Note: This report contains material relevant to NCHRP Project 20-83(03)A extracted from:

Phase II
Task 6: Prepare Transportation-Area White Paper Visions (Revision 1)

Special Report
to the

National Cooperative Highway Research Program (NCHRP)

on Project NCHRP 20-83(03) Long-Range Strategic Issues Affecting Preservation, Maintenance, and Renewal of Highway Infrastructure

April 2014

Texas A&M Transportation Institute
Texas A&M Research Foundation

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1.0 CHAPTER 1—BACKGROUND

1.1 Introduction

The Texas A&M Transportation Institute (TTI) has prepared this revised Task 6 report in response to the National Cooperative Highway Research Program (NCHRP) Panel's request for a clear and concise description of the work performed in Task 6, and to their comments at the July 11 and 12, 2013, Panel meeting in Austin, Texas. The senior program officer made the request in writing on July 29, 2013, and later emphasized the request on November 25, 2013.

The original Task 6 report focused on Task 6: Prepare Transportation-Area White Paper Visions, which is part of Phase II—Vision Development. The intent of the original report was to present *visions* for future needs in 30 to 50 years for maintaining, preserving, and renewing highway facilities, with a particular emphasis on new materials, tools, approaches, and technologies. The content of the white paper visions were presented at the Panel meeting and were well accepted by the Panel members. This revised report builds upon the original Task 6 report.

In addition to what was presented in the original Task 6 report, this report provides:

- The specific *implications* of the visions developed in Task 6.
- The corresponding *strategies* that state transportation agencies (STAs) might employ in response to these implications.

By including this new information, this report addresses the Panel members' request from the July 2013 meeting to clarify the connection between implications and strategies and to provide specific information on the expected product of the research. The multi-driver scenarios used to create the white paper visions are described in detail in Appendix A, and the original versions of the white papers, developed in Task 6, are included in Appendices B through G. These white papers present visions for the future. Implications extracted from the white paper visions, as well as corresponding strategies, are presented in Chapter 5.

1.2 Review of Phase I Deliverables

The Phase I deliverables form the basis for Phase II vision development. A key deliverable from Phase I is the identification of 18 drivers that influence future scenarios in the 30- to 50-year time frame. The 18 drivers are:

1. Climate change.
2. Economic growth.
3. Priority on environmental quality/public commitment to sustainability.
4. Funding—amount.
5. Funding—proportion private.
6. Government role.
7. Mobility—demand.
8. Mobility—capacity and access.
9. Population density.
10. Resources/energy—supply.
11. Resources/energy—demand.

12. Resources/energy—gas or carbon tax.
13. Resources/energy—price.
14. Road freight.
15. Security.
16. Technology—physical and fixed.
17. Technology—information technology.
18. Transportation choices/complexity.

Another key deliverable of Phase I is the seven scenarios developed based on various combinations of the 18 drivers. The seven scenarios are:

- **Baseline Scenario—Managed Decline:** Continuation of current trends results in a measurably degraded highway system, but agencies and users adapt. Significant increases in fuel prices and reduction in serviceable highway capacity are major themes of the baseline scenario.
- **Back to the Future:** The economy returns to health, and transportation has the technology and resources to grow again.
- **Government Redux:** The government reasserts itself as the primary driver of transportation in the United States and develops the funding resources to do so.
- **Bits over Buses:** A higher than expected increase in crude oil reduces the ability of ordinary people to travel as much as they used to. They turn instead to an expanded Internet, not only for communication but for most work and leisure activities that used to require physical movement.
- **Many Ways to Go:** The government seeks new revenue in gas and carbon taxes, but rather than investing in the existing transportation system, it puts its money into new transport and information technology. This leads to a complex but efficient transportation system that includes significant shares of many different modes.
- **Escape to the Centers:** The lack of mobility and increased threats to their well-being drive people out of the suburbs and into the city, reducing the demand for transportation—this is the vision of the advocates of smart growth.
- **Meltdown:** The pessimistic scenarios for climate change end up being more accurate than the optimistic ones. As a result, the most important priority for the next few decades is struggling with nature rather than growing the economy.

These scenarios represent the future environments in which STAs will operate and provide context for developing six transportation visions in the following areas:

1. Highway traffic services (e.g., signals, intelligent transportation systems, striping, signing, and operations).
2. Highway pavements and materials.
3. Highway construction.
4. Highway bridges and structures.
5. Highway roadside and drainage.
6. Highway connectivity to other transportation modes.

1.3 Overview

In general, this research explores the future potential role of new materials, tools, approaches, and technologies in developing and preserving highway infrastructure. The research will develop guidance in the form of strategies involving new materials, tools, approaches, and technologies that can be used to enhance system preservation, maintenance, and renewal in response to anticipated future challenges. The time period is 2040 to 2060.

The purpose of this report is to:

- Present the results of Task 6.1: Draft White Paper Visions and Task 6.2: Develop Summary-Level Information.
- Respond to Panel members' comments, which is part of Task 6.3: NCHRP Review of White Paper Visions.

Chapter 1 provides background information and includes the following sections:

- Section 1.1 provides a short introduction.
- Section 1.2 reviews the Phase I deliverables.
- Section 1.3 provides an overview of what is covered in this report.
- Section 1.4 provides a summary of the project phases.
- Section 1.5 provides a detailed description of Phase II work, with a focus on Task 6 and the associated subtasks.

Chapter 2 describes the research process used for developing the transportation-area white papers and includes the following sections:

- Section 2.1 provides an overview of the research process for developing the white paper visions included in Appendices B through G.
- Section 2.2 provides an overview of the research process for extracting specific implications from the white paper visions and developing strategies for STAs.

Chapter 3 summarizes the seven multi-driver scenarios developed during Phase I. The full descriptions of the multi-driver scenarios that were included in the original Task 6 report are included in Appendix A.

Chapter 4 provides a summary-level narrative that discusses common themes that manifest in all six transportation areas and the overall implications for STAs.

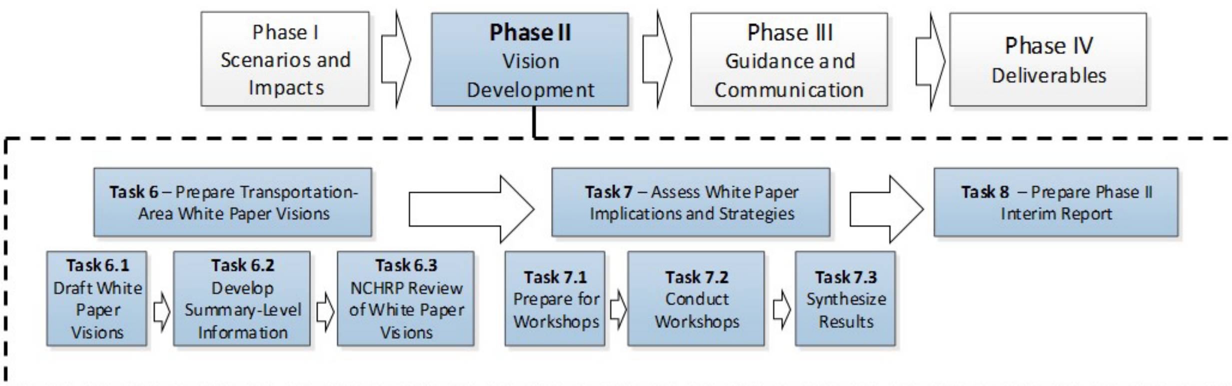
Chapter 5 provides implications extracted from the white paper visions and corresponding strategies in the context of the six transportation areas. The six transportation areas are traffic services, pavements and materials, construction, transportation structures, roadside and drainage, and connectivity.

1.4 Project Phases

The overall project consists of the following four phases:

- **Phase I—Scenarios and Impacts.**
- **Phase II—Vision Development:** This phase:
    - o Identifies and examines the potential of new materials, tools, approaches, and technologies to meet future needs for maintaining, preserving, and renewing the highway infrastructure.
    - o Develops a comprehensive vision for a future, sustainable highway infrastructure. *This report documents the results of Task 6.1: Draft White Paper Visions, Task 6.2: Develop Summary-Level Information, and Task 6.3: NCHRP Review of White Paper Visions within Phase II.*
- **Phase III—Guidance and Communication.**
- **Phase IV—Deliverables.**

Figure 1.1. represents the project phases and project tasks and subtasks covered in this document.



Note: Shaded boxes represent tasks and subtasks in Phase II covered in this report.

Figure 1.1. Project Phases, Tasks, and Subtasks of Phase II.

1.5 Phase II—Vision Development

Accomplishing the Phase II objectives will consist of three tasks (the numbering continues from Phase I):

- **Task 6: Prepare Transportation-Area White Paper Visions:** Subject matter experts create a white paper vision in each of the six transportation areas. Implications and strategies are extracted and summarized from the white paper visions.
- **Task 7: Assess White Paper Implications and Strategies (previously titled "Conduct Focus-Group Workshops"):** A group, consisting of government, industry stakeholders, and academics representing each transportation area, will assess implications and strategies at a workshop.
- **Task 8: Prepare Phase II Interim Report:** The report will document the outcomes of the research to include further development of strategies identified for each transportation area, the workshop analysis of those strategies, and barriers and challenges for STA stakeholders to implement these strategies.

Each task will focus on the potential for new materials, tools, approaches, and technologies to meet the future needs for both professionals and management leaders. Although the main focus of this report is on Task 6, Tasks 7 and 8 are discussed briefly as well.

1.5.1 Task 6: Prepare Transportation-Area White Paper Visions

The objective of Task 6 is to develop a white paper vision for each of the six transportation areas that reflect the future needs (30 to 50 years) as related to maintenance, preservation, and renewal of highway infrastructure.

To guide the development of the white paper visions, the research team used the data collection protocol developed in Phase I as well as the revised updated work plan. The development of the multi-driver scenarios, the future operating context for the highway industry, was also developed in Phase I. Multi-driver scenarios were essential for constructing a white paper vision around the six transportation areas for a 30- to 50-year future time period.

Task 6 has the following subtasks:

- Task 6.1: Draft White Paper Visions.
- Task 6.2: Develop Summary-Level Information.
- Task 6.3: NCHRP Review of White Paper Visions.

Task 6.1: Draft White Paper Visions

This subtask involves drafting of the white paper visions for the six transportation areas.

The development of the draft white paper vision for each of the six transportation areas was accomplished through three meetings held in the months of October, November, and December 2012. A final team meeting was held in late February 2013. All meetings were facilitated by Peter Bishop, the research team's expert in future forecasting, and were attended by the transportation-area leads. Other attendees included members of each transportation area involved in drafting the white paper vision, as well as the team's consultants, John Conrad and Kevin Thompson. The initial draft of each white paper vision was circulated for an internal review. The review included other experts within TTI in the respective transportation areas and the team's consultants. Authors made improvements based on suggestions by reviewers.

Task 6.2: Develop Summary-Level Information

This subtask involves developing key details within the six transportation areas.

The development of the summary-level information involved identifying common drivers, themes, implications, and strategies for STAs that manifested in all six transportation areas. Short descriptions of seven multi-driver context scenarios are provided in Chapter 3, and common themes among these six scenarios are provided in Chapter 4. Implications and strategies for each transportation area are provided in Chapter 5.

The purpose of this subtask is to provide concise material for the workshop participants so that they can understand the overall picture of the future of transportation from the research team's perspective. This will also aid in setting a context for each individual workshop based on the individual transportation-area white paper visions.

Task 6.3: NCHRP Review of White Paper Visions

This subtask involves review by the Panel members.

The research team submitted the draft white paper visions through the original Task 6 report dated May 2013. In July 2013, NCHRP and the TTI research team met to discuss the Task 6 report and the work planned for the remainder of Phase II. As part of this meeting, the team also showed two examples (one for pavement and materials, and one for construction) of taking implications to strategies and then to guidance. The contents of the white paper visions were well accepted. At the July 2013 meeting, the Panel specifically requested a description of the approach to extracting implications and developing strategies for all of the transportation areas.

After receiving NCHRP's comments through the review process and meeting, the research team incorporated relevant comments into this revised report as appropriate. The research team conducted several face-to-face meetings to discuss the plan for extracting implications from white paper visions presented at the meeting and to develop specific strategies for each implication. A detailed explanation of this process is presented in Chapter 2. The research team also discussed workshop plans and development of the workshop materials, which are presented in Chapter 6.

2.0 CHAPTER 2—RESEARCH PROCESS

This chapter presents the overall research process for developing the white paper visions and extracting implications and strategies from them. The overall research process is shown in Figure 2.1. The activities shown in this figure were performed before the July Panel meeting.

A detailed explanation of the method used for developing the white paper visions is included in Section 2.1. The steps for extracting implications and developing corresponding strategies are explained in Section 2.2.

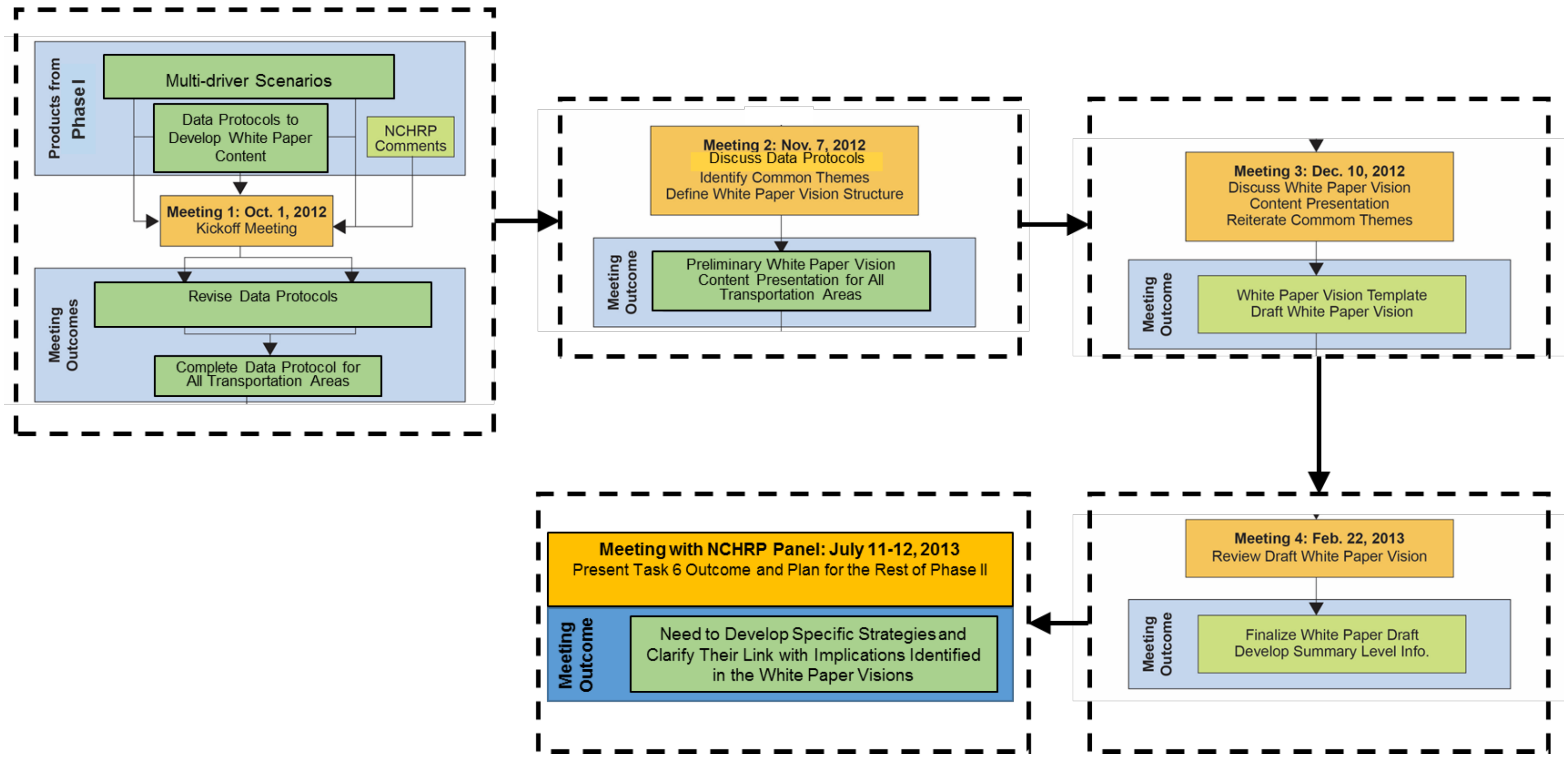


Figure 2.1. Research Process.

2.1 Methodology for Developing White Paper Visions

The purpose of developing the white paper visions for each of the six transportation areas was to reflect the future needs (30 to 50 years) as related to maintenance, preservation, and renewal of highway infrastructure. The white papers are included in Appendices B through G.

The methodology used to develop the original white paper visions reflects a collaborative research team approach. This approach used both the entire research team gathered at meetings and individuals working in smaller groups aligned with each transportation area to develop and discuss content for the white papers. The entire team met four times to work together on developing the structure, layout, and content of the white paper visions and summary-level information.

The research product of Phase I included the development of 21 key drivers (further reduced to 18 final drivers), the baseline scenario (expected future), and six multi-driver scenario narratives applicable to 13 technical areas (technology and innovations, environment, system performance, security, natural resources availability, finance and budget, human resources, coordination, regulations and policies, demographics, customer needs and expectations, traffic, and safety) as identified in the Request for Proposal (RFP). The drivers are forces that influence the future; they are pertinent characteristics of our world that help us determine the direction in which we are headed. The baseline scenario (expected future) is the most likely multi-driver scenario to occur compared to any of the others; the expected future focuses on an assessment of the trend and rate for the key drivers. Multi-driver scenarios are hypothetical sequences of events created by multiple key drivers. The outputs of the Phase I effort, including the NCHRP feedback on the Phase I effort, became the inputs to the Phase II work.

To initiate the work in Phase II, a data collection protocol was developed using the 18 final drivers and six multi-driver scenarios in a table format as part of Task 5 of Phase I. The protocol was outlined in the revised work plan and in the original Task 6 report. The protocol used for developing the white paper visions is fully explained in the original Task 6 report and was also presented at the NCHRP Panel meeting in July 2013.

The protocol was comprised of two tables, each designed to capture the information required to develop the white paper visions by answering a structured set of questions. The questions assess the validity of the futures developed and the implications of those futures in the form of obstacles, opportunities, and strategies for developing a sustainable highway infrastructure in the future. The two tables of the protocol are as follows:

- Table 1 addresses 18 single drivers. The intention of Table 1 is to estimate the impact on the specific transportation area based on at least three of the 18 drivers that will substantially shape the future.
- Table 2 addresses six multi-driver scenarios. The intention of Table 2 is to estimate the impacts on the specific transportation area that result from the multi-driver scenarios.

Table 2.1 summarizes the questions included in the data collection protocol for these two tables.

Table 2.1. Summary of the Data Collection Protocol Tables.

Question	Table 1 (Expected Future Drivers)	Table 2 (Six Scenarios)
A	Which drivers will probably affect the transportation area the most?	To what degree is each scenario plausible, and were it to occur, how strong would its impact be?
B	What effects could these drivers have on the transportation area? Will they affect the facility capital investment phases or the facility operational phases or both?	In what ways does each scenario affect this transportation area? Will the scenarios affect the facility capital investment phases or the facility operational phases or both?
C	Which of these effects are obstacles that would make it harder to achieve a sustainable highway infrastructure in the future? Which effects are opportunities that make it easier?	Which of these effects are obstacles that would make it harder to achieve a sustainable highway infrastructure in the future? Which effects are opportunities that would make it easier?
D	What strategies in materials, tools, approaches, and technologies should STAs and other organizations pursue to mitigate the obstacles and capitalize on the opportunities in the baseline future?	What strategies in materials, tools, approaches, and technologies should STAs and other organizations pursue to mitigate the obstacles and capitalize on the opportunities in the other scenarios?
E	What are the obstacles, opportunities, and strategies if the most important drivers turn out differently than expected?	(No question given.)

Note: Capital phases are planning, scoping, design, and construction. Operational phases are maintenance, preservation, and renewal.

Each transportation area lead completed the data collection protocol. The completed protocols were used to facilitate the development of the white paper visions. The completed white paper visions for all six transportation areas were used to develop summary-level information that discusses common implications for STAs identified throughout the six transportation areas.

Data collection protocols were completed, revised, and synthesized in stages over a period of 2.5 months. This approach was necessary to share information and critique the work of the transportation area leads. The methodology to develop the white papers included a series of team discussions, including four separate team meetings.

