiber monitoring system was designed and built into one span of the five span high performance prestressed concrete I-10 Bridge over University in Las Cruces, NM."	(Idriss and Liang, 2007)
"Fiber Bragg sensors developed for structural health monitoring, and were installed on Hong Kong's landmark Tsing Ma bridge (TMB), which is the world longest (1,377m) suspension bridge that carried both railway and regular road traffic. Forty FBG sensors divided into three arrays were installed on the hanger cable, rocker bearing and truss girders of the TMB."	(Chana et al., 2006)
Switzerland, Siggenthal bridge in Baden, 58 FOS	(Li et al., 2004)
Switzerland Versoix bridge with 104 FOS	(Li et al., 2004)
Waterbury bridge, Vermont, 36+16 FOS, steel bridge (as opposed to concrete)	(Li et al., 2004)
Planned: "The [FOS-based] SHM systems will be implemented on two existing steel bridges: the Government Bridge at Rock Island Arsenal, Rock Island, Illinois, and the Interstate 20 (I-20) Mississippi River Bridge between Mississippi and Louisiana."	(Mason et al., 2009)
I-35 W bridge in Minnesota (the one that collapsed). Array of sensors being used, including FOS.	(Inaudi et al., 2009)
"The Bridge Engineering Center at Iowa State University has been working with the Iowa DOT to improve methods of managing bridge infrastructures. Specifically, the Bridge Engineering Center is developing and utilizing short-term and long-term SHM systems to measure bridge behavior…. The HPS bridge SHM system consists of components developed from several different manufacturers. When possible, standard off-the-shelf components were utilized to maintain minimum cost for the system. The primary components of the SHM system are as follows: Strain sensing equipment: Micron Optics si425-500 Interrogator Strain sensors: 30 Fiber Bragg Grating (FBG) Sensors Video equipment, networking components, and three computers for web service, data collection and data storage. [For real-time status, visit the SHM system online portal at http://www.ctre.iastate.edu/bec/structural_health/hps/index.htm. There clients can view live streaming video of traffic crossing the bridge and the resulting real-time girder strain measurements."]	(Graver et al., 2004)

remainder of this appendix describes those sessions and the findings.

Sessions 1 and 2: Overview of STREAM

In Session 1, the research team provided an overview of the project and STREAM to a group of MnDOT middle and upper level managers from both operational and planning offices. In Session 2, the research team met with personnel involved in technology decision-making and technology use. In these sessions, the research team focused principally on STREAM itself, describing the thinking behind it and how the research team envisioned its implementation.

In both sessions, participants indicated support for implementing STREAM as a technology decision tool in transportation agencies. When presented with the bridge deck inspection example, one participant commented that a side-by-side comparison of technologies illustrated that there are

Table D-2. Characterization of bridge deck evaluation technology alternatives, coefficients of variation for expert survey replies.

Technology Application	Preservation Value	Mobility Value	POSI
Robotic	0.32	0.27	0.22
NDE Suite	0.11	0.19	0.16
FOS	0.49	0.32	0.21
GPR	0.11	0.38	0.15
Visual	0.30	0.38	0.01
Visual + Audible	0.35	0.36	0.03

benefits to increasing the POSI of GPR, a technology application already being considered within MnDOT, and that doing so would add value to MnDOT's bridge operations.

Participants supported rooting the assessment in broad agency missions (safety, mobility, etc.) that are common to agencies and across functions and then defining specific goals based on these fundamental agency missions.

Participants also expressed concerns that STREAM might still not be sufficient to help agencies identify and understand when or how technology will affect them in unforeseen or subtle ways. Computer-assisted drawing (CAD) was offered as an example of a technology that has changed the way DOTs do business, but which agencies may not have identified as a technology to evaluate with STREAM.

Session 3: Introduction to Bridge Deck Inspection Technology Assessment with STREAM

Session 3 was devoted to looking at the example of bridge deck inspection technology applications in detail. This was intended to validate with experts the set of data and inferences that the research team had been using and to frame the conversation about bridge inspection technology within the STREAM framework. This was first done through general discussion of the bridge monitoring function, alternative technological approaches, and the approaches used or tested by MnDOT. The participants then reviewed the research team's work in detail.

Key Insights from Discussion

The discussion offered several insights that the research team used to refine STREAM and the bridge deck inspection case study. Participants noted that bridge deck inspection principally relates to preservation of transportation infrastructure and mobility for travelers. Safety is not a key concern of bridge *deck* inspection (though it is of substructure inspection, for example) because traveler safety is not typically in question. Safety of bridge inspectors is a consideration.