The first meeting was held on October 1, 2012. The objectives of the meeting were to:

- Review project status.
- Review the revised work plan.
- Discuss how to address panel comments (regarding the revised work plan).
- Discuss activities specific to Task 6.
- Review and discuss the use of the data collection protocol (tables covering drivers and scenarios) as a framework for developing the white paper visions.

The next meeting was held on November 7, 2012. The objectives of the meeting were to:

- Discuss the approach used by the leaders of each transportation area in completing the data collection protocol.
- Identify common themes between transportation areas.
- Develop a preliminary structure for the white paper visions.

Many of the transportation areas had considerable similarities and interdependencies in regards to impacts and strategies. These shared motifs or common themes across all six transportation areas were captured during the meeting as each transportation area presented its responses to the data collection protocol.

Discovering common themes is the basis for much of social science research. The research team used qualitative analysis to induce themes from the texts and presentations. The observation techniques adopted to do this were repetitions, similarities and differences, linguistic connectors, and missing data. The research team identified similar concepts, topics, or ideas that occurred and reoccurred in many of the transportation areas. The team also adopted the constant comparison method, which meant searching for similarities and differences across the six transportation areas. Another approach was to search for words that indicated causal relationships such as "because," "since," "hence," and "as a result." Words such as "if" and "then" indicated conditional relationships, and time-oriented relationship expressions such as "before," "after," and "then" were also identified to help identify common themes.

Before developing the draft white papers, the research team met on December 10, 2012. The transportation-area leads were charged with preparing a summary presentation with highlights of their data collection protocol. The objectives for the presentations were to:

- Review and confirm the common themes between transportation areas.
- Review and finalize the white paper structure.

The initial white paper drafts were distributed and cross-checked among the core research team members during December 2012 and January 2013. The review resulted in identifying missing and/or overlapping information to improve the quality and consistency among the six transportation areas. Each transportation-area lead enhanced the paper based on the internal review. The second drafts of the white papers were then distributed to the team's two outside consultants, who had extensive experience working with STAs. The consultants provided feedback with emphasis on future implications for STAs.

Finally, a team review of the white papers was held on February 22, 2013, to effectively and collaboratively integrate the various comments received from the reviews. This was also an opportunity to conduct a final gap analysis. The meeting addressed the following topics:

- Review white papers for consistency (both drivers and scenarios).
- Identify common themes as a group.
- Review transportation-area implications for STAs.
- Brainstorm common themes around implications for STAs.
- Discuss the writing style and use of graphics.

The team decided that the descriptions of scenarios within each transportation area could be unique and preferred an assortment of potential effects. Thus, rather than unifying the descriptions of potential effects among all the transportation areas within the same multi-driver scenario, the team decided the solution was to provide highlights of potential effects that are unique and meaningful in a given scenario for all of the applicable transportation areas.

For example, in the Back to the Future scenario, the pavements and materials area indicated a potential for less innovation and technology because the industry does not feel the need to implement new technology when the economy is doing well. The reasoning behind this thought was that slow adaptation to technology has been the trend in this area for more than 50 years. On the other hand, the transportation structures and construction areas indicated high development and implementation of technology, leading to sophisticated tools and approaches. Both of these explanations were considered to have merit and were highlighted as potential effects to stir a stimulating discussion at the workshop. Therefore, the team decided to proceed with what each paper proposed as potential effects. The conclusions from the draft white papers will be further validated by the collective judgment of a larger scientific and industry community as the project proceeds to Task 7.

Identification of common themes and implications for all six transportation areas also led to finalizing the development of high-level summary information.

A meeting with NCHRP was held at TTI in Austin on July 11 and 12, 2013. All findings were presented at the Panel meeting. As part of the discussion, the research team provided illustrations of how strategies associated with implications identified in the white paper visions would be developed. Illustrations of strategy development from the white paper vision implications were developed for the pavement and materials area and the construction area. Two weeks after the Panel meeting, the project team received comments from the senior program officer. Comments covered presentation of the completed work and a request for developing strategies and clarifying the link between the strategies and implications. The methodology for extracting implications from the white paper visions and developing strategies is presented next.

2.2 Methodology to Extract Implications and Develop Strategies from White Paper Visions

As stated previously, in addition to what was presented in the original Task 6 report, this report provides the specific implications of the visions developed in Task 6 and lists corresponding strategies that STAs might employ in response to those implications. The overall research process for extracting the implications and developing the strategies from the visions is represented in Figure 2.2. Activities shown in Figure 2.2 were performed after the July Panel meeting.

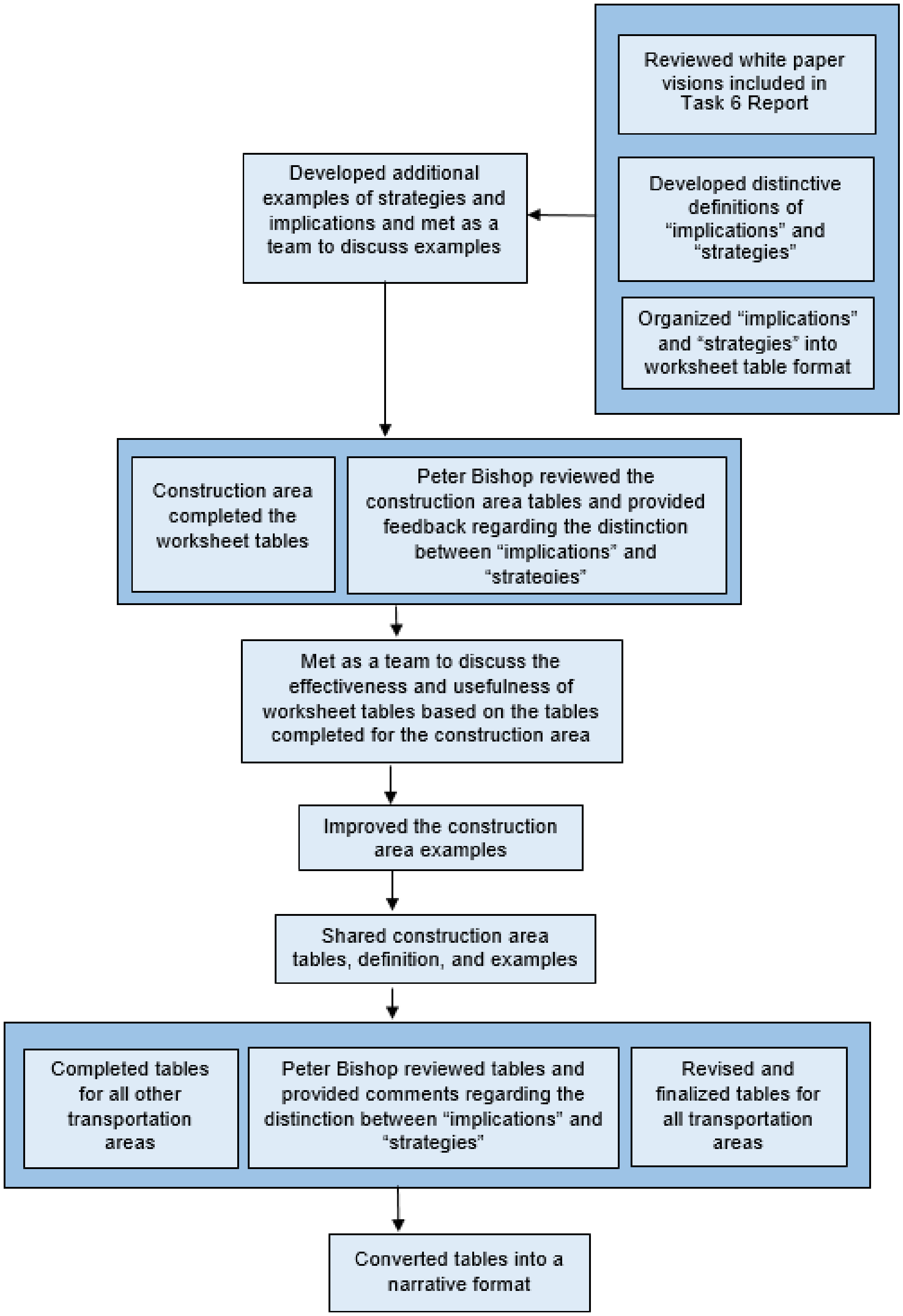


Figure 2.2. The Detailed Methodology to Extract Implications from the White Paper Visions and Develop Corresponding Strategies.

In response to the comments received from the Panel on the Task 6 report and presentation, the project team reexamined the original white paper visions. The Panel advised using specific strategies from the transportation white papers as the basis for the workshop assessment process.

Strategies are elements that will eventually become the guidance for STAs, and the research team agreed to further develop and refine a full set of draft strategies by transportation area.

To strengthen the connection between the drivers, implications, and strategies associated with each scenario—and, more importantly, to clarify the distinction between implications and strategies—the team developed a worksheet table after an intensive review of the six transportation-area white paper visions. The intent of the tables was to provide a systematic process to address and incorporate Panel comments. Tables went through a couple of iterations prior to finalizing the format. The final worksheet included:

- Definition of key terms.
- A baseline scenario table: Managed Decline scenario.
- A table for one scenario from the high-resource scenario group.
- A table for one scenario from the low-demand scenario group.
- The Meltdown scenario.

Each table included three columns:

- Key drivers as identified in the multi-driver scenarios (see the Phase I report dated January 20, 2012, and the Task 6 report dated April 2013).
- Implications as extracted from the original white papers and from Panel comments (if any).
- Strategies as extracted from the original white papers and from additional resources (if any).

These tables assisted in restructuring the revised Task 6 report to contain more detail while maintaining consistency across the transportation areas. For example, implications were defined as inbound changes (changes that are outside the STAs' control), and strategies were defined as outbound changes (any activities or actions STAs would employ to either offset or take advantage of what is occurring in their environment). The research team developed and thoroughly discussed several examples of implications and strategies. Initially, the team developed the worksheet tables to assess the value and benefits of completing the worksheet prior to finalizing the content. Table 2.2 shows a partial table with definitions and examples from the construction transportation area. The team found that the worksheet tables were useful in the following ways:

- Visually allowed a quick scan of key drivers and associated implications and strategies in a condensed format.
- Facilitated identifying any weak connections between the scenarios and the associated implications and strategies. In turn, team members had the opportunity to research and include missing strategies or include additional strategies that had direct associations with the identified implications.
- Provided an opportunity to incorporate Panel comments.
- Permitted quick cross-comparison between the different scenarios.
- Subsequently, revealed (and was able to verify) the common threads of implications between the different scenarios.

- Helped identify and extract high-level implications and strategies that cut across the six transportation areas.

Table 2.2 Partial Worksheet Table with Definitions and Examples

Meltdown scenario (all of the transportation areas completed the worksheet table for this scenario)

Key Driver: Specific to the selected scenario, Meltdown in this example	**Implications**: Specific to the selected scenario or for the transportation area, and are outside the STAs' control	**Strategies**: Specific or as it relates to the selected transportation area, in this case, the construction transportation area
Population density: Drivers were identified in Phase I of this project. This should be identical for all of the transportation areas since these are context scenarios.	*More severe weather*: specific to the selected scenario *Faster deterioration of existing highway infrastructure*: for the transportation area	*Provide reliable communication equipment and emergency response procedures and training for personnel. To make rapid response possible in emergency situations, adopt new contracting regulations that provide flexibility in emergency situations*: to prepare for efficient post-disaster rehabilitation and recovery due to more severe weather *Invest in developing and using advanced damage assessment models for assessing the resilience of existing structures and identifying required maintenance*: to offset faster deterioration of existing highway infrastructure

Obtain from Phase I

Reassess white papers, incorporate Panel comments, and include additional resources

Using the construction area as an illustration, individuals responsible for other transportation areas used examples and definitions discussed in team meetings to complete the worksheet tables. The future forecasting expert, Peter Bishop, then reviewed these transportation-area tables of implications and strategies to make sure the distinction between the implications and their corresponding strategies was clear. Individuals responsible for each area revised the tables in response to comments and feedbacks they received, and then they converted their tables into the narrative format presented in Chapter 5.

In addition to developing strategies, the research team also discussed and finalized details about the potential deliverables. As seen in Figure 2.3, the team determined that scenarios describe and characterize the possible environment that STAs will face in the future. Based on the environment, STAs will need different strategies. Detailed strategies will emerge from individual transportation areas mainly for professionals. For the executive management level, strategies are combined and extracted at a higher level with common threads for implications.

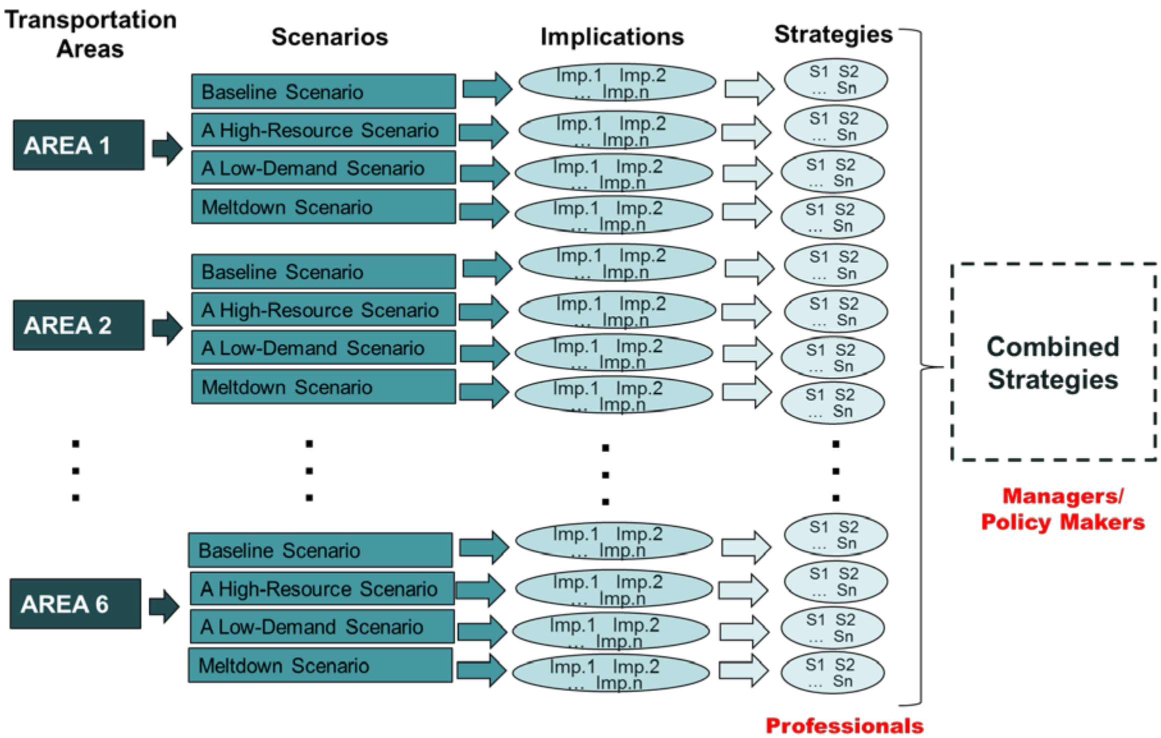


Figure 2.3. Strategies for Professionals and Managers.

Common threads of implications from the six transportation areas were previously developed by assessing the original six white paper visions, and were presented at the July 11 and 12, 2013, Panel meeting. Figure 2.4 shows the common threads running through the implications for the six transportation areas. The common threads include:

- Funding.
- Workforce training.
- Sustainability.
- Organizational policy.
- Improvements in methods.

The guidance developed in this project will provide insight into issues or opportunities to carry out these strategies for both professionals and management leaders, with management leaders strategies developed around the common threads of implications listed above:

- **Management/policy makers:** The management level will focus on the development of comprehensive strategies aimed at those individuals within agencies that make critical decisions regarding the organizational approach and operations of the agency.
- **Professionals:** Strategies will also be developed for each of the six transportation areas with a focus on transportation professionals, that is, those staff mostly closely related to performing operations specific to a transportation area, such as pavement engineers, bridge engineers, etc.

Technical Area	Implication 1	Implication 2	Implication 3
Traffic Services	Funding Allocation to Operations	Privatization	Workforce Training
Pavements and Materials	Sustainability	Efficient Construction, Automated QC/QA, and Intelligent Construction	Workforce Training
Construction	Sustainability	Innovative Financing	Workforce Training
Transportation Structures	Moderate Mechanization	Accelerated Construction	PPP Emphasis
Roadside and Drainage	Sustainable Practices	Workforce Training	-
Connectivity	Alternative Funding	Future Organizational Structures	Workforce Training

Note: QC/QA = quality control/quality assurance; PPP = public-private partnership.

Figure 2.4. Common Threads of Implications for the Six Transportation Areas.

3.0 CHAPTER 3—MULTI-DRIVER CONTEXT SCENARIOS

This chapter gives a condensed description of the multi-driver scenarios. The narratives for the multi-driver scenarios are revised to be presented in a clear and concise manner and to aid readers in better imagining the expected future. Providing a clear *description* of the scenarios was critical since these scenarios became the basis for developing the implications and strategies in each of the six transportation areas. In other words, these scenarios provide a *future context* for the transportation-area visions.

Thus, readers should review this chapter and make efforts to envision the various future settings proposed in this study before reading Chapter 5. This will aid readers in comprehending the implications and strategies presented there.

The expanded descriptions of the multi-driver scenarios are included in Appendix A. In general, the scenarios are vehicles used to depict plausible long-term futures in a vivid and engaging manner. They are not intended to be single-point predictions. A scenario's portrait of the future may or may not actually occur, but that is not the point. Rather, the scenario contains and communicates the long-term implications of major trends and plans going on today, with a number of key assumptions and uncertainties that are currently unresolved and that would create substantially different futures depending on how they are resolved.

Scenarios may be presented as simple analytical descriptions of these futures. More often, however, they are presented in other forms such as stories, historical descriptions or future histories, illustrations, and videos to communicate the *feel* of that future rather than just its intellectual content. The purpose is to make the future real, that is, for the target audience to realize that this scenario is one of their possible futures and that they might actually live and work in that future. And then, of course, they can think about what they should be doing today to prepare—not for *the* future but for one of many plausible futures. The multi-driver scenarios in this study are:

- The baseline scenario—Managed Decline.
- Back to the Future.
- Government Redux.
- Bits over Buses.
- Many Ways to Go.
- Escape to the Centers.
- Meltdown.

The multi-driver scenarios were created based on the trend and rate of change using drivers identified during Phase I. The baseline scenario covers all drivers and represents the expected future, or the scenario most likely to occur compared to any other scenarios. The baseline future is not probable in the strict mathematical sense, that is, a more than 50 percent probability of occurrence. It is simply more likely than any of the other individual scenarios, but it is not more likely than all the other scenarios combined.

The other multi-driver scenarios listed above were created based on the clusters of drivers that emerged from the factor analysis of the cross-impact matrix. The six scenarios are described using historical descriptions or future histories. Future histories are retrospective accounts of how the future has developed. They are written in past tense, looking back to the future so they can be a retrospective report or news feature that describes how the future has developed up to that point; these scenarios also do not follow a technical writing style. Thus, they provide a broad context in which to view the future. Each scenario incorporates a short section that provides insights into the potential implications of the scenario on the future of transportation. The seven integrated scenarios, involving a number of drivers, will serve as a platform to frame and illuminate plausible long-term futures for the six transportation areas and the focus groups in Phase II.

The following sections provide a summarized description of the multi-driver scenarios. The full descriptions are in Appendix A.

3.1 Baseline Scenario—Managed Decline

Table 3.1 shows the key elements for this scenario.

Table 3.1. Key Scenario Elements for Managed Decline.

Scenario	Key Drivers	Scenario Kernel
Managed Decline	All 18 Drivers	

The petroleum age was waning in the 2020s but ever so slowly. The price of gasoline was volatile, but overall it had increased significantly in the last 30 years, just as it had in the previous 30. New supplies, much of it in the United States, kept the prices manageable, but they could not prevent the inevitable. Fuel cost was taking a larger share of the family budget. The result was that voters supported more aggressive fuel standards, both at the voting booth and at the car dealership. That hit the gas tax right away.

The second result was that people simple drove less—combining trips, carpooling, running errands on the way home from work, using more public transit, and taking fewer automobile vacations and trips to the beach. People now stopped to think whether the trip was worth it. Previously, they had just jumped in the car and driven off.

Going to work was still the major use of personal vehicles, but now people went to work less. Slowly they negotiated flex hours along with the ability to work at home. And eventually, even the form of the urban space changed—higher density, not only in the central core but surrounding the satellite business centers. More condos, more apartments, and smaller lots amid retail meant that the mega shopping malls had disappeared. Walking was in; driving was out. People no longer expected to be able to “go anywhere, anytime” the way their parents and grandparents had done.

Total vehicle miles traveled (VMT) was still going up, though quite slowly, due to larger populations and more economic activity, but VMT per capita was decidedly down. That meant that the gas tax, barely higher from its 1990s level due to a tax-averse government, was bringing in only about two-thirds of what it had been at its peak. Added to that decline was the surprising strength of natural gas and electric vehicles, which further cut into the consumption of gasoline and its associated tax. Governments instituted taxes for these fuels at the service station, but many people were fueling at home, making the collection difficult. Many states had proposed a surtax on excessive use of gas and electricity at home, but every agency from transportation to public safety to environmental quality to energy regulation was fighting for a piece of that pie.

So the amount of revenue generated from gasoline and natural gas taxes had to cover the maintenance and preservation of an aging system, even though the cost of materials and construction had increased at more than the rate of inflation. And forget about expansion! The private sector toyed with the idea of stepping in, but that made little business sense since the projects were so huge and expensive and the expectation of return on investment was declining.

Technology had done its part to mitigate the difficulties. New materials and better practices, particularly clever information technology (IT) systems, made the roads marginally safer, less congested, and a little less expensive than they would have been otherwise. But highway construction and maintenance were mature technologies, even 30 years ago, so few real breakthroughs had appeared. Fewer research and development labs were turning out fewer innovations in a downward spiral of less opportunity and less funding.

The result was a highway system that had reached the end of its design life. There was no money to fix it, much less to expand it.

3.2 Back to the Future

Table 3.2 shows the key elements for this scenario.

Table 3.2. Key Scenario Elements for Back to the Future.

Scenario	Key Drivers	Scenario Kernel
Back to the Future	High economic growth High transport use High resource use High technology development	The economy returns to health, and transportation has the technology and resources to grow again.

3.2.1 An Economic Trigger

The Great Recession of 2007–2008 was fueled by debt rather than by sustainable growth, which inevitably led to bubbles and busts.

Then a giant rethinking began. The health of the economy was always measured in gross domestic product growth. The more money, the more goods and services purchased, the higher the standard of living and the presumed increase in happiness and well-being. But what was originally “You can never be too rich” soon became “Enough is enough.” People and even businesses were sick and tired of the boom and bust cycle. While the booms were fun, the busts were not.

People finally realized that they were not that much better off at the end of the cycle than they were at the beginning. What is more, the aging Baby Boomers wanted more steady and predictable growth as well, so they got their representatives to put a second mandate on the

Federal Reserve—to control growth and reduce risk. Just as the inflation of the 1970s forced the Federal Reserve to keep inflation in check, now they had two missions. They also had to keep growth in check. But what heresy! Everyone agreed that inflation beyond a low level was bad, but everyone also agreed that too much growth was bad. Now sustainable growth, somewhere around 2.5 percent per year, was the new target—not less but also not much more.

So after 20 years, with nary a recession in sight, the economy was booming. “Enough is enough” now meant just enough growth to keep the economy improving, but not so much that it got out of hand.

3.2.2 A Technological Trigger

People said it was like the beginning of the industrial revolution all over again. Of course, that was an exaggeration, but it felt pretty good anyway. A convergence of technologies in the 2010s and 2020s had cured most of the ills that the economy had suffered in the first decade. Rarely do technological breakthroughs live up to their promise, but these did.

First of all, nanotechnology had far outstripped even its most optimistic advocates, revolutionizing water desalination, heat reflective coatings, lighter and stronger metals, and ultra-high-storage batteries.

Biotechnology, another micro-technology, has begun to actually lower the cost of health care by keeping people healthier longer and treating them more effectively when they do get sick.

Japan led the world in the application of robotics to almost every physical task.

IT still had a lot to offer through ubiquitous sensor networks, voice recognition, natural language processing, huge databases, and apparently intelligent responses and actions to most queries or commands.

And, finally, the new miniature technologies had reduced society’s demands on the environment, but it had not eliminated the threat of resource scarcity or climate change.

3.2.3 A Cultural Trigger

“Nothing succeeds like failure,” and the Millennials had plenty of that. Their Baby Boom parents and grandparents had left the world in quite a mess—high unemployment, high education debt, unsustainable government deficits, increasing global temperatures, and apparently no way to succeed on a regular basis. The American Dream had become the American Nightmare. The Baby Boom invented the Me Generation in the 1980s and pushed it as hard as they could until they retired and eventually died in the second quarter of the century. But just as the Depression and WWII generation (called the Greatest Generation in a popular book in the 1990s) had laid the foundation for American prosperity in the second half of the 20th century, so the Millennials and their descendants began fixing the problems in the first third of the 21st. They first realized that while many had been brought up in relative security and prosperity, long-term security and prosperity had to be earned, not assumed. Entitlements were out; hard work was the new black. You get what you produce in this world, not just what you want. Secondly, they balanced individual interests with community interests. They resurrected long-dormant values of service, responsibility, and sacrifice. They took care of each other as they took care of themselves. “Do unto others" was popular again, an astounding revival from the days of Gordon Gekko when greed was good. In fact, greed had become unfashionable and mildly distasteful to most. Along with a healthy dose of creativity and ingenuity, the United States was again the leading economy in the world—and this time, not only in services like finance and entertainment, but also in technology and manufacturing around the world. They had experienced the searing pain of the first two decades of their century just as their great-grandparents had in theirs, and they turned out much better for it.

3.3 Government Redux

Table 3.3 shows the key elements for this scenario.

Table 3.3. Key Scenario Elements for Government Redux.

Scenario	Key Drivers	Scenario Kernel
Government Redux	High transport funding through new taxes More highway technology	The government reasserts itself as the primary driver of transportation in the United States and develops the funding resources to do so.

Few things mimic a pendulum more than the public mood. Having discovered the magic of fossil fuel, division of labor, and return on capital investment, societies endowed merchants with extraordinary power and scope. First in the British Isles and the European Continent, then in the British colonies and Japan, and now operating throughout the world, the "captains of industry" pushed their advantage to the hilt. Capitalism is about capital. "Them that has gets." The rich get richer, and the poor get welfare. In the United States, the 1890s and 2000s were the Gilded Ages when the trusts and the 1 percent, controlled by a few ultra-wealthy individuals, ran the country.

But the pendulum started swinging back after the second "great recession" in 15 years. A full-scale reformist movement arose from splinter groups like the Tea Party, Occupy Wall Street, and a host of other popular uprisings. People were angry, and when angry enough, they usually get what they want.

The electoral system had been hijacked by the two political parties so that almost all legislative representatives ran in "safe" districts. That meant that winning the primary was tantamount to winning the election, and winning the primary required securing the support of the base, the most extreme members of the party. The first reform then was to mandate that districts be drawn by expert panels rather than state legislators.

The system of governance had also been hijacked by special interests who stormed Congress with the relentless pursuit of their goals. The reform in this case was twofold: eliminating private money from elections through public funding, and limiting the time for campaigning to four months before an election. The result was that the influence of special interests was severely reduced, and legal representatives had more time to actually govern since they were not running for office and raising money all the time.

A final reform was a constitutional amendment to balance the budget. The Second Great Recession (the Sovereign Debt Recession) was the result of government guaranteeing the bad debts of the banks and financial institutions in 2007 and 2008 without having the resources do so. The reform in this case was restricting government spending to a fixed percent of the national economy, except during times of war, over a five-year period; and requiring a surplus in two of those five years.

The result was some restrictions on some freedoms, such as redistricting, lobbying, and spending, but the benefit was a democracy that elected the right people and gave them the time, incentive, and means to see to the country's needs to the best of their ability.

3.4 Bits over Buses

Table 3.4 shows the key elements for this scenario.

Table 3.4. Key Scenario Elements for Bits over Buses.

Scenario	Key Drivers	Scenario Kernel
Bits over Buses	Private funding Government role centralized High gas prices High IT	A higher than expected increase in crude oil prices reduces the ability of ordinary people to travel as much as they used to. They turn instead to an expanded Internet, not only for communication but for most work and leisure activities that used to require physical movement.

Peak oil production had been discussed for decades, and now it was here. We were not running out of oil exactly, but we were running low on the cheap, easy stuff. And then the Mideast war of 2018, in which Iran attacked Saudi oil facilities and the Saudis responded in kind, caused the price of oil to jump to more than $400 a barrel. The sudden jump reminded people of the 1970s—rationing, price controls, long lines, and, most of all, the inability to drive anywhere you wanted because the price was simply too high. Wrenching the automobile from the fabric of American life was not just difficult; it was disastrous.

So they jumped on the Internet. The Internet had already transformed every institution in society, even schools, but it had been used along with physical mobility, not instead of it. Now it really had to perform.

The first and easiest fix was for people to work from home rather than in the office. But not everyone had participated in the knowledge economy before the shock, and not everyone would do so afterward. But what would they do in a society without easy access to transportation? The answer was staring them right in the face. Manual work still needed to be done—building, painting, fixing, and maintaining. The difference was that a few people in the neighborhood were good at that, so they became local contractors to the stay-at-home workforce. It wasn't a prosperous life, but it did earn the fixers, as they were called, a certain local respect because their skills improved as time went on. And they didn't have to travel to get to work.

Another big adjustment was commerce and trade. The cost of transportation in the Oil Era was a single digit percent of the total cost of goods to the consumer, but that ratio was now upside down. Buying local had been a mantra of the progressive class for a long time. Now business had to take up the refrain. Very low-volume manufacturing based on new materials and 3D printing helped, as did low-maintenance crops from the biotech sector.

After a while and with great reluctance, people's enhanced capabilities and skills with remote communication changed personal relations as well. Families living across the country, initially separated by high gas prices, eventually moved closer together. You could work just as easily from Cleveland as from the suburbs. Parents were home with their children; neighbors became friends (and enemies!) again; folks used the new tools and sites for entertainment and even virtual travel. It was the rural village all over again, but this time connected to the world.

3.5 Many Ways to Go

Table 3.5 shows the key elements for this scenario.

Table 3.5. Key Scenario Elements for Many Ways to Go.

Scenario	Key Drivers	Scenario Kernel
Many Ways to Go	Economic growth Funding amount Private funding Centralized government role Gas/carbon taxes High technology development Multimodal approaches	The government seeks new revenue in gas and carbon taxes, but rather than investing in the existing transportation system, it puts its money into new transport and IT. This leads to a complex but efficient transportation system that includes significant shares of many different modes.

The Oil Era and the Automobile Era were over, for the time being at least, until a new transportation alternative could be found. Would it be the electric-, biofuel-, or fuel-cell-powered car that could use the existing road system? Or perhaps no cars at all, using the Internet as the "highway of the future"? At least, the steep carbon tax made one of those much more likely before a return to the internal combustion engine, if ever.

The decision depended on the need for humans to have face-to-face interaction. The high-tech enthusiasts said that virtual interaction was just as good as face to face once you got the hang of it. Others disagreed. Social scientists arrayed themselves on all sides of the question. Concerns included:

- People would get claustrophobic with such a small circle of face-to-face contacts.
- Instead of being a boon, parents at home with their children all day might actually narrow or even stifle their interpersonal growth.
- Neighbors who had enough face-to-face contact at work could easily avoid each other at home, but now they would crave the contact, even if it led to more neighborly conflict.
- The looser ties between employer and employee, between manager and worker, would lead to listlessness, lack of loyalty, and a churning labor force.

Nevertheless, business and government went ahead. Funds from investment, taxes, and fees have been budgeted. A world-class transit system was planned and built. Now it's time to see if the system actually works.

3.6 Escape to the Centers

Table 3.6 shows the key elements for this scenario.

Table 3.6. Key Scenario Elements for Escape to the Center.

Scenario	Key Drivers	Scenario Kernel
Escape to the Center	High population density Low mobility capacity Low security	The lack of mobility and increased threats to their well-being drive people out of the suburbs and into the city, reducing the demand for transportation—the arrival of the vision of the advocates of smart growth.

The end of the Automobile Era was difficult, but it provided lots of options for policy makers and the public alike. One of the most serious questions was the form of the metro environment after the automobile. No one disputed the fact that the automobile had done more to shape the form of the country's metropolitan areas in the 20th century than anything else.

So would that density continue with the automobile much less useful than it was before? Now we know the answer, and the advocates of what used to be called "smart growth" are cheering now that their dream might actually become a reality. Denser city living was a tough sell in the first quarter of the century when the automobile was still viable, particularly for families with children and for aging Boomers who wanted to be close to social services and cultural hubs. Now it might be thrust on a reluctant population by necessity.

At the same time, the advocates of smart growth should not celebrate too soon. Just because people have to live closer to work does not mean that that work has to be in the central city. Rather than an overall increase in population density, businesses can move to the suburbs where the people already are, rather than staying in the city. Suburban complexes are already quite common, such as Silicon Valley in California, Route 128 in Boston, or the Energy Corridor in Houston. People will still have to move to be closer to these relocated businesses. They can't live anywhere because they won't have the transportation they used to have to get to work. But they might move from one suburb to another, leaving the central city even less populated than it was. That form would be islands of density in an overall less dense metro area, much like Northern Virginia where business clusters around the metro stops.

However, it turns out that the automobile built the post-war city, and it has a big effect when it can no longer sustain that form. Nothing this substantial changes overnight, and remnants of the past remain, but the city of 2050 has a much denser feel than was true during the previous 100 years.

3.7 Meltdown

Table 3.7 shows the key elements for this scenario.

Table 3.7. Key Scenario Elements for Meltdown.

Scenario	Key Drivers	Scenario Kernel
Meltdown	Climate change Environmental quality/sustainability Gas/carbon tax Government role Population density	The pessimistic scenarios for climate change ended up being more accurate than the optimistic ones. As a result, the most important priority for the next few decades was struggling with nature rather than growing the economy.

The debate over climate change is over. Abrupt climate change, a term coined in 2005, was now the new reality. The atmosphere contained a number of reinforcing feedback loops that, once started, had run out of control. The most obvious was the methane locked into the permafrost of the Arctic. Once the permafrost started to melt, it released methane into the atmosphere, which in turn increased the temperature and melted more permafrost, which released more methane, etc. The cycle was a runaway by 2025. Greenland ice and glaciers all over the world were melting at an increasing rate, and the breakup of the Ross Ice Shelf in Antarctica added meters to the sea level, inundating low-lying areas around the country and around the world. The East and Gulf Coasts were hit the hardest. Florida, Louisiana, and Texas had lost valuable land. Millions were displaced, and whole industries, like the petrochemical industry in Houston and the tourist industry in Florida, relocated or simply closed. Transportation planners scrambled to re-build roadways and train lines in more inland locations. In the end, adaptation, the incremental ability to protect society and its way of life from climate change, seemed an impossible venture for what would be required in the face of the actual emergency.

The public mood shifted rapidly once the runaway warming started. Legislation to control carbon was put into effect even though scientists said that it could well be too little too late. The large CO_2 emitters were severely restricted by a carbon tax that neared $90 per ton—affecting coal plants, manufacturing facilities, and of course transportation. Farmers had to use less diesel and fertilizer, and some famines ensued. The construction industry had to get its material locally and cut down on waste altogether. It was all hands on deck!

It was a generation before life settled into a more local, quieter, less hectic, and less stressful way of life. Some of the old-timers longed for the “good old days” of go-go and perpetual motion. Most, however, taught their children that the world they had grown up in was a unique historical moment, but that they were glad it was over! And their children looked back on the society of their grandparents and felt superior, as most generations are wont to do when they look to the past. They judged that their ancestors had done as well as they could under the circumstances, but that they, the present generation, had achieved a much better life. They saw the effects of the catastrophe as progress, as most generations are also wont to do.

4.0 CHAPTER 4—COMMON THEMES AND OVERALL IMPLICATIONS FOR THE TRANSPORTATION INDUSTRY

This chapter contains summary-level information from the seven multi-driver scenarios, and identifies themes and common implications for STAs across the six transportation areas. This summary-level information provides readers with high-level implications for transportation around various scenarios. Specific details appear in the white paper visions for each individual transportation area.

As explained in Chapter 3, the baseline scenario covers all drivers and represents the expected future. Upon further examination, it became clear that the other multi-driver scenarios were similar in important ways. Back to the Future and Government Redux are a return to higher levels of funding for transportation, albeit by different routes. Back to the Future gets its funding from a revived and robust economy; Government Redux from higher taxes and more government support for transportation infrastructure. As a result, these scenarios are characterized as high-resource scenarios.

The next three scenarios (Bits over Buses, Many Ways to Go, and Escape to the Centers) also have much in common, namely reduced demand for highway transportation in the future, and again for different reasons. Bits over Buses presents the classic mobility versus telecommunications trade-off where digital communication becomes almost as good as being there, resulting in more telecommuting and fewer long-distance trips for business and leisure. Many Ways to Go reduces demand through investment and a shift in consumer perception of public transit. Escape to the Centers describes a change in the urban form where people gravitate to the central and satellite cities in a metro region that are relatively self-contained for employment, retail, and amenities, reducing the need to travel across the region to work and play. As a result, these scenarios are characterized as low-demand scenarios.

Of course, the baseline scenario (Managed Decline) and disruptive scenario (Meltdown) are in classes by themselves. The result is four scenario categories (baseline, high resource, low demand, and disruptive) rather than six distinct scenarios. The authors of the white paper visions, therefore, only have to address one scenario from each of these four categories, rather than the initial seven multi-driver scenarios, because the implications for the six transportation areas are relatively the same despite the rationale behind their emergence as scenarios.

Table 4.1 shows the drivers discussed in the white papers for different transportation areas. Each driver is discussed in at least one technical-area white paper.

Table 4.1. Drivers Addressed in Each Technical-Area White Paper.

Traffic Services	Pavements and Materials	Construction	Transportation Structures	Roadside and Drainage	Connectivity
4. Funding—amount 5. Funding—proportion private 7. Mobility—demand (need to work, shop, etc.) 10. Resources/energy—supply 13. Resources/energy—price 14. Road freight (amount and proportion) 16. Technology—physical and fixed 17. Technology—IT	2. Economic growth 6. Government role (large/small [attitudes toward regulation and tax] and federal/state/local) 11. Resources/energy—demand 13. Resources/energy—price 16. Technology—physical and fixed	3. Priority on environmental quality/public commitment to sustainability 4. Funding—amount 5. Funding—proportion private 7. Mobility—demand (need to work, shop, etc.) 12. Resources/energy—gas or carbon tax 16. Technology—physical and fixed 17. Technology—IT 18. Transport-ation choices/complexity	1. Climate change 2. Economic growth 4. Funding—amount 12. Resources/energy—gas or carbon tax 14. Road freight (amount and proportion) 15. Security 16. Technology—physical and fixed	1. Climate change 3. Priority on environmental quality/public commitment to sustainability 16. Technology—physical and fixed	4. Funding—amount 7. Mobility—demand (need to work, shop, etc.) 8. Mobility—capacity and access 9. Population density 16. Technology—physical and fixed 17. Technology—IT

Table 4.2 shows different scenarios discussed in the white papers developed for each transportation area. Each scenario is discussed in at least one transportation white paper, and each white paper includes at least one scenario from the high-resource group of scenarios and one scenario from the low-demand group of scenarios. The baseline scenario and the disruptive scenario are addressed in all of the white papers.

The white papers identify the implications of four categories of scenarios for the six transportation areas. The white papers contain a wealth of insight and detail on how the highway establishment might respond to the changes in each of these futures.

This section takes a high-level view, identifying the implications for each scenario as a whole.

Table 4.2. Scenarios Addressed in Each Technical-Area White Paper.

Technical Area	Baseline Scenario (Managed Decline)	High-Resource Scenarios		Low-Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Traffic Services	✓	✓				✓	✓
Pavements and Materials	✓	✓		✓			✓
Construction	✓	✓			✓		✓
Transportation Structures	✓	✓				✓	✓
Roadside and Drainage	✓	✓			✓		✓
Connectivity	✓		✓	✓			✓

4.1 Baseline Scenario—Managed Decline

The baseline scenario describes the surprise-free future in which present conditions, trends, and plans change little from what is expected. It is characterized by steadily declining funding due to higher fuel prices, resulting in lower VMT per capita, higher Corporate Average Fuel Average (CAFE) standards, lower fuel purchases per mile, and alternative-fuel vehicles (which pay no gas tax at all). Combine that with the public's and the government's reluctance to raise taxes to maintain—much less expand—the highway infrastructure, and the result is the inevitable decline in the highway infrastructure, with increases in congestion and decreases in safety.