Participants also noted that the effect of bridge deck inspection on mobility depends not only on the length of time that a bridge or bridge lane is closed, but also the number of people who use the bridge. A technology that involves a half-day of bridge closure may have little impact on mobility in a very rural region, but even a 1-hour closure may be costly in an urban region.

As in previous sessions, participants made several comments related to technologies that fundamentally change how DOTs perform certain functions. For example, fully adopting FOS as a means of bridge deck inspection involves implementing fiber optics in every new bridge during construction and retrofitting existing bridges. Fiber-optic systems could eliminate the need for recurring bridge deck inspection. This approach is different from GPR and visual inspection, which both involve routinely scanning the bridge with sensors of some kind to obtain information. In contrast to fiber-optic systems, these technologies allow DOTs to use the same equipment and resources on multiple bridges.

Participants agreed that it was important for DOTs to be able to assess both "business as usual" and revolutionary technologies. There was some disagreement over whether different technologies should be evaluated side by side. Some participants thought that doing so would be comparing "apples to oranges" while others noted that such comparisons were necessary in order to adopt technology. The group discussed how STREAM could facilitate such a comparison, noting that comparisons of cost, impact on goals, and feasibility assisted in this comparison.

Participants also noted that DOTs typically experiment with and adopt technologies in phases, conducting larger pilot trials of technologies. They emphasized that STREAM should be able to assist in narrowing in on appropriate trials and incorporating information from trials into the decision-making process.

Several of these points shaped how STREAM was developed. For example, STREAM's ability to facilitate "apples and oranges" comparisons was made explicit and intentional. Other aspects of discussion provided valuable input as the research team refined not only the STREAM method, but also the materials the research team used to present it.

Review of Cost Model

The research team also shared with MnDOT its assumptions about the costs of different bridge deck inspection technologies. Table D-3 shows a sample of the assumptions used in the cost model developed by the research team. Participants discussed several of these assumptions in detail.

Among the most important was the scope of application. The relatively low share of bridges evaluated using the alternative technology each year (5%) is based on a presumption that no technology will completely replace the existing statutory methods of visual and audible inspection. Rather, instances in which further evaluation, higher reliability, or lessened impact are desired (e.g., inspecting a heavily traveled bridge in a dense urban area) would be key candidates for assessment using an alternative or supplemental technology.

The resulting calculations, incorporating much additional data on the candidate technology applications, are shown in Table D-4. This table shows the breakdown of net fixed and recurring costs for each technology during the initial 5-year period of its use.

Table D-3. Base case assumptions for calculating fixed and recurring costs for candidate bridge inspection technology applications.

Assumption	Base Value	Assumption	Base Value
Percent Using Chain-drag	10%	Discount Rate	7.0%
Bridges in Area of Responsibility	20,419	Hourly Labor Cost	$20.0
Percent of Potential Bridges Using Alternative	5%	Overhead Rate	50%
Bridges per year	1,000	Burdened Labor Rate	$ 30.0
Average Inspection Labor (CD)(man-hrs)	40	Cost per Mile	$ 0.56
Average Inspection Labor (VI)(man-hours)	8	People trained/year for 1000 bridges/year	4
Average Distance to Bridge (mi)	100		

Session 4: Real-Time Application of STREAM to Bridge Deck Inspection

In the final session, the research team worked with participants to apply STREAM to bridge deck inspection technologies. This exercise focused on the Characterize and Compare steps in STREAM and used the forms shown in Figure D-1 to solicit participants' rating of the benefits, barriers, and costs of the six alternative technology approaches for bridge deck evaluation that had been discussed. The research team used the results of participants' input to generate new plots comparing technologies along these dimensions.

This exercise was more than a field test of STREAM. MnDOT has a high level of experience and familiarity with specific technology alternatives, gained through studies performed by MnDOT following the collapse of the 35-W bridge over the Mississippi River. The research team therefore used the results from this exercise as a proxy for the results that would be produced by an expert STREAM panel under the institutional Board/panel. The results could then be used as

Table D-4. Fixed and recurring costs for candidate bridge deck inspection technology applications over five-year period following implementation.