4.1.1 Implications

There is somewhat more demand for mobility based on the growing population and economic activity. On the other hand, there is flat or slightly less funding for transportation based on the fuel tax because of somewhat lower VMT per capita due to:

- Higher fuel prices.
- More use of public transit.
- More efficient vehicles.
- Less driving by the younger generation.
- More natural-gas vehicles being fueled at home.

Therefore, agencies devote a higher proportion of their declining funds to simply maintaining the existing system, with few funds remaining for expanding the system. The private sector funds, at least partially, whatever expansion there is because highway revenues are a reliable source of cash flow in a volatile global economy. Still more congestion is the result, particularly on non-tolled roads.

Agencies also take steps to control costs even more aggressively than they had, though few had a great deal of funding to make such investments. Some of the strategies for controlling costs are as follows:

- Higher energy costs increase the return on investments in fuel efficiency although few government agencies have the spare funding to make such investments.
- In line with the rest of the U.S. economy, the transportation sector also increases its labor productivity and reduces its costs by employing more robotics, more automation, sophisticated design and planning techniques, and fewer but more highly skilled workers.
- Some government agencies turn to outsourcing to save money. Some do save money, and many do not. The ones that do use performance contracts with strict schedules, deliverables, and warranties.[1]
- Agencies also move to reduce the growth in their health care costs due to accidents by instituting procedures and practices that are ergonomically justified, including the redesign of some machines and equipment.

Agencies also focus more on traffic services to increase flow and reduce congestion in the absence of funds to expand capacity.

4.2 High-Resource Scenarios—Back to the Future and Government Redux

These two scenarios reverse the funding decline in the baseline scenario and describe new funding levels more like the 1980s and 1990s—not luxurious by any means but at least sufficient to do more than in the baseline.

4.2.1 Back to the Future

Back to the Future describes the return to the relative prosperity of the economy through the twin mechanisms of technological development and generational change. The technologies are an assortment of bio-, nano-, and energy-technologies coupled with the maturing IT that transformed the world over the last turn of the century. The generational change was the emergence of the Millennial Generation as another round of “the Great Generation”—smart, able, civic minded, and ready to tackle the big challenges of the age. They had great relationships with their parents, but they also realized that those same parents had left the country in an awful mess.

4.2.2 Government Redux

Government Redux is a rebound to previous funding levels due to a re-thinking of the role of government in society. The movement toward free market solutions had run its course. The Millennials realized that government had to provide many critical functions in society, transportation being a major one, and that you had to pay for what you got. Therefore, they moved to reform government so it could responsibly raise and spend the money necessary to provide the mobility that society needed.

[1] An illustrative example of a federal government report on outsourcing is available at http://www.huffingtonpost.com/david-isenberg/the-chimerical-cost-savin_b_690673.html.

Implications

The first thing agencies had to decide was how to spend the relatively higher funding levels they experienced. A number of schools of thought emerged:

- The Back to the Future school, echoing the first high-resource scenario, breathed a sigh of relief and prepared to return to the tried and true practices of the late 20th century: “We know how to build and maintain highways. We did it for 50 years. All we need now is the money. So let’s do it.”
- The Forward to the Future school thought just the opposite. They saw the new funding as an opportunity to build highways the way they should be built in the 21st century, not in the 20th. But they also had their divisions:
  - Should they emphasize the material technologies, like new pavements, robotic construction equipment, and autonomous vehicles?
  - Or they should they emphasize the soft technologies, like mechanized design and planning, three-dimensional visualization, embedded sensor networks, and the most sophisticated intelligent transportation systems (ITS)?

Of course, these strategies are not mutually exclusive, so different states made their own plans for how to invest these new funds based on their own mix of priorities.

Another even more fundamental decision was the extent to which they would meet growing demand from a larger population: the old way, by expanding capacity, or in a new way, by focusing mostly on IT-enabled services. Metro areas had grown up around their highways, trapping them in a commercial and residential matrix and leaving little right of way for horizontal expansion. On the other hand, ITS was still largely untried, and a big bet on it might not pay off.

Another surprise, given the relative prosperity that the agencies enjoyed, was that their costs had increased more than expected. Labor, energy, and materials were tight because demand was high from the economy in general in Back to the Future and from other government programs in Government Redux.

In any event, the increased funding allowed those who wanted to experiment and create the means to do so. So research labs were churning out new, longer-lasting materials. Prefabrication and modularization were used to speed the disruptions caused by maintenance and renewal. IT was used to increase the size and safety of work zones.

In the end, however, the dream of smart growth, of dense, walkable neighborhoods filled with offices, homes, and retail, was not to be. The metro areas expanded just as fast as they had in the second half of the 20th century.

With increased public trust (in Government Redux), the door is open to federal leadership in significant expansion of tolling to the interstate system and ultimately to full network pricing. The initial motivation is the generation of sustainable revenue sources, but the incremental application of tolling across the system serves a demand management function in congested areas through variable pricing, thus reducing significant infrastructure expansion to meet demand.

Leading-edge vehicle technologies improve safety and reduce vehicle headway so that the system can be more efficiently operated.

Privately administered payment mechanisms allow drivers to pay for road user fees while also paying for other services such as premium toll facilities, parking, navigation and location assistance with real-time traffic conditions, and pay-as-you-drive car insurance.

4.3 Low-Demand Scenarios—Bits over Buses, Many Ways to Go, and Escape to the Centers

The demand for mobility, of course, is the prime reason that the highway system exists in the first place. Three of the multi-driver scenarios discovered in this study describe futures where demand for highways actually goes down, if ever so slightly. The result is that demand peaks in the early part of the forecast period and begins to taper off toward the later parts, reducing the pressure for new highway construction. Without new funds, therefore, agencies can focus almost exclusively on maintenance, preservation, and renewal. But demand backs off for very different reasons in each scenario.

One overarching implication of all three of these scenarios is a challenge. Drivers were prepared to pay to "hit the open road" in the 1950s and 1960s and, to a lesser extent, to not be in gridlock on the way home from work. But people were using highways less in these scenarios, so they were less inclined to fund the agencies that maintained them.

The hardest sell of all was freight. Since people were using their private vehicles less, freight use climbed in its proportion of overall demand, with consequent increase in wear and tear on the roadway. Funding the increased maintenance due to freight was a challenging political problem because freight transportation was largely invisible to voters, who were still taxpayers but less and less highway users.

4.3.1 Bits over Buses

In Bits over Buses, the promise of IT that moving one's body around the city or the world would be unnecessary and obsolete was realized. Almost magical IT took the place of the daily commute and the five-hour flight to New York for a two-hour meeting. People simply drove less; fewer cars were sold, and fewer people even had driver's licenses. Highways still served a necessary function, but the peak wave had passed.

Implications

Society embraced digital technologies in the first half of this century as they had embraced the railroad, telephone, electric light, and motor car in their day. Government agencies could not stand aside while they were being offered almost magical capabilities in the following areas:

- Construction (real-time monitoring of equipment and activities).
- Pavements and structures (embedded sensors that signaled use and wear).

- Roadside technologies (sensors that warned vehicles away from fixed objects).
- Services (real-time alerts to re-route traffic around construction or accidents).

Realizing that little new capacity was necessary, agencies are all about flow and safety, and spend their money maintaining and preserving the existing system rather than expanding it.

STAs turn over roads with local-access functionality to transportation cooperatives for maintenance and preservation.

STA partnerships and advocacy campaigns encourage cultural transitions for demand-reduction strategies via telepresence alternatives to work and personal services (e.g., trips to the doctor and retail shopping).

Federal, state, and local funding may shift to expand broadband access (urban/rural) that enables access to telepresence. The result could be less funding for transportation.

Agencies may use land (asset) sales or co-development of former road corridors that are now closed to traffic.

4.3.2 Many Ways to Go

In Many Ways to Go, the public finally got over its love affair with the car and embraced the very comfortable, more affordable, and more technologically sophisticated multimodal options available to them. Not only did this new system include traditional mass transit like buses, trolleys, trains, and subways, but autonomous vehicles zipped around town picking people up and dropping them off for short hops. The growing wellness movement also encouraged people to demand and then use all manner of self-propelled transportation—bicycling and walking being the most common.

Implications

The demand for highway transportation was less, but the demand for mobility overall was not. So money had to be found to fund the transformation from an almost exclusively highway-centric transportation system to one where highways were only one of many options. And this is where the private sector saw an opportunity. People had gotten used to the fact that streets and highways were free—that is, funded by tax dollars. At the same time, they knew that trains and buses were not. So private investors were eager to get a piece of the steady cash flow from a well-designed multimodal transportation system.

Different highway forms became common. No longer were highway and freeway the two dominant forms. Now people could choose from a variety of high-occupancy vehicles (HOVs), high-occupancy tolls (HOTs), and tolls (fixed and congestion priced). The freeway was the only form left that was really free, at least to the user!

Right of way had traditionally been synonymous with highways. Now that society wanted to move around in different ways in urban areas that were already developed, highways had to give up their precious right of way and accommodate the newly desired forms of transportation. But placing all of this in the same linear strip was quite a challenge. The need to create a truly multimodal transportation system provided the first opportunity for real creativity in transportation design since the beginning of the interstate era. At the same time, it also ran the risk of creating some horrible and expensive failures. Some few got it spectacularly right, another few spectacularly wrong, and most were somewhere in the middle.

One of the greatest challenges was how to connect these modes together so people could seamlessly and safely move from one to the other. Pedestrians and cyclists had to move in the same system as automobiles and high-speed trains.

One result of these challenges was a revolution in the research and education arm of the highway industry. Universities and research labs were churning out designs and schemes. Every city had its own solution. A few eventually stood the test of time, but the transition was full of energy and creativity.

A new sustainable revenue source is available to invest in transit and alternative modes, and support strategic capacity expansion for freight and alternative freight modes.

The bus/jitney industry may fragment as new players compete for rising demand. This could lead to innovation driven by competition—or a negative consumer experience if the industry's market structure does not allow for sustainable business models (e.g., hyper-competition leads to failed companies and abandoned routes).

Autonomous vehicle fleets and transit partners may use new multimodal hubs along highways to bring last-mile services to suburban communities.

Transportation agencies and engineering-solution providers shift toward place-based planning principles, taking a more holistic approach to multimodal systems.

STAs push for regulatory certainty on funding commitments to urban-based multimodal hubs. Constraints (e.g., fines and taxes) are placed on competing sprawl developments that might undermine efforts.

STAs, transit providers, and real estate developers form stronger partnerships and may merge organizationally. This allows them to reduce overhead costs and leverage existing assets (e.g., highway lanes transformed into bus-only lanes or rail) to meet the needs of rising urban center demands.

4.3.3 Escape to the Centers

In Escape to the Centers, the most difficult change of all, the reformation of the urban form itself, was finally accomplished in the 2040s. Tired of paying high fuel cost and wasting hours in commuting, people opted to live closer to work. Developers seeing a market created the urban villages that the smart growth crowd had been advocating for decades. People left their enclaves, of course, but not very often since they could live, work, shop, and entertain themselves within a short walk or bicycle trip.

Implications

Transportation in the modern world had always been with vehicles—railroad, steamship, auto, and airliner. Now the total VMT in society declined, not just the VMT in automobiles. As a result, the agencies had no more pressure to maintain the highway system of the past. Highways were still there, but the demand had dropped precipitously. The resulting focus became city streets and thoroughfares, the arteries that connected these urban villages together.

The denser city required construction and maintenance practices that were suited to confined spaces—smaller, more flexible vehicles, small footprints of the work zone, and less noise and dust from the construction activity.

Agencies may use land (asset) sales or co-development of former road corridors that are now closed to traffic.

4.4 Disruptive Scenario—Meltdown

The common elements in the disruptive scenario are a significant event that disrupts the transportation system and highways in particular in a very short period of time. Systems can recover from such disruptive events, but they rarely do so unchanged in fundamental ways.

The scenario describes the world after a relatively rapid change in the earth’s climate due to the greenhouse effect. Transportation, of course, runs on fossil fuel, one of the largest sources of greenhouse gases (GHGs). When society decides that it can no longer afford the benefits of these high-density fuels, everything changes and usually in quite unpredictable ways.

But climate change is only one of a number of game changers that could cause disruptive change. Some parts of the United States are subject to tectonic disruptions (earthquakes), principally though not exclusively along the West Coast. The white paper on transportation structures outlines the implications of a major tectonic event on the highway system.

Another serious threat to the transportation infrastructure is terrorist infiltration of the digital environment of the system, particularly that part that monitors or even controls the flow of autonomous vehicles. The threat of cyber-terrorism or even cyber-war is growing in the United States. This threat would be more serious the more that agencies invest in digital infrastructure to manage the highway system, such as in the Bits to Buses scenario.

4.4.1 Implications

Every aspect of society is getting used to the idea of a sustainable (green) economy and infrastructure although the movement toward implementation is painfully slow. Highway construction and maintenance will experience pressure to move in that direction just as all other aspects of society had to do. Were significant climate change to occur, however, that movement would change from gentle pressure to an emergency. Some of the strategies to be employed would be:

- More fuel-efficient equipment.
- Less material use and the recycling of the material used.

- Lower carbon content in the materials used.
- More HOVs and HOTs to encourage multi-rider vehicles.
- Streamlining of the array of agencies that now have a portion of the oversight concerning material and energy use.
- A new requirement to create and maintain smoother roads to reduce fuel use and GHG emissions.

Carbon taxes increase the cost of energy and material.

Roads are under increased stress due to the alternation of drought and heavy rain.

Highways become more important as evacuation routes from storms and other disruptive events.

Traffic in rural areas represents a smaller proportion of all traffic; consequently rural roads receive less attention and funding.

Heavier battery-powered vehicles might induce more wear on roadways.

Governments might have to protect and re-align roadways in low-lying areas.

The recovery and rebuilding after a severe regional event could use up funding that was intended to be more widely distributed.

Focus shifts to self-sustenance with investments in breakthrough technology to support clean water, super foods, and medical technologies. Expansion of the network progresses at a moderate pace in keeping with sustainability principles.

5.0 CHAPTER 5—IMPLICATIONS AND STRATEGIES FOR STATE TRANSPORTATION AGENCIES

As explained in Chapter 2, Section 1, in response to the comments received from the Panel on the Task 6 interim report, the project team reexamined the original white paper visions. This chapter provides further implications extracted from the white paper visions and examples of corresponding strategies. The white papers identify the implications of four multi-driver scenarios for six transportation areas. Strategies are elements that will eventually become the guidance for STAs, and the research team agreed to further develop and refine a full set of draft strategies by transportation area. For each area, the team identifies emerging or new materials, tools, approaches, and technologies in relation to highway maintenance, preservation, and renewal.

5.1 Traffic Services Implications and Strategies

The original version of the traffic services white paper vision developed as a part of Task 6.1 is included in Appendix B. In the white paper, the research team identified the potential for new tools, technologies, and approaches for four multi-driver scenarios:

- The baseline scenario—Managed Decline.
- Back to the Future.
- Escape to the Centers.
- Meltdown.

The implications extracted from the white paper were further developed into specific strategies on how new materials, tools, approaches, and technologies can be used to enhance system preservation, maintenance, and renewal in response to anticipated future challenges for the traffic services area.

5.1.1 Description of Transportation Area: Traffic Services

The term *traffic services* describes the management and operation of traffic on a roadway using devices and technologies, including static and dynamic signs, signals, pavement markings, roadside lighting, and ITS. It includes the use of ITS to support the management of traffic flow in urban regions—in both recurring and nonrecurring congestion conditions—to maximize throughput and minimize the impacts to system reliability. Appendix B provides more detailed information about different types of activities that the traffic services area covers.

5.1.2 Baseline Scenario—Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for transportation traffic services and recommended strategies are as follows:

Implication 1. Due to the lower VMT per capita and slower demand growth, the pressure on growth in roadway capacity will decline. A possible strategy is:

- **Strategy 1.1.** Accommodate demand growth through technology-enabled mobility and system operations, placing a lower priority on increasing capacity. Infrastructure operations will take a more prominent role, and a workforce that is oriented toward system management will be critical to maintenance and preservation activities.

Implication 2. Due to the limited amount of funding, STAs will have fewer funds for new capacity addition and ongoing maintenance and operations. A possible strategy is:

- **Strategy 2.1.** Shift the transportation services delivery method from a “build it” to an “operate it” approach. Place greater emphasis on traffic operations supported by ITS, which plays a significant role in managing and optimizing the system. New infrastructure-based IT systems will be required, as will a significantly higher level of ITS maintenance to ensure system reliability for safety applications.

Implication 3. A higher proportion of funding for new capacity through the private sector will ease pressure on traditional sources for funding maintenance, preservation, and expansion. A possible strategy is:

- **Strategy 3.1.** Advance infrastructure improvements using private equity and a greater reliance on tolling and user fees. Management and operations of the system will increasingly shift to the private sector due to public resource limitations. New procurement structures will require legal and financial skills to manage and structure organizational agreements.

Implication 4. Much higher use of IT in both vehicles and infrastructure enables next-generation in-vehicle and infrastructure technologies. The technological advances will improve safety and reliability in a data-rich environment that facilitates traveler choices. A possible strategy is:

- **Strategy 4.1.** Shift infrastructure investment to focused applications of “smart infrastructure” to support the automated driving environment. Traffic control devices will evolve to dynamic signs and pavement markings, and eventually to in-vehicle messaging. Optimize traffic operations based on the transportation data generated from vehicles and roadways. To support technology, re-orient the workforce to IT integration, standardization, data management, and data security.

Implication 5. The increase in freight demand results in larger loads and road freight trains, requiring new methods to accommodate increased wear on the roadways. A possible strategy is:

- **Strategy 5.1.** Accommodate demand growth through technology-enabled mobility, which will allow larger vehicle combinations absent the safety risks. Advances in commercial vehicle automation will mitigate traditional safety concerns. Use pavement rehabilitation and preservation strategies that can accommodate higher loading.

5.1.3 Back to the Future

In the Back to the Future scenario, the economy returns to health, and transportation has the technology and resources to grow again. Potential implications of this scenario for transportation traffic services and recommended strategies are as follows:

Implication 1. The country's economic growth is high, and STAs have greater budgets. But they balance their investments between building strategic capacity and operations, given advancements in technology that help maximize the use of existing capacity through operations and traffic services. A possible strategy is:

- **Strategy 1.1.** Although funding will be less of a concern, the public will expect greater efficiencies, which can be accomplished with a technologically data-rich environment. Advance capacity additions in strategic corridors that provide economic returns, and give greater attention to operations and management. Focus on improvements in ITS and materials for traffic services.

Implication 2. Due to high transport use, pressure increases for more freight and greater multimodalism. A possible strategy is:

- **Strategy 2.1.** Engage with partners in enhancing alternative modes, and expand the mission and performance management toward mobility rather than highways. Implement policies to address demand, including road pricing (oriented to economic value provided by the infrastructure) and allocation of lanes according to economic benefits. Construction, maintenance, and preservation implications relate to pavement impacts of alternative allocation of highway lanes by vehicle group.

Implication 3. Due to high technology development, next-generation in-vehicle and infrastructure technologies provide improved safety and reliability in a data-rich environment that facilitates traveler choices. A possible strategy is:

- **Strategy 3.1.** Orient infrastructure investment toward focused applications of "smart infrastructure" to support the automated driving environment. Smooth traffic operations using the transportation data generated from vehicles and roadways. To support technology, re-orient the workforce to IT integration, standardization, and data management. Cybersecurity becomes a high priority, so hire employees with the expertise to manage risks and prevent attacks.

5.1.4 Escape to the Centers

In the Escape to the Centers scenario, the lack of mobility and increased threats to individuals' well-being drive people out of the suburbs and into the city, reducing the demand for transportation—this is the vision of the advocates of smart growth. Potential implications of this scenario for transportation traffic services and recommended strategies are as follows:

Implication 1. The high and increasing population density results in lower VMT, but congestion is rife due to societal densification and limitations on space for expansion. Continual congestion causes preservation of the infrastructure to be more difficult and costly. A possible strategy is:

- **Strategy 1.1.** Shift emphasis to urban centers, with high-impact maintenance and construction operations in densely developed metropolitan areas facilitated by technology innovations in construction and materials. Mitigating traffic impacts will drive greater efficiency in maintenance and preservation operations.

Implication 2. The low mobility capacity causes STAs to focus more on public transportation, bicycles, and pedestrians. A possible strategy is:

- **Strategy 2.1.** Engage with partners to enhance alternative modes, expanding mission and performance management toward mobility rather than highways. Implement policies to address demand, including road pricing (oriented to economic value provided by the infrastructure) and allocation of lanes according to economic benefits.

Implication 3. The high technology development results in integrated traveler information for multiple modes. A possible strategy is:

- **Strategy 3.1.** Integrate public data (from all modes) with private data to provide a seamless information stream. An IT workforce is essential.

5.1.5 Meltdown

In the Meltdown scenario, abrupt climate change shifts priorities from growing the economy to struggling with nature. Potential implications of this scenario for transportation traffic services and recommended strategies are as follows:

Implication 1. The rapid climate change and more severe weather put roads under increased stress due to the alternation of drought and heavy rain. Bridges are severely damaged in affected regions. A possible strategy is:

- **Strategy 1.1.** Provide traveler information and in-vehicle communication for emergency weather and evacuations. The methods for collecting and disseminating data will involve private-sector providers, but STAs will need skilled staff in IT to manage public data integration.

Implication 2. Due to increases in gas/carbon tax, prices surge, increasing the cost of driving for all motorists. VMT declines as a result, and transit and multimodal transportation become true substitutes. A possible strategy is:

- **Strategy 2.1.** Collaborate with state and local entities to provide choices to drivers other than personal vehicles. Use traffic service equipment powered exclusively by alternative energy products.

Implication 3. Government agencies work in close coordination to develop more environmental regulation and monitoring, and federal policies incentivize states heavily to reduce dependence on non-renewable resources. A possible strategy is:

- **Strategy 3.1.** Integrate data across modes and government agencies for operational optimization and notification of the public under emergency situations.

Implication 4. Increasing urban density results in lower VMT, but congestion is rife due to societal densification and limitations on space for expansion. Continual congestion causes preservation of the infrastructure to be more difficult and costly. A possible strategy is:

- **Strategy 4.1.** Engage with partners to enhance alternative modes, expanding mission and performance management toward mobility rather than highways. Implement policies to address demand, including road pricing (oriented to economic value provided by the infrastructure) and allocation of lanes according to economic benefits.

5.2 Pavements and Materials Implications and Strategies

The original version of the pavements and materials white paper vision developed as a part of Task 6.1 is included in Appendix C. In the white paper, the research team identified the potential for new tools, technologies, and approaches for four multi-driver scenarios:

- The baseline scenario—Managed Decline.
- Back to the Future.
- Bits over Buses.
- Meltdown.

The implications extracted from the white paper were further developed into specific strategies on how new materials, tools, approaches, and technologies can be used to enhance system preservation, maintenance, and renewal in response to anticipated future challenges for the pavements and materials area.

5.2.1 Description of Transportation Area: Pavements and Materials

The term *pavements and materials* describes the production of raw materials, use of recycled materials, pavement thickness design, materials selection, recycling, production of the finished material, pavement placement and compaction, and subsequent renewal, maintenance, and preservation activities. Currently, pavement activities occupy the greatest proportion of highway agency budgets in most states. Consequently, any scenario that would impact the use of roadways would have major implications for the funding, construction, and upkeep of pavements.

5.2.2 Baseline Scenario—Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for pavements and materials and recommended strategies are as follows:

Implication 1. Due to the decrease in VMT per capita and prevalent use of natural-gas and electric vehicles, consumption of gasoline is lower. Lower consumption of gasoline results in a lower amount of revenue generated from the gas tax for transportation projects. A possible strategy is:

- **Strategy 1.1.** Place a much greater emphasis on the development of pavement preservation materials, techniques, and selection methods. Apply preventative measures ahead of catastrophic distresses. Pavement preservation becomes a more mature engineering practice.

Implication 2. Due to the lower amount of funding, STAs are continuously faced with enormous challenges to simply maintain and rehabilitate an aging system of highway infrastructure, and there is less emphasis on capacity expansion. A possible strategy is:

- **Strategy 2.1.** Refine maintenance and pavement preservation techniques to provide the best life-cycle cost. Use nondestructive techniques to assess conditions at or near highway speeds to minimize operational costs and reduce liability. Develop firm guidelines to select preservation and maintenance techniques based upon anticipated distresses and expected performance to maximize the benefit and lower the costs of these treatments.

Implication 3. The increase in population density increases traffic in urban areas and results in traffic congestion. A possible strategy is:

- **Strategy 3.1.** Change contracting procedures to accommodate rapid construction to minimize user delay costs, which will be embodied in political directives. For the relatively fewer capital highway improvement projects, develop rapid paving practices to allow roadways to be built and maintained with minimal traffic disruption (user delay costs). Increase the efficiency of construction by using intensive lane shutdowns, high material production methods, and high-speed placement and material hardening or curing. Efficient construction will also translate to lower energy consumption by equipment as metrics are developed, which will allow contractors to more accurately estimate production per gallon. Existing examples of energy-efficient and high-speed construction include the demonstration and use of modular pavements and surfaces that can be rolled out and then anchored with microwave units. Make adjustments to QC/QA to facilitate such approaches to pavement construction.

Implication 4. The increasing urban population forces political decisions that emphasize urban highways instead of rural highways. A possible strategy is:

- **Strategy 4.1.** Revert severely deteriorated secondary roads in rural areas to unsurfaced roadways. This will impact the transportation of agricultural goods to urban markets unless methods are found to provide low-cost all-weather pavements in these areas.

Implication 5. The higher use of IT in both vehicles and infrastructure enables next-generation in-vehicle and infrastructure technologies to provide improved safety and reliability in a data-rich environment that facilitates traveler choices. This increases the requirement of a sophisticated workforce. Possible strategies are:

- **Strategy 5.1.** Improve QC/QA to provide feedback to construction operations in a more rapid manner. As accelerated construction becomes the norm, QC/QA practices will need better accuracy and timeliness. Onboard paving sensors such as global positioning system (GPS) and infrared (IR) technology will need to be combined with materials-testing techniques that allow for the production and assessment of possibly tens of thousands of tons per day. This will require rapid decision-making processes for the acceptance of materials.
- **Strategy 5.2.** Develop a more sophisticated material production and paving workforce, in terms of applying IT and troubleshooting. The workforce will need to be attuned to high material production and placement, and be able to rapidly react to feedback. Workers' decisions will have a higher dollar impact than those typically made by paving personnel currently. Make workforce training available on demand to meet the requirements of

rapid technology deployment and paradigm changes. Certification of construction workers may become normal as the required skill sets become more complex. Use simulation of scenarios at material production plants, job site conditions, and equipment operations as a part of a sophisticated set of training tools.

Implication 6. The increasing environmental concerns and depletion of resources increase the use of sustainable materials and practices. Possible strategies are:

- **Strategy 6.1.** Increase emphasis on sustainability in design and construction, and implement environmental rating systems for all highway projects. Such systems rely on data associated with life-cycle analysis to ensure that the best environmental decisions are made.
- **Strategy 6.2.** Use alternative binders for asphalt and concrete pavements that reduce petroleum resource consumption or the energy required for production. This will be done as much for economic as environmental considerations.
- **Strategy 6.3.** Encourage industries to develop life-cycle analysis (LCA) data and improve their processes to minimize waste, lower emissions, increase the amount of recycled materials used, and provide efficient design methodologies to minimize resource depletion. Efficient design methodologies will include the use of long-life design procedures to reduce overall materials consumption, pollution, and traffic congestion.
- **Strategy 6.4.** Use porous pavements as a means of mitigating stormwater runoff and providing a natural filtration treatment for typical highway pollutants before they reach ground-water tables, streams, rivers and lakes.

Implication 7. The severe weather results in different weather conditions at different locations and in accelerated deterioration of roadways. A possible strategy is:

- **Strategy 7.1.** Use improved materials and pavement systems capable of withstanding higher temperatures or increased rainfall to help avert an infrastructure crisis. Update the current performance grading (PG) system for asphalt with new temperature ranges. Use alternative binders or binder replacements to mitigate higher temperatures. Use low-expansion concrete to reduce or eliminate the potential for pavement buckling. Use improved anti-stripping additives to reduce moisture damage in asphalt pavements, and improved pavement design and jointing techniques to reduce moisture-induced damage to concrete.

Implication 8. The demand for more freight results in higher loads and eventually increases the rate of deterioration of roadways. A possible strategy is:

- **Strategy 8.1.** Improve long-life design standards, such as long-life concrete pavements and perpetual asphalt pavements, and pavement materials, such as high-polymer asphalt binders. This will provide the means to rehabilitate existing pavements and construct new alignment to resist the effects of larger traffic loads. Phase in larger legal loads so that agencies can adjust standards ahead of the implementation. As with the severe weather scenario, improved standards for materials will give agency engineers more choices to deal with larger loads.

5.2.3 Back to the Future

In the Back to the Future scenario, the economy returns to health, and transportation has the technology and resources to grow again. Potential implications of this scenario for pavements and materials and recommended strategies are as follows:

Implication 1. The country's economic growth is high, and STAs have greater budgets for transportation projects. Due to an increase in the number of transportation projects, the industry faces shortage of materials and labor. Possible strategies are:

- **Strategy 1.1.** Support large transportation projects to mitigate congestion created by the economic growth. A number of capacity improvement projects, such as lane widening and interchange redesign, will create opportunities for paving contractors. However, rapid construction practices will be required to reduce the time that roadway lanes are out of service. This will necessitate the development of contracting procedures, construction practices, and QC/QA techniques that will allow tens of thousands of tons of material to be produced and placed within 24 hours. Typically, full road or multi-lane closures last for a 55-hour window over weekends.
- **Strategy 1.2.** Allow greater flexibility in the choice of materials and pavement designs up to the point of construction to address the shortage of materials and labor. Demand for materials in the housing and commercial markets as well as in the transportation sector will result in the allocation (rationing) of materials such as Portland cement and asphalt binders in certain areas of the country. This will inevitably increase the cost of materials. Labor and materials cost increases will result in higher costs for transportation projects.

Implication 2. The economic boom pushes the consumption of resources, resulting in a price increase for these resources. A possible strategy is:

- **Strategy 2.1.** Identify the cost risk to STAs and infrastructure in general by looking at trends in material price indexes and employment data. Define the competition for materials and labor by monitoring other construction sectors and understanding their impacts on hiring and consumption.

Implication 3. The availability of funds results in higher technology development, but these developments fail to enhance efficiency. Possible strategies are:

- **Strategy 3.1.** With the contracting industry and agencies confronted with a large backlog of work, the emphasis should be on the construction of projects rather than the refinement of techniques. Technology for the private sector will evolve at a slower pace for the purpose of improving profitability. Research sponsored by the public sector will likely result from the availability of funding rather than in response to technological needs. Implementation of research finding is likely to be slow since there will be little incentive for agencies or contractors to change from their current practices.
- **Strategy 3.2.** Use health-monitoring systems (in-situ instrumentation) to feed information into pavement management systems to alert agency engineers of the development of distresses before they become critical. This will allow agencies sufficient time to program activities, re-allocate budgets if necessary, and develop plans to prevent

catastrophic failures. Direct research efforts toward the development of sensors, monitoring systems, and criteria for reacting to the information.

5.2.4 Bits over Buses

In the Bits Over Buses scenario, a higher than expected increase in crude oil prices reduces the ability of ordinary people to travel as much as they used to. They turn instead to an expanded Internet, not only for communication but for most work and leisure activities that used to require physical movement. Potential implications of this scenario for pavements and materials and recommended strategies are as follows:

Implication 1. Due to a centralized government role and higher urban population density, the government shifts more focus to population centers from lower-population rural areas. This will reduce the availability of funds for capacity expansion. Possible strategies are:

- **Strategy 1.1.** Politics and policies need to focus on population centers. Lower funding and greater concentration of people in urban areas will mean neglect for low-volume rural routes. There will be a reversion from paved surfaces to unsurfaced roadways that will affect the transport of agricultural goods to markets.
- **Strategy 1.2.** Place an increased emphasis on pavement preservation as a part of the overall decision-making process. With lower VMT, the pavement preservation approach will have an appreciable impact on pavement performance.

Implication 2. The higher price of gas results in a decrease in VMT, which leads to less congestion. The cost of construction increases due to high gas prices. Possible strategies are:

- **Strategy 2.1.** With reduced congestion and lower VMT, there is less demand for construction and maintenance of roadways. This will ultimately force less-prepared contractors from the market and may result in increased competition for fewer projects.
- **Strategy 2.2.** Create pavement management systems that provide better decision making for maintaining road systems. Instead of pavement treatment differentiation, emphasize pavement preservation, maintenance, and rehabilitation to provide better resource allocation in an era of high construction costs.

Implication 3. The higher use of IT will provide magical capabilities in construction, pavements and structures, and roadside technologies and services, but will lower the VMT. Possible strategies are:

- **Strategy 3.1.** Use health-monitoring systems (in-situ instrumentation) that will feed information into pavement management systems to alert agency engineers of the development of distresses before they become critical. This will allow agencies sufficient time to program activities, re-allocate budgets if necessary, and develop plans to prevent catastrophic failures.
- **Strategy 3.2.** Improve QC/QA to provide feedback to construction operations in a more rapid manner. Onboard paving sensors such as GPS and IR technology will need to be combined with materials-testing techniques that reduce the need for physically sampling and testing the materials from the roadway.

- **Strategy 3.3.** Develop alternative binders that can detect and partially heal pavement distresses. These will be the first applications of nanotechnology in the pavements field, and they will have a profound impact on the longevity of roadways.

5.2.5 Meltdown

In the Meltdown scenario, abrupt climate change shifts priorities from growing the economy to struggling with nature. Potential implications of this scenario for pavements and materials and recommended strategies are as follows:

Implication 1. The rapid climate change and more severe weather put roads under increased stress due to the alternation of drought and heavy rain. Bridges are severely damaged in affected regions. A possible strategy is:

- **Strategy 1.1.** Use improved materials and pavement systems capable of withstanding higher temperatures or increased rainfall to help avert an infrastructure crisis. Update the current PG grading system for asphalt with new temperature ranges. Use alternative binders or binder replacements to mitigate higher temperatures. Use low-expansion concrete to reduce or eliminate the potential for pavement buckling. Use improved anti-stripping additives to help reduce moisture damage in asphalt pavements, and improved pavement design and jointing techniques to assist in reducing moisture-induced damage to concrete.

Implication 2. The government agencies work in close coordination to develop more environmentally friendly processes. Possible strategies are:

- **Strategy 2.1.** Put policies into practice requiring that environmental considerations be given top priority in pavement construction, maintenance, and preservation.
- **Strategy 2.2.** Innovation will be much more prevalent in order for the pavement industry to remain viable as the environmental crisis unfolds and STAs should support these strategies.
- **Strategy 2.3.** Emphasize sustainability in design, construction, maintenance, and preservation. Implement environmental rating systems for all highway projects and activities. Decisions by agencies and contractors alike will be driven by environmental policies. Use life-cycle analysis at all levels to ensure that the best environmental decisions are made.
- **Strategy 2.4.** Develop alternative binders for asphalt and concrete pavements that reduce petroleum resource consumption or energy required for production.
- **Strategy 2.5.** Encourage industries to develop LCA data and improve their processes to minimize waste, lower emissions, increase the amount of recycled materials used, and provide efficient design methodologies to minimize resource depletion. Efficient design methodologies will include the use of long-life design procedures to reduce overall materials consumption, pollution, and traffic congestion.

Implication 3. Due to an increase in the gas/carbon tax, prices surge, increasing the cost of energy and materials, eventually increasing single-occupant (SOV) operation costs. This increase in cost will increase the use of cheaper but heavier battery-powered vehicles, causing more wear on roadways. A possible strategy is:

- **Strategy 3.1.** Higher rates of recycling will result from a carbon tax being levied on petroleum-derived and energy-intensive carbon-producing binders. Use alternative low-carbon binders from biomass, which will become more common and viable as the price of traditional asphalt and concrete binders continues to increase.

Implication 4. The increase in urban population density shifts the focus from rural highways to urban transportation systems. A possible strategy is:

- **Strategy 4.1.** As the population is drawn ever-increasingly to urban centers, the rural population will have a diminished influence, and the rural secondary road system will suffer from neglect. More roads will revert to unsurfaced pavements, which may have a detrimental mobility and environmental impact. Transport of natural resources such as aggregate and agricultural goods will become more difficult.

5.3 Construction Implications and Strategies

The original version of the construction white paper vision developed as a part of Task 6.1 is included in Appendix D. In the white paper, the research team identified the potential for new tools, technologies, and approaches for four multi-driver scenarios:

- The baseline scenario—Managed Decline.
- Back to the Future.
- Many Ways to Go.
- Meltdown.

The implications extracted from the white paper were further developed into specific strategies on how new materials, tools, approaches, and technologies can be used to provide a means for enhancing system preservation, maintenance, and renewal in response to anticipated future challenges for the construction area.

5.3.1 Description of Transportation Area: Construction

Construction in this study focuses on transportation predesign, design, building, and assembly services and the means and methods related to delivering new and maintaining existing roadways and infrastructures. Construction services and activities cover a wide range of operations related to earthwork, such as subgrade preparation, foundation courses, base courses, shoulder construction, and gravel surfacing; installation of lighting, signs, and traffic control devices; laying of pavements; erection of bridges and culverts; and roadside development and erosion control.

5.3.2 Baseline Scenario—Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for transportation construction projects and recommended strategies are as follows:

Implication 1. Due to the decrease in VMT per capita and prevalent use of natural-gas and electric vehicles, consumption of gasoline is lower. Lower consumption of gasoline results in a lower amount of revenue generated from the gas tax for transportation and specifically less funds for large construction projects. Possible strategies are:

- **Strategy 1.1.** Improve the accuracy of investment (both construction and maintenance) decisions, and prioritize funding allocations based on performance-driven criteria to direct funds toward problem areas where improvements are highly needed. Require life-cycle analysis for all projects.
- **Strategy 1.2.** Use innovative contracting methods, such as design-build, for integrated project delivery to accelerate projects. Ask contractors to provide feedback during the design phase before the start of construction to improve the contractibility of designs and reduce costly changes during the construction phase. Investigate ways to increase the number of qualified bidders to bid on a project. Strategies include reducing the administrative process to motivate qualified bidders. In order to streamline the administrative process, adopt integrated project delivery approaches to give all parties a vote in the final contract terms, share decision making, pool contingencies, and provide incentives for team performance. Support integrated project delivery with the use of relational contracts, in which one agreement is signed by the owner, engineer, and contractor.
- **Strategy 1.3.** Work extensively with local universities to support infrastructure, internships, and fellowships to recruit qualified workers to become more efficient.

Implication 2. Due to the lower amount of funding, STAs are continuously faced with enormous challenges to simply maintain and rehabilitate an aging system of highway infrastructure. There is less emphasis on capacity expansion and large construction projects. A possible strategy is:

- **Strategy 2.1.** A lot of maintenance activities tend to be done repetitively and require dealing with relatively lightweight tools and materials. Accordingly, although in general less funding is available, support the use of new technology for maintenance activities to increase the productivity and safety of the construction workforce and the public. Examples include using remotely driven dump trucks as a barrier during slow-moving maintenance operations, automated paving machines, robotic paint-removal systems, laser-guided lane stripe painting machines, industrial and mobile robots for roadway crack sealing, tele-operated aerial systems for bridge inspection, placement of highway safety devices, and application of sensor-based guidance of road pavers.

Implication 3. Investment in new construction projects needs to be attractive to the private sector. A possible strategy is:

- **Strategy 3.1.** Support innovation and faster project delivery. Use PPPs and congestion pricing to enhance the role of the private party. Use performance-based contracting to encourage private companies to improve their performance and efficiency.

Implication 4. Development in IT provides an opportunity to improve the safety of construction activities and lower costs. Possible strategies are:

- **Strategy 4.1.** Employ visualization techniques and simulation methods such as illustrations, photo simulation, photorealistic three-dimensional (3D) Computer-Aided Design CAD, multimedia animations, and geographical information systems (GIS).
- **Strategy 4.2.** Develop machines that require software-driven platforms to support complex operations, such as GPS, GIS, and radio-frequency identification (RFID).