		Technologies					
Cost Factors		Visual	Visual +Audible	GPR	Fiber Optics (New)	Sensor Suite (GPR +IR)	Sensor Suite on Robotic Platform
Net Fixed Costs	Acquisition (net value of redundant equipment)	$87,285	$87,285	$129,463	$4,404,041	$217,311	$471,246
	Taxes/Penalties/Fees (net TPF no longer required)	$0	$0	$0	$0	$0	$0
	Training (net training no longer required)	$0	$0	$43,200	$10,000	$97,200	$97,200
	Licenses, Royalties, etc. (net)	$0	$0	$15,000	$6,186	$24,405	$61,518
Net Recurring Costs	O&M (net O&M of equipment made redundant)	$278,588	$278,588	$269,813	$278,588	$282,975	$282,975
	Training (net training no longer required)	$52,647	$52,647	$115,822	$67,271	$194,792	$194,792
	Taxes/Penalties/Fees (net TPF no longer required)	$0	$0	$0	$0	$0	$0
	Licenses, Royalties, etc. (net)	$0	$0	$0	$0	$0	$0
	Personnel (net personnel made redundant)	$1,491,652	$2,680,586	$2,024,867	$1,491,652	$2,249,852	$2,249,852
Total		$1,910,172	$3,099,106	$2,598,165	$6,257,738	$3,066,535	$3,357,583

Please note the extent to which you believe the given technology will improve preservation and safety.

	Little or None	Small	Large	Significant
Visual	☐	☐	☐	☐
Visual+Audible	☐	☐	☐	☐
GPR	☐	☐	☐	☐
Fiber Optics	☐	☐	☐	☐
Sensor Suite (GPR+IR)	☐	☐	☐	☐
Sensor Suite on Robotic Platform	☐	☐	☐	☐

Please note the extent to which you believe the given technology will improve mobility (by reducing congestion due to lane closure or major bridge repair.)

	Little or None	Small	Large	Significant
Visual	☐	☐	☐	☐
Visual+Audible	☐	☐	☐	☐
GPR	☐	☐	☐	☐
Fiber Optics	☐	☐	☐	☐
Sensor Suite (GPR+IR)	☐	☐	☐	☐
Sensor Suite on Robotic Platform	☐	☐	☐	☐

Please assess how the costs of each technology relate to your agency.

	No net cost/savings	"Little" net cost	"Major" net cost	"Excessive" Net Cost
Visual	☐	☐	☐	☐
Visual+Audible	☐	☐	☐	☐
GPR	☐	☐	☐	☐
Fiber Optics	☐	☐	☐	☐
Sensor Suite (GPR+IR)	☐	☐	☐	☐
Sensor Suite on Robotic Platform	☐	☐	☐	☐

Please assess which of the following technical barriers apply to each technology:

Please Mark: __	if you believe the barrier does not apply
L	if you believe the barrier is a *small* concern
M	if you believe the barrier is a *major* concern
S	if you believe the barrier is a "showstopper"

	Unfamiliarity with core or applied technology	Uncertainty concerning actual performance	Additional implementation requirements (training, standards, etc.)
Visual	_____	_____	_____
Visual+Audible	_____	_____	_____
GPR	_____	_____	_____
Fiber Optics	_____	_____	_____
Sensor Suite (GPR+IR)	_____	_____	_____
Sensor Suite on Robotic Platform	_____	_____	_____

Figure D-1. Sample workshop input collection form.

Please assess which of the following process and institutional barriers apply to each technology:

	Need for new or conflict with existing regulations & stds.	Non-fungibility of funding for required expenditures	Extended or problematic approval processes
Visual	_____	_____	_____
Visual+Audible	_____	_____	_____
GPR	_____	_____	_____
Fiber Optics	_____	_____	_____
Sensor Suite (GPR+IR)	_____	_____	_____
Sensor Suite on Robotic Platform	_____	_____	_____

Please assess which of the following external barriers apply to each technology:

	Inertia of existing processes and methods	Insufficient political or public acceptance	Lacking presence of necessary vendor or support base
Visual	_____	_____	_____
Visual+Audible	_____	_____	_____
GPR	_____	_____	_____
Fiber Optics	_____	_____	_____
Sensor Suite (GPR+IR)	_____	_____	_____
Sensor Suite on Robotic Platform	_____	_____	c

Figure D-1. (Continued).

input to workshops and meetings with other DOTs that focus on how an agency would receive and use such input from the Board-sponsored body.

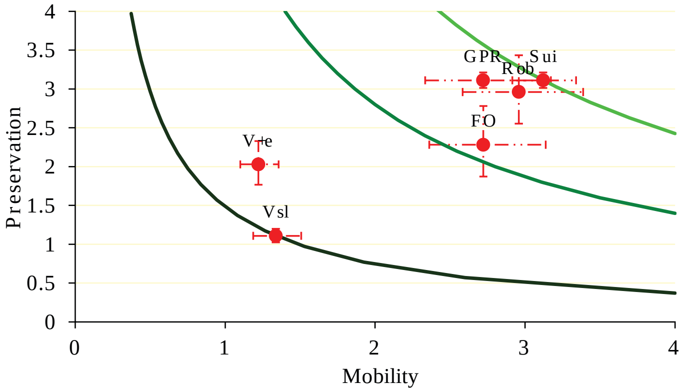
Technology Comparison

Figure D-2 shows how the six alternatives compare in terms of potential benefits.[75] The current approaches—visual inspection alone and visual inspection coupled with audible inspection—score the least well. Visual inspection coupled with audible inspection provides some additional benefit over visual inspection alone on the Preservation axis. Three alternatives, GPR, a suite of sensor technologies, and the roboticized platform version of the latter, are clustered together and outperform visual and audible inspection on both preservation and mobility. However, large uncertainties mean they are largely indistinguishable from one another.

Figure D-3, however, clarifies the choices faced by transportation agencies. The vertical axis captures the findings in Figure D-2, combining (multiplicatively) the two benefit measures of preservation and mobility. The horizontal axis plots the POSI and makes clearer the distinctions between technologies. The current standard techniques are precisely that because of the almost nonexistent barriers to their application and use. Both the GPR and mixed sensor suite alternatives provide greater benefit from use, but have commensurately higher barriers to adoption and implementation than current approaches. Although they represent two distinct points, both are approximately located on the highest tradeoff curve within the range of uncertainty that surrounds them. Though close, the relatively narrow uncertainty ranges give the edge to GPR in terms of higher POSI.

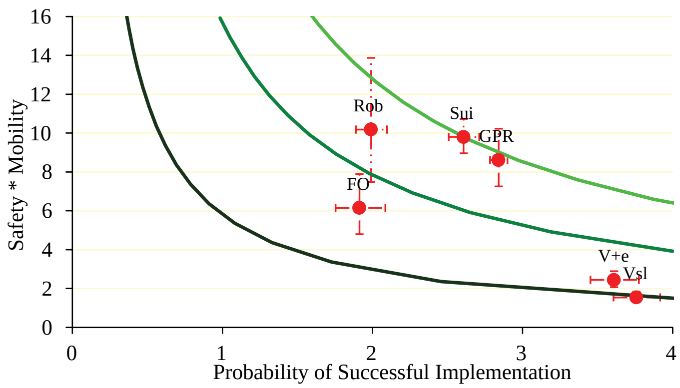
Figure D-4 provides a third view of the results. The benefit values on the vertical axis remain the same as in Figure D-3, but the horizontal axis plots the cost barriers associated with each technology. Technologies follow a similar pattern in terms of cost barriers as they do in terms of non-cost barriers in Figure D-3. There is more dispersion along this axis than before. Fiber-optic systems and a robotic testing suite have serious cost implications when compared to benefits they return. As expected, the present standards of visual and audible inspection have the least serious cost implications. GPR and a sensor suite represent an increase in costs relative

[75] The results shown are for nine of the ten worksheets because one was apparently filled incorrectly on some responses. We therefore excluded all the responses from this participant.



Note: The vertical and horizontal bars show the range of estimates from the nine participants. The curves show the points of equivalent tradeoff between Preservation and Mobility assuming them to be weighted equally (i.e., equally important).
Key: **Vsl**=visual; **V+e**=visual+audible; **GPR**=ground penetrating radar; **FO**=fiber optics; **Sui**=sensor suite; **Rob**=sensor suite on robotic platform.

Figure D-2. Estimated relative benefit values for Preservation [Safety] and Mobility for six candidate bridge inspection technology applications based on results from a workshop at MnDOT.