Implication 5. Increasing environmental concerns require using recycled content material and heavy construction equipment that is fuel efficient. A possible strategy is:

- **Strategy 5.1.** Provide incentives for contractors using recycled-content materials or green equipment.

5.3.3 Back to the Future

In the Back to the Future scenario, the economy returned to health, and transportation had the technology and resources to grow again. Potential implications of this scenario for transportation construction projects and recommended strategies are as follows:

Implication 1. Due to sustainable economic growth and increased revenue, more funding is available to support large transportation projects. However, material and labor shortages occur due to this growth. A possible strategy is:

- **Strategy 1.1.** Spend additional money on researching ways to optimize operations and improve efficiency by using new and high-technology-based software and tools for construction and maintenance activities. Research topics may include the cost-benefit comparison of adopting building information modeling (BIM) for all future projects and training STA inspectors to use mixed reality (MR) and augmented reality (AR) tools to inspect construction from off-site locations. These technologies allow for totally autonomous construction equipment, which can be programmed in advance and require no real-time human interaction.

Implication 2. The increase in the size and number of construction and maintenance projects and the shortage of material and labor lead to an increase in project costs. A possible strategy is:

- **Strategy 2.1.** Use innovative contracting methods, such as design-build, for integrated project delivery to accelerate projects and meet the need for more highways. Ask contractors to provide feedback during the design phase before the start of construction to improve the contractibility of designs and reduce costly changes during the construction phase.

Implication 3. Advancements in IT and visualization techniques allow for more autonomous construction equipment. Possible strategies are:

- **Strategy 3.1.** Support using digital models and tools at job sites. Field superintendents use AR applications to verify the design and identify, process, and resolve its discrepancies in reality before carrying out the construction activity. MR-based human-machine interfaces provide an immersive and compelling way to view the world, and AR increases worker safety. AR allows the workforce to work in a real-world environment while visually receiving additional computer-generated or modeled information to support and make decisions while performing tasks.

- **Strategy 3.2.** Adopt the use of sustainable infrastructure such as solar roadways. Solar roadways are glass pavement embedded with solar cells that generate power from the sun and store it in batteries that can be used at night. Solar roadways also offer embedded light-emitting diodes (LEDs) to illuminate the road and display information on current traffic conditions. High-strength glass allows tires to grip the roadway and water to run off.

5.3.4 Many Ways to Go

In the Many Ways to Go scenario, the government invests in new transportation information and IT that include significant shares of many different transportation modes. Potential implications of this scenario for transportation construction projects and recommended strategies are as follows:

Implication 1. A new sustainable revenue source comes from a variety of sources including private investment, taxes, and user fees. STAs have many other transportation options for the general public and for movement of goods. A possible strategy is:

- **Strategy 1.1.** Close some of the obsolete road corridors and repurpose them for other uses. These lands are sometimes sold off for a profit, co-developed with the private sector, repurposed as green belts, or repurposed for growing food and even generating alternative energy. Since sustainability is an issue, STAs and the government can use the surplus real estate to develop green infrastructures such as areas to manage (hold and filter) stormwater runoff and recover the damaged ecosystem.

Implication 2. Private investors are eager to get a piece of the steady cash flow from a well-designed multimodal transportation system. The private sector introduces different types of skill sets, including operation research applications for improving efficiency and effectiveness of activities, innovations related to IT (AR, virtual reality [VR], BIM, and GIS), financial and risk management skills, and project management skills. Possible strategies are:

- **Strategy 2.1.** Outsource in-house activities, including maintenance operations. Use new approaches, such as performance-based contracting, total asset management, and performance-specified maintenance contracts, to pay service providers and contractors based on the results achieved, not on the methods for performing the work.
- **Strategy 2.2.** Reinforce project management methodologies for enhancing project configuration management to make sure work performed by multiple private companies are managed in a coordinated way and different parts of the project end item are compatible.

Implication 3. Construction of new transportation systems brings various challenges (staging multiple systems and the integration of systems), which require creativity in transportation design and construction. Universities and research labs seek new designs and schemes to address this need. Execution and quality control tasks are complex in construction projects. Prefabrication and assembly techniques become prevalent, and require a significant amount of structural and construction monitoring during the assembly and construction process. Possible strategies are:

- **Strategy 3.1.** Design a new infrastructure with disassembly and deconstruction techniques in mind. Support techniques for modularization and prefabrication techniques. For example, use precast modular concrete panels formed at an offsite location and installed during off-peak travel times. Use precast panels with built-in scales for weigh-in-motion sites. Support usage of incremental launching methods as well as lateral slide and self-propelled modular transporters for bridge superstructures.
- **Strategy 3.2.** Train construction managers with advanced knowledge in prefabrication and assembly techniques. Increase use of virtual teams and visualization technology during project scoping and design, which will lead to increased innovation of these processes.
- **Strategy 3.3.** Use construction and maintenance activities that support innovative public transit systems. For example, combine visualization techniques with semi-automated technologies for efficient construction, and use simulation models for effective maintenance. Use simulation models to reduce downtime and errors during the construction phase. Use BIM and project management information systems (PMIS) to improve the interoperability among project participants. Enhance communication regarding the project end item (using BIM) and regarding the process of creating the end item (using PMIS).

Implication 4. Autonomous vehicle fleets and transit partners will use new multimodal hubs along highways to bring last-mile services to suburban communities. Many other transportation options are available for the general public and for movement of goods. A possible strategy is:

- **Strategy 4.1.** Support the multimodal approach considering transit users, bicyclists, and pedestrians. Work with cities to provide guidelines for developing neighborhoods and communities that support non-motorists of all ages and abilities. Examples include shared-use paths, safe and well-maintained sidewalks, increased street connectivity, and land-use mix.

5.3.5 Meltdown

In the Meltdown scenario, abrupt climate change shifts priorities from growing the economy to struggling with nature. Potential implications of this scenario for transportation construction projects and recommended strategies are as follows:

Implication 1. Rapid climate change requires a strict policy of reducing GHG emissions. More severe weather and the alternation of drought and heavy rain result in faster deterioration of the existing highway infrastructure. Roads are under increased stress, and bridges are severely damaged in affected regions. The network requires more maintenance in more efficient ways without further affecting the environment. Possible strategies are:

- **Strategy 1.1.** To prevent failure of the network, change design standards and approaches to improve emergency preparedness. Develop technologies to support modularization, efficient construction, and green construction to meet aggressive GHG policy requirements. Modularization and prefabrication significantly improve the efficiency of construction activities related to rehabilitation recovery, such as repairing bridges, clearing debris, and restoring utilities, water, and communication services. Many elements of bridges and structures can be built and prefabricated off site to avoid extreme weather conditions, such as high winds, extreme heat, and heavy rains. Extreme weather conditions directly affect worker productivity and safety in the construction site, and prefabrication also addresses this issue. Prefabrication technology increases the demand for versatility (i.e., transportable cranes capable of handling concrete panels).

- **Strategy 1.2.** To be prepared for post-disaster rehabilitation and recovery, provide reliable communication equipment and emergency response procedures and training for personnel. To make rapid response possible in emergency situations, adopt new contracting regulations that provide flexibility in emergency situations. Require medical equipment and emergency supplies to be available at the construction sites.
- **Strategy 1.3.** Invest in developing and using advanced damage assessment models for assessing the resilience of existing structures and identifying required improvements.

Implication 2. Legislative mandates will require public agencies to have more environmentally friendly processes. Possible strategies are:

- **Strategy 2.1.** Make green construction in transportation a standard practice and a requirement. Recycle construction and demolition debris to further reduce GHG emissions. Incentivize highway contractors to reduce emissions by cutting fuel use through improving efficiency, reducing idling time, performing better equipment maintenance, and using alternative fuels in the field. Incentives include tax credits for contractors that use recycle materials or alternative fuels in the field.
- **Strategy 2.2.** Develop sustainability rating systems to guide contractors and evaluate their work.

Implication 3. Federal policies incentivize states heavily to reduce dependence on non-renewable resources. Possible strategies are:

- **Strategy 3.1.** Take on more project development and delivery with less outsourcing to the private sector. Start supporting labor-intensive public works programs as an economic policy tool to create employment and mitigate the economic downturn resulting from the GHG policies.
- **Strategy 3.2.** Develop sustainability rating systems to guide contractors and evaluate their work. Offer tax credits and incentives for contractors that use recycle materials or alternative fuels in the field.

Implication 4. Transportation shifts toward metropolitan transportation hubs. Possible strategies are:

- **Strategy 4.1.** Develop a new generation of equipment and machinery that are smaller, more maneuverable, and easier to transport to facilitate construction projects in the limited space available in populated areas.
- **Strategy 4.2.** Improve construction methodologies to support city-center-oriented transportation hubs. For example, new construction machinery should be capable of

assessing quality during construction to identify non-conformance with quality requirements. Use positioning systems (sensors) in structural elements and BIM tools for increasing the accuracy of structural element placements and reducing duration and waist.

5.4 Transportation Structures Implications and Strategies

The original version of the transportation structures white paper vision developed as a part of Task 6.1 is included in Appendix E. In the white paper, the research team identified the potential for new tools, technologies, and approaches for four multi-driver scenarios:

- The baseline scenario—Managed Decline.
- Back to the Future.
- Escape to the Centers.
- Meltdown.

The implications extracted from the white paper were further developed into specific strategies on how new materials, tools, approaches, and technologies can be used to provide a means for enhancing system preservation, maintenance, and renewal in response to anticipated future challenges for the transportation structures area.

5.4.1 Description of Transportation Area: Transportation Structures

The discussion of *transportation structures* in this white paper focuses on the design and construction of new structures to both renew and expand the highway system, as well as the ongoing maintenance and preservation of existing structures. Transportation structures include but are not necessarily limited to:

- Bridges, viaducts, and culverts.
- Tunnels and their ancillary equipment.
- Earth-retaining structures.
- Structural supports for highway signs, luminaires, and traffic signals.

5.4.2 Baseline Scenario: Managed Decline

In the baseline scenario, much of the future turned out as expected. The potential implications of this scenario for transportation structures and recommended strategies are as follows:

Implication 1. Due to the economic malaise, traditional governmental tax and spending are mostly directed to social entitlements, leaving less than necessary resources for infrastructure. Insufficient funding is available for maintenance and renewal of highway system, which causes assets to have to serve beyond their design life. A possible strategy is:

- **Strategy 1.1.** Divert most funding to maintenance. Very little will be available for renewal, so focus on retrofitting and upgrading existing bridges and tunnels.

Implication 2. The aged and functionally obsolete structures still require replacement, but the funding available is insufficient for renewal. A possible strategy is:

- **Strategy 2.1.** Perform mostly on-line renewals under lane closures. Arrange contracts so that most work and maintenance are done at night or under partial closure to minimize congestion. The workforce will need to become quite sophisticated.

Implication 3. The lack of capital for land acquisition results in highways renewed where possible but rarely expanded, leading to congestion of the existing system, especially during maintenance. A possible strategy is:

- **Strategy 3.1.** Replace functionally obsolete structures; e.g., many bridge decks require widening as a preferred method to replacement. The remaining life of assets remains an issue for older upgraded structures. Defer replacement through rejuvenation to extend life by about 25 years.

Implication 4. Due to the government playing a controlling role, funding through PPPs is very limited. At the same time, STAs face high expectations from public users for the quality of new assets. A possible strategy is:

- **Strategy 4.1.** Double design life to 150 years; however, this leads to more costly projects and fewer asset replacements and expansions. Specify durable high-strength materials (stainless steel and ultra-high performance concrete.). Use longer bridge spans to minimize the environmental damage/footprint.

Implication 5. The increase in freight demand results in wear and tear taking a toll on the existing bridge asset inventory. This increases the large backlog of deferred maintenance. Possible strategies are:

- **Strategy 5.1.** Develop existing and new methods to address and reduce the fatigue proneness of aging bridge infrastructure. One method is to provide continuity between existing simple span systems for steel and pre-stressed concrete bridges.
- **Strategy 5.2.** Tunnel linings deteriorate over time due to toxic exhaust fumes. Renew and upgrade tunnel linings.

5.4.3 Back to the Future

In the Back to the Future scenario, the economy returns to health, and transportation has the technology and resources to grow again. Potential implications of this scenario for transportation structures and recommended strategies are as follows:

Implication 1. The country's economic growth is high, and this leads to capital aplenty in all economic sectors: high-tech industries abound, sensor networks abound, and there is more investment for transportation. However, this growth results in material and labor shortages due to competition from other sectors of the economy and tends to short-change the transportation sector. A possible strategy is:

- **Strategy 1.1.** Creative finance portfolios thrive for investment in civil infrastructure, particularly big-ticket items such as bridges, tunnels, and other similar large turnkey new assets. The burgeoning robotics industries reduce the laborious manual tasks of the past. Deploy sensor networks to trigger just-in-time maintenance of the existing transportation sector. The expansion of new highway systems leads to development of an exotic new range of bridges and tunnels. Minimize maintenance of existing structures; use renewal and expansion as a more robust long-term investment.

Implication 2. The government attitude of "tax and spend" shifts to "invest for a return to the owner." The government would prefer that ownership reside in the private sector, especially for big-ticket items such as bridges and tunnels. A possible strategy is:

- **Strategy 2.1.** Seek revenues from new sources intrinsic to the highway system. For example, seek energy-harvesting opportunities from vibrations in bridges to drive low-voltage sensors and bridge lighting. Use pile foundations as an energy source for heat to de-ice bridge decks and nearby approach pavements in the winter. In the summer, use the system for deck cooling, which minimizes adverse thermal stresses in bridge decks.

Implication 3. Due to the increase in road freight, more freight and higher axle loads are permitted. This results in greater bridge (fatigue) deterioration, and new bridges are preferred. A possible strategy is:

- **Strategy 3.1.** Replace prematurely aged bridges with a family of new high-performance fatigue-resistant structures. Prioritize continuous pre-stressed (high-performance) concrete structures.

Implication 4. The increase in road freight results in more wear and tear on older (20th century) structures. The fatigue life of bridges is halved, and bridge decks and pavements need renewal on a more frequent cycle. Possible strategies are:

- **Strategy 4.1.** Maintain older structures. This burden remains with the state.
- **Strategy 4.2.** Renew ill-maintained structures. The preferred course of action is to remove the assets from the state's liability list.
- **Strategy 4.3.** Maintain older mega-structures that cannot be quickly replaced (such as historic iconic bridges) as was done historically.

Implication 5. The debate of public versus private ownership of assets is resolved. The private sector gradually takes over ownership of former public-sector assets. This practice becomes the socially responsible thing to do because the investment is long term and dependable. Possible strategies are:

- **Strategy 5.1.** Transfer the highway system, bridges, tunnels, and other major highway assets to private ownership. The private sector is responsible for maintenance and indemnification against loss. Leased use is made back to the state and motoring public.
- **Strategy 5.2.** Allow individual assets, such as bridges and tunnels, worth up to $100 million to be traded as commodities on capital markets. They are considered a solid and stable investment due to their long life and relatively low maintenance cost.
- **Strategy 5.3.** Allow significant assets to be owned by small groups of investors and individuals. The investment is attractive due to tax incentives.

Implication 6. Due to funding and the government role in ownership of highway sections, the design-build-own-operate-lease-back model is used for longer sections of highways (tens to hundreds of miles). Possible strategies are:

- **Strategy 6.1.** Vest ownership of the billions of dollars in assets (which include the subgrade all the way up to bridges and other major structures) in big corporations.
- **Strategy 6.2.** Allow initial ownership to be held with the developer/constructor/contractor, and then to be sold within five years of commissioning to other large corporations that want to minimize their stock volatility with stable investments. Pension funds and other quasi-government agencies invest heavily on behalf of their employees.

Implication 7. The increase in technology development, automated construction, accelerated construction for bridges (ABC), and other assets becomes common practice. A possible strategy is:

- **Strategy 7.1.** Use ABC to minimize the time cost of money, and to minimize high congestion on operational highway systems. ABC consists of using lightweight, high-strength, high-performance components. ABC matures to become the norm rather than the exception. Perform most construction at night or other off-peak hours. For specific assets:
    - *Bridges:* Specify design and construction methods to capitalize on using high-performance materials (ultra-high performance concrete and stainless steel) and modular construction that involves longer spans and wider decks with a smaller (greener) footprint. Embedded sensors are commonly used in critical members.
    - *Tunnels:* Simplify construction methods to encompass mostly rapid, modular cut-and-cover approaches to provide extra lane capacity beneath existing crowded cities. Low-vibration boring machines are developed using significant robotics.
    - *Earth-retaining structures:* Use cut slopes, embankment fills, and retaining walls extensively to avoid tunneling where possible.

5.4.4 Escape to the Centers

In the Escape to the Centers scenario, the lack of mobility and increased threats to individuals' well-being drive people out of the suburbs and into the city, reducing the demand for transportation—the arrival of the vision for the advocates of smart growth. The potential implications of this scenario for transportation structures and recommended strategies are as follows:

Implication 1. The increase in higher population density causes the population concentration to exceed 20 million in approximately a dozen mega-cities. A possible strategy is:

- **Strategy 1.1.** Curb travel demand through policy incentives, telecommuting, and other modern communications. However, getting freight between main centers is demanding and puts a heavy burden on the wear and tear of bridge structures in particular. Provide freight corridors with higher-load-rated bridges.

Implication 2. The higher population density results in lower VMT, congestion due to societal densification, difficulty in maintenance work due to continual congestion, difficult/costly renewals, scarcity of land for expansion, and slow expansion due to environmental permitting obstacles. Possible strategies are:

- **Strategy 2.1.** Meet lane capacity needs in densely populated cities by implementing long sections of elevated viaducts (preferred) and cut-and-cover tunnel systems beneath city streets.
- **Strategy 2.2.** Maintenance is often performed by complete road closure for up to one week. To minimize disruption and congestion, use the get-in-get-out-fast approach to complete sections or roadways that need to be entirely rehabilitated.
- **Strategy 2.3.** Perform renewals in a piecemeal fashion (e.g., decks or substructure but not both) as an on-line renewal within an operational system.
- **Strategy 2.4.** Rarely fund new expansion projects because delivery times are lengthy. Prioritize on-line renewals/rehabilitation of existing systems.

Implication 3. The low mobility capacity results in more bicycle and pedestrian traffic. A possible strategy is:

- **Strategy 3.1.** Develop pedestrian (and cycle-way) bridges and under-road culverts/mini-tunnels to meet increasing demand.

Implication 4. The demand for automated construction results in wide use of robotics for renewal and maintenance to minimize labor. Possible strategies are:

- **Strategy 4.1.** Perform off-site manufacture of most structures, bridge decks, piers, culverts, and tunnel linings using strong, lightweight members. Maximize mechanization installation.
- **Strategy 4.2.** Construct long viaducts above existing roadways using large traveling road-train gantry erectors. This permits continued use of the roadway beneath it during construction.

5.4.5 Meltdown

In the Meltdown scenario, the pessimistic scenarios for climate change ended up being more accurate than the optimistic ones. As a result, the most important priority for the next few decades is struggling with nature rather than growing the economy. The potential implications of this scenario for transportation structures and recommended strategies are as follows:

Implication 1. Natural disasters occur throughout the United States and markedly affect the dense population centers. These are low-probability, high-consequence events of either the tectonic or weather type. A possible strategy is:

- **Strategy 1.1.** This strategy includes:
  - *Preparedness and pre-disaster prevention:* Implement damage-avoidance seismic design on major structures. Continue, extend, and refine retrofitting programs.
  - *Response* (first 72 hours): Draw down and quickly exhaust maintenance budgets.
  - *Recovery:* Divert capital budgets to reconstruction.

Implication 2. Due to the tectonic-related widespread destruction of these low-probability, high-consequence events, the government takes charge of response and recovery. A possible strategy is:

- **Strategy 2.1.** The strategy includes:
  - *Preparedness and pre-disaster prevention:* Implement damage-avoidance seismic design on major structures. Continue, extend, and refine retrofitting programs.
  - *Response* (first 72 hours): Draw down and quickly exhaust maintenance budgets.
  - *Recovery:* Divert capital budgets to reconstruction.

Implication 3. The tectonic-related widespread destruction results in severe damage to bridges due to shaking and ground failure. A possible strategy is:

- **Strategy 3.1.** Shore up bridges where possible for immediate (but restricted) reuse (up to one year). Divert capital budgets to reconstruction. Due to extraordinary demand for accelerated construction, implement a huge price surge (50–100 percent) to incentivize early completion. Innovation is restricted due to the haste of reconstruction.