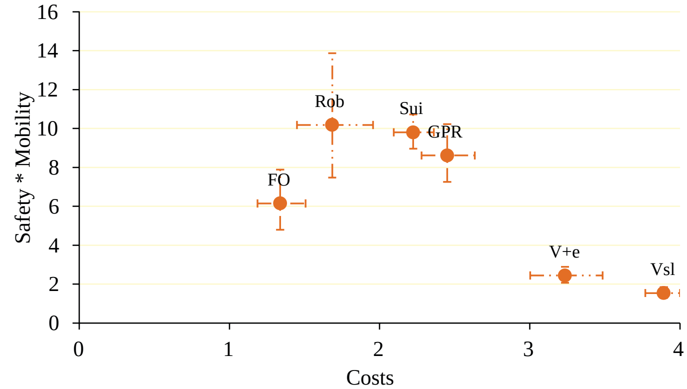


Note: The vertical and horizontal bars show the range of estimates from the ten participants. The curves show the points of equivalent tradeoff between the combined Safety and Mobility benefit and the POSI.
Key: **Vsl**=visual; **V+e**=visual+audible; **GPR**=ground penetrating radar; **FO**=fiber optics; **Sui**=sensor suite; **Rob**=sensor suite on robotic platform.

Figure D-3. Estimated total combined benefit values for Preservation [Safety] and Mobility compared to scores for POSI for six candidate bridge inspection technology applications based on results from a workshop at MnDOT.

to this baseline. Again, GPR appears to have a slight edge over the sensor suite.

The research team shared and discussed these results with participants during Session 4, after data entry into the software designed to support the Compare step. The exercise had two favorable outcomes. First, the results seemed to capture the actual relationship among these technological alternatives as understood individually and collectively by this group. Second, even though not surprising, the results provided insights that were considered valuable. They provided a comprehensive means to represent disparate information in a manner that could be understood and could (and did) provoke additional rounds of usefully focused discussion. Participants recognized and valued that the purpose was not to cause the computer to offer a single "answer" *deus ex machina,* but rather to provide a platform to facilitate weighing of alternatives by a group of technical staff, managers, and decision makers.



Notes: Costs are less of a barrier to adoption as one moves further from the origin.
Key: **Vsl**=visual; **V+e**=visual+audible; **GPR**=ground penetrating radar; **FO**=fiber optics; **Sui**=sensor suite; **Rob**=sensor suite on robotic platform.

Figure D-4. Estimated total combined benefit values for Preservation [Safety] and Mobility compared to measures of cost for six candidate bridge inspection technology applications based on results from a workshop at MnDOT.

Summary

Several lessons emerged from the workshop at MnDOT. STREAM appeared to pass the first market test to which it was subjected. While far from complete validation of the concepts and their application, it was informative that practitioners playing several managerial, planning, research, and operational roles in a transportation agency reacted largely favorably.

The research team also received valuable input on how to present STREAM to agencies and how to provide instruction in its operation. This includes describing how STREAM can facilitate decision-making about successive implementations of technology alternatives that will co-exist to some extent with existing means, how better to motivate the Frame step, and similar insights. It also became clear that there were unintended ambiguities, for example, in the lay out of the questionnaire and visualizations, which the research team subsequently improved.

APPENDIX E

Supporting Information for STREAM Application Case Studies

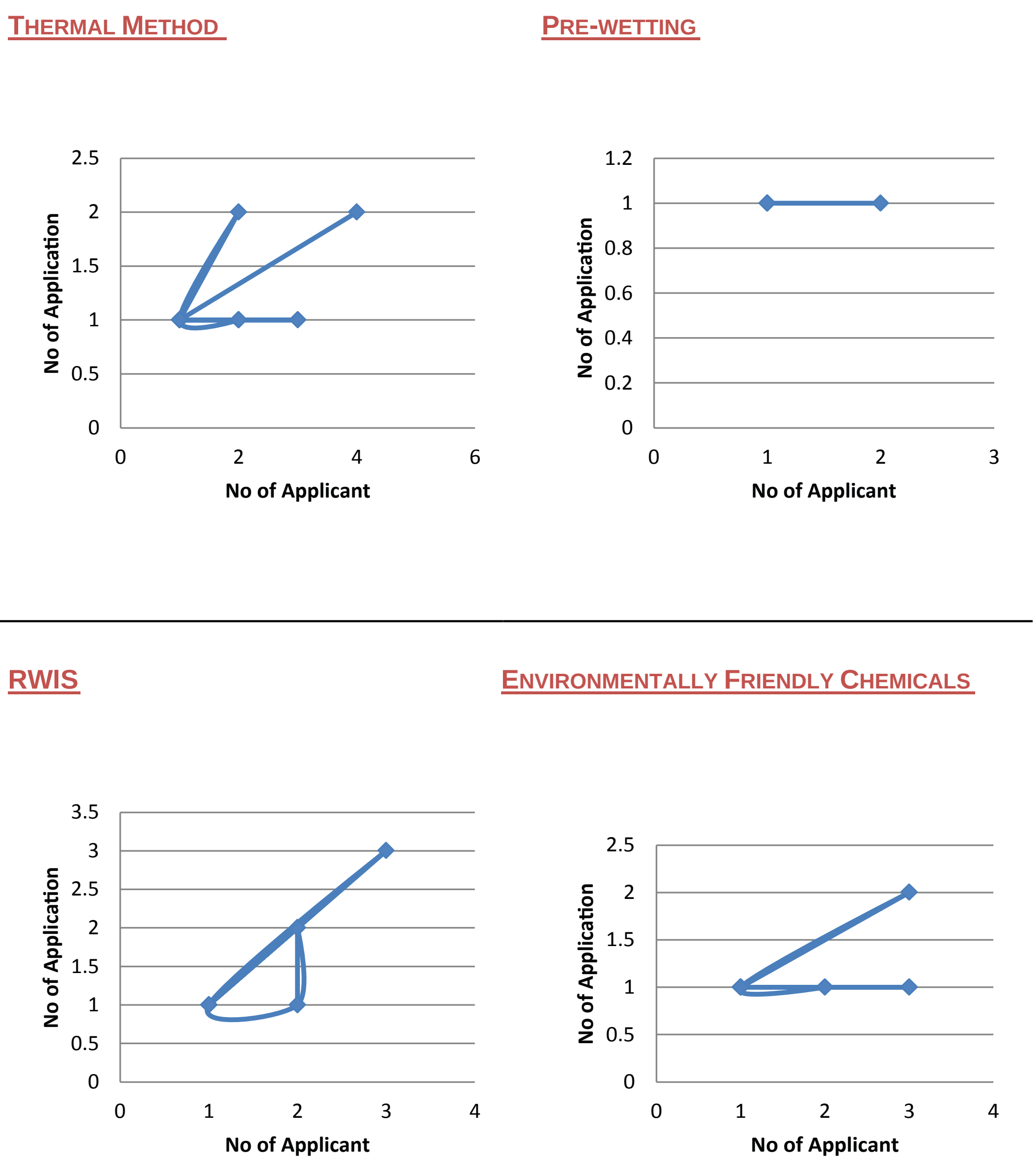


Figure E-1. Technological maturity of several snow removal and ice control technologies.

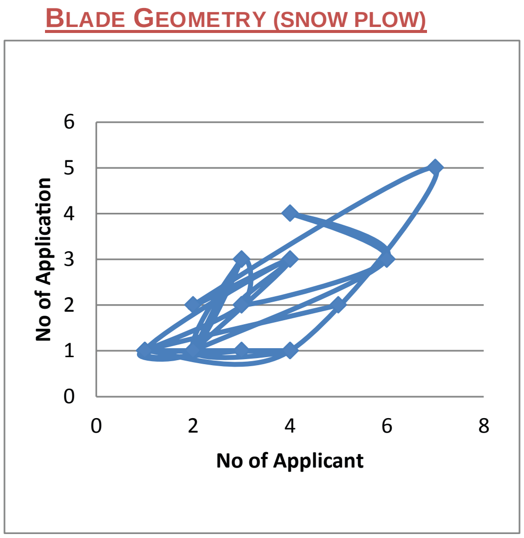


Figure E-1. (Continued).

Table E-1. MnDOT recommended standard values for use in economic analysis in FY2004.

MN-DoT Office of Investment Management (OIM) Recommended Standard Values for Use in Economic Analysis in FY 2004		
Assumption	Unit	Value
Discount Rate	%	3.5
Auto time value per person hour	$ / hour	10.04
Truck driver time value per person hour	$ / hour	18.61
Auto variable operating costs	$ / mile	0.28
Truck variable operating costs	$ / mile	1.45
MN-DoT Crash Values		
Fatal	$ / crash	3400000
Injury Type A only	$ / crash	270000
Injury Type B only	$ / crash	58000
Injury Type C only	$ / crash	29000
Property Damage only	$ / crash	4200

Assumption		
Description	Unit	Value
delayed time (chemicals/vehicle)	hour	0.04
delayed time (chemicals/FAST)	hour	0.02
delayed time (thermal methods)	hour	0.01
effective snow days	day	10
corrosion and environmental costs (CaCl)	times	5
corrosion and environmental costs (KAc)	times	1

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Abbreviations and acronyms 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