Implication 4. Due to tectonic-related widespread destruction, tunnels are moderately damaged, often causing portals to collapse, rock to falls in unlined tunnels, and lining to fail in lined tunnels. A possible strategy is:

- **Strategy 4.1.** Repair tunnels during recovery. This repair is relatively straightforward although slow due to ongoing safety concerns. The public is very nervous about reuse. Therefore, abate tolls to encourage reuse of facilities.

Implication 5. The tectonic-related widespread destruction results in common failure of retaining walls and engineered slopes. A possible strategy is:

- **Strategy 5.1.** Retaining wall repair methods are slow and dangerous due to ongoing instability. Deploy innovative (but costly) methods to improve safety and stability.

Implication 6. The tectonic-related widespread destruction severely damages signs, signals, and other services. A possible strategy is:

- **Strategy 6.1.** Convert control systems to local temporary wireless systems or the old manual methods on a temporary basis.

Implication 7. The natural weather-related disasters are higher-probability, moderate-consequence events over widespread areas: coastal flooding, inundation storm surges, inland river flooding and washouts, and tornados. Many are not limited to the plane states. Blizzards are increasingly common in northern states. Due to weather-related widespread destruction, the government takes charge of response and recovery. A possible strategy is:

- **Strategy 7.1.** The strategy includes:
  - *Preparedness and pre-disaster prevention:* Implement damage-avoidance weather-proofing designs on major structures and waterways where possible. Strengthen levees, and retrofit bridges to avoid washouts.

- *Response* (first 72 hours): Draw down and quickly exhaust maintenance budgets.
- *Recovery:* Divert capital budgets to reconstruction.

Implication 8. The weather-related widespread destruction results in severe damage to bridges due to scour approach-embankment ground failure. A possible strategy is:

- **Strategy 8.1.** Shore up bridges where possible for immediate (but restricted) reuse (up to one year). Divert capital budgets to reconstruction. Implement a huge price surge (50–100 percent) to accelerate construction activities and to incentivize early completion.

Implication 9. Due to weather-related widespread destruction, tunnels are moderately damaged, often causing portals to collapse. A possible strategy is:

- **Strategy 9.1.** Recover relatively rapidly after de-watering. The public is very nervous about reuse, so abate tolls to encourage reuse.

Implication 10. The weather-related widespread destruction results in common failure of retaining walls and engineered slopes. A possible strategy is:

- **Strategy 10.1.** Repair methods are slow and dangerous due to ongoing instability. Deploy innovative (but costly) methods to improve safety and stability.

Implication 11. The weather-related widespread destruction severely damages signs, signals, and other services. A possible strategy is:

- **Strategy 11.1.** Convert control systems to local temporary wireless systems or the old manual methods on a temporary basis.

5.5 Roadside and Drainage Implications and Strategies

The original version of the roadside and drainage white paper vision developed as a part of Task 6.1 is included in Appendix F. In the white paper, the research team identified the potential for new tools, technologies, and approaches for four multi-driver scenarios:

- The baseline scenario—Managed Decline.
- Back to the Future.
- Many Ways to Go.
- Meltdown.

The implications extracted from the white paper were further developed into specific strategies on how new materials, tools, approaches, and technologies can be used to provide a means for enhancing system preservation, maintenance, and renewal in response to anticipated future challenges for the roadside and drainage area.

5.5.1 Description of Transportation Area: Roadside and Drainage

The term *roadside and drainage* describes the transportation facility area between the edge of the pavement and the right-of-way (ROW) boundary that has the general functions of:

- Stormwater conveyance, treatment, and storage.
- Pedestrian, bicycle, streetscape, and other activities.
- Vegetation management for safety, traffic operations, and invasive weed control.
- Creation/maintenance of self-sustaining and complex biological/ecological systems.
- Erosion control for infrastructure stability.
- Roadside development for aesthetic enhancement.

5.5.2 Baseline Scenario: Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for transportation facilities' roadside and drainage issues and recommended strategies are as follows:

Implication 1. Lower consumption of gasoline results in a lower amount of revenue generated from the gas tax for transportation and increasingly scarce funding for transportation. Due to the lower amount of funding, STAs are continuously faced with enormous challenges to simply maintain and rehabilitate an aging system of highway infrastructure, and there is less emphasis on capacity expansion and large construction projects. A possible strategy is:

- **Strategy 1.1.** Design more efficient roadsides. Water conservation and reuse are at the forefront. Require roadside design techniques that maximize efficient designs for stormwater quality and quantity control. This includes sustainable, low-impact development that requires less maintenance.

Implication 2. Due to scarce governmental funding, a higher proportion of funding for new capacity is provided by the private sector, and private investment becomes increasingly sought to provide maintenance where it is needed. A possible strategy is:

- **Strategy 2.1.** Seek partnerships with public/private entities for roadside management. Urban and suburban roadside vegetation management/maintenance activities are mostly privatized, or contracted by local/municipal agencies and volunteer groups. Design and install the minimum necessary to meet regulatory requirements for effective erosion control and vegetation establishment. Negotiate agreements with other entities for installations and maintenance beyond this scope.

Implication 3. Technological advances facilitate much higher use of IT in both vehicles and infrastructure. Next-generation in-vehicle and infrastructure technologies provide improved flow and safety. Progress in IT allowed for the development of autonomous vehicles and semi-autonomous roadside maintenance equipment, yet human interaction is still an integral part of roadside management/maintenance. The roadside management/maintenance workforce is more sophisticated to accommodate the increased technology present in the ROWs. A possible strategy is:

- **Strategy 3.1.** Consider technology impacts through all phases. Use autonomous and semi-autonomous vehicles and equipment in roadside maintenance and repair activities. Implement strategic training to support the technology needed for these systems located within the ROWs; the technology requires more sophisticated management and maintenance techniques to conduct routine roadside operations and drainage activities without disruption of service. Personnel tasked with the planning, design, construction, and maintenance of transportation facilities incorporate technology in all phases of planning and operation. Many IT-to-vehicle commands are sent via wireless communications, but put backup systems in place within the roadsides to meet emergency demands. Work with universities or colleges that offer design/construction programs to prepare the transportation industry for the next generation of workers.

Implication 4. Due to limited funding, less opportunity exists to expand ROWs. A possible strategy is:

- **Strategy 4.1.** The diminishing roadside within the ROW is a complex mixture of utilities, IT, and transportation modes. Coordinate and cooperate with multiple users for the best use of the space.

Implication 5. Increasing environmental concerns require more efficient and effective roadside development and drainage designs. A possible strategy is:

- **Strategy 5.1.** Use roadside equipment that is efficient in using green technology and practices for less energy consumption. Design the roadside to be more efficient and effective, with drainage designs that focus on stormwater conveyance, storage, treatment, and reuse. Use porous pavements as a means of mitigating stormwater runoff and providing a natural filtration treatment for typical highway pollutants before they reach groundwater tables, streams, rivers, and lakes.

Implication 6. More severe weather results in the deterioration of roadways, and more highways will be underwater in low-lying areas. A possible strategy is:

- **Strategy 6.1.** Respond to severe weather events proactively rather than reactively. Train maintenance and aftermath cleanup personnel to deal with the safety hazards produced by power outages and debris on roadways and roadsides. Replace aging drainage infrastructure with pipes, culverts, etc. that have a greater capacity to further facilitate the movement of water away from roadways and areas inundated by extreme weather events.

Implication 7. The increase in freight demand results in increased wear on the roadways and increased demand for freight trains. Freight traffic volume increases traffic incidents and spills. A possible strategy is:

- **Strategy 7.1.** Allocate additional personnel for cleanup and removal.

5.5.3 Back to the Future

In the Back to the Future scenario, the economy returned to health, and transportation had the technology and resources to grow again. Potential implications of this scenario for transportation facilities' roadsides and drainage issues and recommended strategies are as follows:

Implication 1. Due to sustainable economic growth, there is high transport use, and more specifically, freight traffic is higher, resulting in an increased potential for introduction of invasive species and habitat degradation. A possible strategy is:

- **Strategy 1.1.** Implement rigorous freight inspection and tracking. Use highway designs and materials that minimize the impacts from large and heavy freight loads. Develop proactive and rigorous methods for inspecting and tracking cargo to reduce the introduction of invasive and undesirable plant and animal species through international freight movement.

Implication 2. Economic growth increases use of resources, resulting in an increase in the cost of transportation activities. A possible strategy is:

- **Strategy 2.1.** Use the roadside as a commodity. Treat the ever-diminishing ROW as a valuable commodity for use/lease/trade in alternative energy and fuels production, and carbon sequestration/offsets.

Implication 3. Advancements in technology provide the opportunity to improve the efficiency and effectiveness of roadside and drainage activities. Possible strategies are:

- **Strategy 3.1.** Train and retain a more sophisticated workforce. Equip roadside management and maintenance personnel with advanced IT vehicles and robotic equipment to increase worker safety and efficiency. Use unmanned aerial vehicles (UAVs) to monitor drainage structures, habitats, and waterways, and to inspect construction sites for environmental regulatory compliance.
- **Strategy 3.2.** Use autonomous and semi-autonomous vehicles that use IT sensor networks to sense danger, avoid the danger, and redirect the vehicle. This technology diminishes the need for a safety clear zone in some areas, giving transportation agencies valuable space for alternative travel modes and streetscapes. In rural areas, use surplus ROWs for energy capture and reuse such as solar, wind, and biofuel.
- **Strategy 3.3.** Make roadsides more efficient. Roadside vegetation and soils are designed to maximize their effectiveness for stormwater treatment and carbon sequestration. Use soils and soil amendments that are biotechnically enhanced to work in concert with the plants and stormwater to retain available moisture, consume pollutants, and enable greater carbon capture. Enhance soils using genetically engineered microorganisms and adapted recycled materials.
- **Strategy 3.4.** Use designer pavements, and reuse stormwater. Research produces designer pavements that use specialized aggregates that work at the molecular level to chemically bond with and remove the specifically targeted pollutants from stormwater runoff. This technology eventually leads to totally permeable roadways able to remove the targeted pollutant, capture it, store it, and treat surface runoff under the roadway. The treated stormwater is then discharged to municipal non-potable or grey-water storage facilities for reuse.

5.5.4 Many Ways to Go

In the Many Ways to Go scenario, the government invests in new transport technology and IT that include significant shares of many different transportation modes. Potential implications of this scenario for transportation facilities' roadside and drainage issues and recommended strategies are as follows:

Implication 1. A new sustainable revenue source exists from private investment. Private investors are eager to get a piece of the steady cash flow from a well-designed multimodal transportation system. A possible strategy is:

- **Strategy 1.1.** Cluster maintenance activity at transportation hubs. Urban areas may consist of dedicated areas such as transportation hubs. Although many of these are privatized, some STA responsibilities exist. Management and maintenance of such facilities require advanced training to meet ever-changing technologies. As with any cluster of human activity, trash, debris, and other pollutants remain a maintenance concern. As the number of these facilities increases, so does the need for private-sector investment, not only for construction but for long-term maintenance requirements. Many have additional aesthetic components that come with restaurant and retail clusters at these locations that add to the maintenance and operations requirements.

Implication 2. High-technology development increases the opportunity for implementing real creativity in transportation design. Universities and research labs churn out designs and schemes. A possible strategy is:

- **Strategy 2.1.** Use ROW for biomass production. Alternative binders for asphalt and concrete pavements will be developed that reduce petroleum resource consumption or energy required for production. The low-carbon binders from biomass will become more common and viable as the price of traditional asphalt and concrete binders continues to increase.

Implication 3. The gas and carbon tax provides additional revenues. A possible strategy is:

- **Strategy 3.1.** Accommodate IT applications in transportation for most travel modes. IT systems and active transportation modes necessitate system support. Embed pavements, structures, and roadsides with sensors tied to IT systems in vehicles and equipment.

Implication 4. The multimodal approach results in new multimodal hubs along highways. Autonomous vehicle fleets and transit partners use these hubs to bring last-mile services to suburban communities. Possible strategies are:

- **Strategy 4.1.** Implement complete streets and active transportation policies. These policies impact the roadsides in limiting the available space to perform necessary roadside functions. Not only are separate access lanes/paths provided, but many travel lanes are designated for other uses such as streetscape development, with additional landscape plantings and other appurtenances that require management and maintenance.
- **Strategy 4.2.** Manage the competition for useful space within the ROW. There is fierce competition for roadside space in the built-out environment. Innovations in porous or

pervious pavements help to maintain site hydrology by facilitating movement of stormwater while providing usable multi-purpose surfaces. Snow removal and storage are problematic with limited space. Strategic roadways use solar energy to power subsurface heating to reduce the quantity of snow that needs to be removed and stored at these locations.

- **Strategy 4.3.** Re-purpose obsolete roadways. Many transportation options are available for the general public and for movement of people and goods. Consider options such as selling ROW, co-developing with the private sector, repurposing as green belts or for growing foods, and generating alternative energy. Sustainable practices include use of the surplus real estate to develop green infrastructures such as areas to manage (hold and filter) stormwater runoff and recover the damaged ecosystem. Roadside and drainage activities related to repurposing include the development of sustainable landscape areas; restoration and preservation of diverse habitats/ecologies; incorporation of stormwater collection, treatment, and reuse systems into the landscape; and surfacing of bike paths and walkways that maintain site hydrology. More landscape maintenance activities grow out of these transformations.

5.5.5 Meltdown

In the Meltdown scenario, abrupt climate change shifts priorities from growing the economy to struggling with nature. Potential implications of this scenario for transportation facilities' roadside and drainage issues and recommended strategies are as follows:

Implication 1. Rapid climate change results in more severe weather. Alternation of drought and heavy rain results in increased stress, and bridges are severely damaged in affected regions. The infrastructure system is compromised by roadside/slope instability. A possible strategy is:

- **Strategy 1.1.** Minimize the impacts of extreme weather events through emergency preparedness. Minimize the burden of restoring utilities, water, and communication services through their relocation to the subsurface. Roadside areas are valued as evacuation corridors and designed as alternative traffic lanes. Structural pervious surfaces accommodate vehicle flow demands while maintaining stormwater drainage capacities to the maximum extent possible. The ROWs are a conduit for re-routing excessive water via pipelines to facilities for desalination and/or grey-water storage/treatment and distribution for non-potable uses.

Implication 2. Concerns for environmental quality and sustainability change priorities from growing the economy to struggling with nature. A possible strategy is:

- **Strategy 2.1.** Reduce GHG. Comply with environmental regulations by using alternative fuels and/or fuel-efficient equipment. The ever-diminishing roadside area becomes a focus for its ability to sequester carbon in the soil and vegetation. Use genetically engineered vegetation and designer soils to maximize roadsides' effectiveness for water quality and quantity treatment, and carbon sequestration.

Implication 3. The carbon and gas tax results in a price surge and increases the cost of energy and materials. VMT decreases with the carbon tax and caps. The increase in price results in increased SOV operation costs, decreasing its use. Transit and multimodal transportation become true substitute goods for SOVs. Heavier battery-powered vehicles cause more wear on roadways. A possible strategy is:

- **Strategy 3.1.** Make roadsides more efficient. Roadside vegetation and soils are designed to maximize their effectiveness for stormwater treatment and carbon sequestration. Use soils and soil amendments that are biotechnically enhanced to work in concert with the plants and stormwater to retain available moisture, consume pollutants, and enable greater carbon capture. The soils are enhanced using genetically engineered microorganisms and adapted recycled materials.

Implication 4. The government increases its role in environmental regulation and monitoring. Federal policies incentivize states heavily to reduce dependence on non-renewable resources. A possible strategy is:

- **Strategy 4.1.** Generate public works projects that solve problems. Severe and repetitive weather events generate widespread and enduring power outages that are safety hazards for the general public and the maintenance workforce tasked with clean-up, repair, and restoration. Implement public works projects including burying all overhead pole/wire-based technologies subject to high winds, extreme heat, wildfires, and severe storms. Work together with municipalities, private-sector communications, and utilities to determine the best approaches to accommodate numerous services such as telephones, electricity distribution, natural gas, cable television, fiber optics, traffic lights, street lights, storm drains, water mains, and wastewater pipes. In some locations, major oil and gas pipelines, national defense communication lines, mass transit, rail, and road tunnels also compete for space underground in an ever-diminishing roadside area.

Implication 5. Due to the increase in population density, transportation shifts to metropolitan transportation hubs. A possible strategy is:

- **Strategy 5.1.** Use more efficient equipment. Renewal and maintenance of roadways in the limited space available in populated areas lead to the development of a new generation of equipment and machinery that are smaller, more maneuverable, and easier to transport.

5.6 Connectivity Implications and Strategies

The original version of the connectivity white paper vision developed as a part of Task 6.1 is included in Appendix G. In the white paper, the research team identified the potential for new tools, technologies, and approaches for four multi-driver scenarios:

- The baseline scenario—Managed Decline.
- Government Redux.
- Bits over Buses.
- Meltdown.

The implications extracted from the white paper were further developed into specific strategies on how new materials, tools, approaches, and technologies can be used to provide a means for enhancing system preservation, maintenance, and renewal in response to anticipated future challenges for the connectivity area.

5.6.1 Description of Transportation Area: Connectivity

The term *connectivity* in this study focuses on how highway infrastructure interfaces with all other modes: transit, aviation, ports, trains, subways, pedestrians, and cycling. The highway infrastructure can interact with these modes in essentially two ways:

- Direct integration—these modes can be incorporated into the highway system either longitudinally or laterally: transit, passenger rail, pedestrians, bicycles, and trucks/commercial.
- Indirect integration—these modes will not likely have direct integration with highways, but highway planning could incorporate techniques for enhancing accessibility to them: aviation, ports, subways, and freight rail.

5.6.2 Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for transportation connectivity and recommended strategies are as follows:

Implication 1. In the baseline scenario, in general, less funding is available for developing new capacity and ongoing maintenance and operations of existing infrastructure. A possible strategy is:

- **Strategy 1.1.** Make transit, walkable cities, and bus services high priorities. State and local governments coordinate efforts to modify existing infrastructure to support multiple modes.

Implication 2. Due to the decrease in VMT, per-capita growth in the demand for mobility becomes slower, which results in declining pressure on growth in roadway capacity. A possible strategy is:

- **Strategy 2.1.** Accommodate demand growth through technology-enabled mobility and system operations across modes, placing a lower priority on increasing capacity. Multimodal infrastructure operations will take a more prominent role, and a workforce that is oriented toward system management will be critical to maintenance and preservation activities.

Implication 3. High population density closer to work and retail creates extreme localized congestion in urban core areas. A possible strategy is:

- **Strategy 3.1.** As densification promotes the viability of transit and non-motorized modes, engage with partners to enhance alternative modes, expanding mission and performance management toward mobility rather than highways.

Implication 4. Technological advances facilitate much higher use of IT in both vehicles and infrastructure. Next-generation in-vehicle and infrastructure technologies provide improved safety and reliability in a data-rich environment that facilitates traveler choices. A possible strategy is:

- **Strategy 4.1.** Maintain staff knowledgeable about IT. Skills in data integration and analysis are required to optimize multimodal system performance.

5.6.3 Government Redux

In the Government Redux scenario, the government reasserts itself as the primary driver of transportation in the United States and develops the funding resources to do so. Potential implications of this scenario for transportation connectivity and recommended strategies are as follows:

Implication 1. Under this scenario, the government increases its revenues for transportation projects through taxes and user fees. High investment in additional capacity reduces the demand for multimodal transportation. A possible strategy is:

- **Strategy 1.1.** Adequate funding for transportation results in mega-projects that overcome space barriers through tunneling or elevated structures. Reorganize the agency into highly efficient, strategically managed units.

Implication 2. The government strengthens its role in determining how technology is applied to transportation projects to improve performance. A possible strategy is:

- **Strategy 2.1.** Focus heavily on ITS and improving road operations that integrate multiple modes seamlessly.

5.6.4 Bits over Buses

In the Bits over Buses scenario, higher than expected increases in crude oil prices reduce the ability of ordinary people to travel as much as they used to. They turn instead to an expanded Internet, not only for communication but also for most work and leisure activities that previously required physical movement. Potential implications of this scenario for transportation connectivity and recommended strategies are as follows:

Implication 1. Although transit demand and consumer-level trips decrease in this scenario, companies must still ship goods. Freight movement is still required—and increases—to sustain commerce. A possible strategy is:

- **Strategy 1.1.** Focus on improving freight throughput and efficiency. Convert special-use facilities to freight hubs and dedicated commercial vehicle lanes. Convert ROW to rail.

Implication 2. The decreased demand for mobility from expanded IT results in lower VMT. This creates opportunities in other transportation areas to improve their capabilities. For example, for the construction area, a great opportunity exists to improve real-time monitoring of equipment and activities, for pavements and structures to expand the application of embedded sensors that signal use and wear, for roadside technologies to enhance the use of sensors that warn vehicles away from fixed objects, and for traffic services to invest in using real-time alerts to re-route traffic around construction or accidents. A possible strategy is:

- **Strategy 2.1.** Goods movement will be the focus of demand on the system. Prioritize IT systems that support efficient goods movement. Create IT systems that facilitate real-time asset management, such as providing real-time information to travelers—both commercial and non-commercial—that offers guidance on the optimum travel mode and departure time, coordinated centrally to smooth demand.

5.6.5 Meltdown

In the Meltdown scenario, the most pessimistic climate change projections end up being more accurate than the optimistic ones. As a result, the most important priority for the next few decades is struggling with nature rather than growing the economy. Potential implications of this scenario for transportation connectivity and recommended strategies are as follows:

Implication 1. Climate change results in severe weather, with roads under increased stress due to the alternation of drought and heavy rain. Bridges are severely damaged in affected regions. A possible strategy is:

- **Strategy 1.1.** More directly engage in multimodal options for response to severe weather events. For example, make transit a more integral mode in evacuation and response planning.

Implication 2. The gas and carbon tax results in a price surge, increasing the cost of driving for all motorists. VMT declines as a result, and transit and multimodal transportation become true substitute goods for SOVs. A possible strategy is:

- **Strategy 2.1.** Invest heavily in transit and multimodal travel solutions. Refocus on optimizing multimodal integration through gathering and analyzing data. Managed and special-use lanes proliferate as bus transit and carpooling become the norm.

Implication 3. The government enhances its role in environmental regulation and monitoring, creating federal policies that incentivize states heavily to reduce dependence on non-renewable resources. A possible strategy is:

- **Strategy 3.1.** Integrate data across modes and government agencies for operational optimization and notification of the public under emergency situations. Environmental regulation will incentivize modes that reduce fossil-fuel use.

Implication 4. Increasing urban density results in lower VMT, but congestion is rife due to societal densification and limitations on space for expansion. Continual congestion causes preservation of the infrastructure to be more difficult and costly. A possible strategy is:

- **Strategy 4.1.** As densification promotes the viability of transit and non-motorized modes, engage with partners to enhance alternative modes, expanding mission and performance management toward mobility rather than highways.

6.0 APPENDIX A - FULL DESCRIPTION OF MULTI-DRIVER CONTEXT SCENARIOS

6.1 Baseline Scenario—Managed Decline (Developed during Phase II)

Table A.1 shows the key elements for this scenario.

Table A.1. Key Scenario Elements for Managed Decline.

Scenario	Key Drivers	Scenario Kernel
Managed Decline	All 18 Drivers	

What was amazing about how things turned out was how utterly predictable it all was. Futurists had been warning us ever since the 2010s to "expect the unexpected" and "be prepared to be surprised." What actually happened, however, was exactly what was expected. Most of the trends that had been going on since the 1990s pretty much continued, and relatively few events occurred to disrupt them. We had some breakthroughs and successes, but they were too few and too weak to stem the tide toward a measurably degraded highway system in 2040. The fact that it was expected, however, did not make it any easier, but at least we had time to smoothly adapt to a much different world.

The petroleum age was waning in the 2010s but ever so slowly. The price of gasoline was volatile, but overall it had increased significantly in the last 30 years, just as it had in the previous 30. New supplies, much of it in the United States, kept the price rise manageable, but no one could prevent the inevitable. Fuel cost was taking a larger share of the family budget, but that was something that people felt they could do something about—albeit with difficulty.

One result was that voters supported more aggressive fuel standards, both at the voting booth and at the car dealership. That hit the gas tax right away.

The second result was that people simply drove less—combining trips, carpooling (did we ever think that would happen?), running errands on the way home from work, taking more public transit (buses rather than trains because they were cheaper), and taking fewer automobile vacations and trips to the beach. People now stopped to think whether the trip was worth it, whereas previously they had just jumped in the car and driven off.

Going to work was still the major use of personal vehicles, but now people went to work less. Slowly they negotiated flex hours (three- and four-day weeks) along with the ability to work at home. And eventually, though it took many decades, the form of the urban space changed—higher density, not only in the central core but surrounding the satellite business centers. More condos, more apartments, and even smaller lots with retail interspersed meant that the mega shopping malls had disappeared about 15 years ago. Walking was in; driving was out. People no longer expected to be able to "go anywhere, anytime" the way their parents and grandparents had.

Total VMT was actually still going up, though quite slowly, due to larger populations and more economic activity, but VMT per capita was decidedly down. That meant that the gas tax, barely larger than its 2010 levels due to a tax-averse government and population, was bringing in only about two-thirds of what it had been at its peak. Added to that decline was the surprising strength of natural-gas-powered vehicles, which further cut into the consumption of gasoline and its associated tax. Governments instituted a natural gas tax at the service station, but many people were fueling at home, making the collection most difficult. Many states had proposed a surtax on excessive use of gas at home, but every agency from transportation to public safety to environmental quality to energy regulation was fighting for a piece of that pie. And with three-dimensional printing everywhere, for which gas was a common feedstock, one could not be sure that the gas was going into a vehicle.

So the amount of revenue generated from gasoline and natural gas taxes at the fueling station had to cover the maintenance and preservation of an aging system, even though the cost of materials and construction had increased at more than the rate of inflation over all those years. And forget about expansion! The private sector toyed with the idea of stepping in, but that made little business sense since the projects were so huge and expensive, and the expectation of return on investment was actually declining.

Technology had done its part to retard the trend. New materials and better practices, particularly clever IT systems, made the roads marginally safer, less congested, and a little less expensive than they would otherwise have been. But highway construction and maintenance were mature technologies, even 30 years ago, so few real blockbusters had appeared. Fewer research and development (R&D) labs were turning out fewer innovations in a downward spiral of less opportunity and less funding.

The result was a highway system that had reached the end of its design life. There was no money to fix it, much less to expand it.

Potential Implications for Transportation

In the Managed Decline scenario, the continuation of current trends results in a measurably degraded highway system, but agencies and users adapt. Significant increases in fuel prices and reduction in serviceable highway capacity have multiple effects that are interrelated and compounding:

- Users shift to more fuel-efficient vehicles in response to fuel price. The shift to higher-efficiency and alternative-fuel vehicles causes a sustained decline in highway funding.
- The lack of highway funding results in underfunded maintenance and preservation, and no additional resources for new capacity to address population growth. Research that would lead to significant breakthroughs takes a diminished role as available funding is used to sustain the most basic levels of highway service.
- Highway users react to fuel prices and degraded service by choosing trips of high value, trip-chaining, forgoing trips, and using alternate modes. Gradual changes in land use toward denser development occur as people attempt to locate housing closer to employment and offset high transportation costs associated with vehicle operation and lost time. Both reactions result in reduced VMT per capita. But without breakthrough technologies, there is no significant change in aggregate demand on the system resulting from population growth, and no methods for greatly reducing agency costs to provide basic highway services.

6.2 Back to the Future

Table A.2 shows the key elements for this scenario.

Table A.2. Key Scenario Elements for Back to the Future.

Scenario	Key Drivers	Scenario Kernel
Back to the Future	High economic growth High transport use High resource use High technology development	The economy returns to health, and transportation has the technology and resources to grow again.

An Economic Trigger

The economy has finally turned around and is producing jobs the way it used to, but this time in a more sustainable way. Growth in the late 20th century had many of the same characteristics as growth the late 19th century—essentially boom and bust. The 1970s started the cycle, and it was repeated five times into the 2010s. First it was oil shocks and stagflation—high inflation with low growth. The 20-times increase in the price of oil in 1980 would have astounded oil experts in 1970, yet it fueled a high-growth (and highly inflationary) economy as the government poured money in the economy to offset the ripple effects of high gas prices. But the bust came right after that, one of the worst recessions in the 20th century, intentionally created to wring inflation out of the economy. Intentionally or not, people still lost their jobs and their savings. The bust of 1987 was fueled by loose money again, this time due to the deregulation of the savings and loan industry. They were making sky-high profits by taking sky-high risks, even though their deposits were still insured by the Federal Deposit Insurance Corporation (FDIC). A 500-point loss in October 1987 showed that the system was unsustainable with another hard landing. The recession of 2001 and 2002 followed a period of irrational investment in Internet companies that had no profits or even revenue to speak of and no plans to get any except hope. The Great Recession of 2007 and 2008 was fueled by debt rather than sustainable demand. The only way to produce economic growth with incomes stagnant for most people was to grow consumption by growing debt. Deregulation led to overleveraged bets in the financial industry that also contributed to the collapse, requiring another—and much more expensive—government bailout. And finally, those bailouts lay the foundation for another Great Recession in 2014 and 2016. We thought they only came about once every 70 years. First Europe, then Japan, and finally the United States pulled the banking systems of the world down around their heads as they were unable to service their enormous debts.

And thus a giant rethinking began. The value of the economy was always measured in growth. The more money and the more goods and services purchased, the higher the standard of living and the presumed increase in happiness and well-being. But what was originally “You can never be too rich” soon became “Enough is enough,” the phrase for the new era. People and even businesses were sick and tired of the boom and bust cycle. While the booms were fun, the busts were not. People finally realized that they were not that much better off at the end of the cycle than they were at the beginning. Then why all the pain of the cycle? What was the point? The aging boomers wanted more steady and predictable growth as well, so they got their representatives to put a second mandate on the Federal Reserve—to control growth and reduce risk. Just as the inflation of the 1970s convinced the Federal Reserve that keeping inflation in check was their primary mission, now they had two missions. They also had to keep growth in check. But what heresy. Everyone agreed that inflation beyond a low level was bad, but everyone also agreed that as much growth as possible was good. But now they changed their minds. Sustainable growth, somewhere around 2.5 percent per year, was the new target—not less but also not much more. The Federal Reserve had always had the tools necessary to cool growth when it got above 3 percent. They just never had the mandate to use them to control growth. After 20 years, however, with nary a recession in sight, the economy was booming by historical standards, though it never raced ahead as it had before only to come to a screeching halt with all the subsequent pain and recrimination. "Enough is enough" now meant just enough growth to keep the economy improving, but not so much that it got out of hand.

A Technological Trigger

People said it was like the beginning of the industrial revolution all over again. Of course, that was an exaggeration, but it felt pretty good anyway. A convergence of technologies in the 2010s and 2020s had cured most of the ills that the economy suffered in the first decade. Rarely do technological breakthroughs live up to their promise as well as these have:

- Nanotechnology far outstripped even its most optimistic advocates. Water desalination, heat-reflective coatings, lighter and stronger metals, and ultra-high-storage batteries all became possible thanks to the manipulation of matter at the atomic level. Traditional manufacturing seemed crude by comparison. Given their experience with manufacturing, the old Midwestern Rust Belt emerged as the new Polymer Belt that brought advanced manufacturing jobs back to America.
- Biotechnology, another micro-technology, has begun to actually lower the cost of health care by keeping people healthier longer and treating them more effectively when they do get sick. A completely unexpected spinoff of this new bio-inspired age was how we could apply what we had learned about biological organisms to human organizations (human organisms) as well. Overhead rates dropped, and teams became much more effective once they were allowed to self-organize around a task.
- Japan led the world in the application of robotics to almost every physical task. Robots had populated factories for years, but now they were taking over the service industries as well by cooking, cleaning, and moving all manner of things around the factory, office, hospital, and even home. The Japanese were even working on robot freight haulers given their incredibly small workforce compared to the size of their economy.
- Of course, information technology still had a lot to offer through ubiquitous sensor networks, voice recognition, natural language processing, huge databases, and apparently intelligent responses and actions to most queries or commands. Intelligent "assistants," first pioneered by IBM's Watson and Apple's Siri, were taking over many of the tasks that had occupied much of people's time in the old work-oriented environment.
- And, finally, the new miniature technologies had reduced society's demands on the environment, but it had not eliminated the threat of resource scarcity or climate change. Nanotechnologies consumed less bulk material than older chemical processes did because it produced less waste. And biotechnology was actually creating energy, turning sunlight into hydrocarbons in large algae farms fueled by carbon dioxide from coal plants and saltwater from coastal areas. The cost, however, was the new threat that nano- or bio-

materials in the natural environment would alter species or even affect humans in subtle but significant ways.

Nevertheless, the growth in productivity was truly large by historical standards, if it were not for one problem—people were being squeezed out of the workplace with machines doing all the work. The unemployment rate never recovered from the 2007 and 2008 recession. In fact the rate today would be between 20 percent and 25 percent had we kept measuring it that way. But the Bureau of Labor Statistics gave that up years ago because “work” had become optional. With so much abundance and prices lower than ever, it was simply easier to support people on a small public stipend than to continually flog the economy into producing more jobs. People still worked, but more on something they wanted to do or thought that someone else could use. The Maker culture that emerged in the 2000s became a way of life for many. Home-grown nano- and bio-hacks were now more common than large industrial firms. The term for the new economy was WikiWorld, a huge open-source collaboration that seemed impossible given the economic and psychological theories of the 19th and 20th centuries.

But magic bullets still cause damage as they ripple through society. Not everyone embraced the new normal. In particular, the work ethic took a big hit, making many people feeling useless and left behind. They needed the discipline of having to make a living to get them out of bed in the morning. The disorientation from reorganizing the very fabric of work fueled rising rates of depression and crime. A new generation waking up in this world would accept it as normal, if not inevitable, so the dislocation was mostly confined to the transition generation.

A Cultural Trigger

“Nothing succeeds like failure,” and the Millennials had plenty of that. Their Baby Boom parents and grandparents had left the world in quite a mess—high unemployment, high education debt, unsustainable government deficits, increasing global temperatures, and apparently no way to succeed on a regular basis. The American Dream had become the American Nightmare. The Baby Boom invented the Me Generation in the 1980s and pushed it as hard as they could until they retired and eventually died in the second quarter of the century. But just as the Depression and WWII generation (called the Greatest Generation in a popular book in the 1990s) had laid the foundation for American prosperity in the second half of the 20th century, so the Millennials and their descendants began fixing the problems in the first third of the 21st century. They first realized that while many had been brought up in relative security and prosperity, long-term security and prosperity had to be earned, not assumed. Entitlements were out; hard work was the *new black*. You get what you produce in this world, not just what you want. Secondly, they balanced individual interests with community interests. They resurrected long-dormant values of service, responsibility, and sacrifice. They took care of each other as they took care of themselves. “Do unto others…” was popular again, an astounding revival from the days of Gordon Gekko when greed was good. In fact, greed had become unfashionable and mildly distasteful to most. Along with a healthy dose of creativity and ingenuity, the United States was again the leading economy in the world; and this time, not only in services like finance and entertainment, but also in technology and manufacturing around the world. They had experienced the searing pain of the first two decades of their century just as their great-grandparents had in theirs, and they turned out much better for it.

Potential Implications for Transportation

The Back to the Future scenario has the following implications for transportation:

- Demand for mobility is consistent with the level of infrastructure development.
- Focus shifts to self-sustenance with investments in breakthrough technology to support clean water, super foods, and medical technologies. Expansion of the network progresses at a moderate pace in keeping with sustainability principles.
- Private-sector development of new technologies allows data generated from vehicles and roadside to contribute to smart, interactive, and real-time trip planning, and to provide for balancing of system loads.
- Funding is generated by fuel tax primarily and is declining, but is less of a crisis and crippling problem because demand is reduced through:

    - Higher density development: Demand is more dispersed than concentrated, and people are committed to principles of sustainability in urban land form.
    - Technology advancements: Technology provides alternatives to traditional travel modes, including increased use of telecommuting and home-based work.

6.3 Government Redux

Table A.3 shows the key elements for this scenario.

Table A.3. Key Scenario Elements for Government Redux.

Scenario	Key Drivers	Scenario Kernel
Government Redux	High transport funding through new taxes More highway technology	The government reasserts itself as the primary driver of transportation in the United States and develops the funding resources to do so.

Few things mimic a pendulum more than the public mood. As a result, governance in the modern world behaved just like a pendulum. Having discovered the magic of fossil fuel, division of labor, and return on capital investment, societies initially endowed merchants with extraordinary power and scope. First in the British Isles and the European Continent, then to the British colonies and to Japan, and now operating throughout the world, the captains of industry pushed their advantage to the hilt. Capitalism is about capital: "Them that has gets." The rich get richer, and the poor get welfare. In the United States, the 1890s were called the Gilded Age when the trusts, controlled by a few ultra-wealthy individuals, ran the country. In Japan, they were *Keiretsu*; in Korea, *Chaebol.*

But a strange thing happened at the end of the 19th century in Europe, around the beginning of the 20th century in the United States and later elsewhere. Most people did not like the kind of society that the Trusts created. They were poor, worked in dangerous jobs, and enjoyed few if any rights. Even children were subjected to the discipline of the workplace, so they limited the Trusts through government action. First it was the Progressive Movement in the 1910s, the New Deal in the 1930s, and finally, the Great Society in the 1960s. From 1900 to 1965, government was good, and the market, which they believed produced mostly economic misery including the Great Depression, could not be trusted.

But the pendulum started swinging back at the height of the Great Society, as pendulums are wont to do. First in the U.K., Margaret Thatcher adopted the economics of Frederick Hayek, and Ronald Regan followed suit with the supply-side economics of Milton Friedman. Government was now bad, the source of all trouble, and the market was good. Let's run things like a business, not like overpaid bureaucrats. Over the decades, that philosophy produced the savings and loan crisis of the 1980s, the tech bubble of the 1990s and the Great Recession of the 2000s. It was a mini-Gilded Age all over again.

And the pendulum started swinging again, of course, in the opposite direction. A full-scale reformist movement arose from the splinter groups like the Tea Party, Occupy Wall Street, and a host of other popular uprisings. People were angry; when angry enough, they usually get what they want.

The electoral system had been hijacked by the two political parties so that almost all legislative representatives ran in "safe" districts. That meant that winning the primary was tantamount to winning the election, and winning the primary required securing the support of the base, the most extreme members of the party. When elected, therefore, those representatives had to represent the people who elected them—not all or even a majority of the voters in their district, but rather the minority of party extremists. As a result, politics became an extended game of chicken—who would blink first, rather than an attempt to achieve reasonable actions on pressing issues. The reform was first to mandate that districts be drawn by expert panels rather than state legislators. Some states even adopted an algorithm that produced even more geographically contiguous and balanced districts than the panels did. Moderation reined in Congress and in state legislature for the first time in decades.

The system of governance had also been hijacked by special interests who stormed Congress with the relentless pursuit of their goals. Backed by the enormous financial resources required to be elected in the 2010s, the lobbyists pressed their case on the hapless representatives. And woe to legislator who stepped out of line. The reform in this case was twofold:

- To eliminate private money from elections through public funding.
- To limit the time for campaigning to four months before an election.

As a result, the influence of special interests was severely reduce, and the legal representatives had more time to actually govern since they were not running for office and raising money all the time.

A final reform was a new type of balanced-budget constitutional amendment. The two economic theories of the 20th century that took an explicit position on the role of government in society were the mixed economy of John Maynard Keynes and the free-market economy of Milton Friedman. Either one may have worked by itself, but politicians tended to practice them one at a time. They used free-market, supply-side theories in times of prosperity, and they resorted to government bailouts in times of distress. The Second Great Recession (the Sovereign Debt Recession) of 2014 through 2016 was the result of government guaranteeing the bad debts of the banks and financial institutions in 2007 and 2008 without having the resources do so. Had they been running budget surpluses during the good times, they would have had the resources to aid the ailing economy, but they did not. The reform in this case was a new form of Balanced Budget Amendment to the Constitution, finally adopted in 2021. Rather than balancing the federal budget every year, the way many states have to, the amendment offers more flexibility to save and to spend depending on the conditions of the economy. It restricts government spending to a fixed percent of the national economy, except during times of war. It requires that the budget be balanced over a five-year period, not every year, and it requires that the government run a surplus in two of those five years. While the federal debt is still enormous, at least the government may not be adding to it anymore with deficits each year for decades.

The result was some restrictions on some freedoms, such as redistricting, lobbying, and spending, but the benefit was a democracy that elected the right people and gave them the time, incentive, and means to see to the country's needs to the best of their ability.

Potential Implications for Transportation

The Government Redux scenario has the following implications for transportation in the pre-reform period:

- Funding limitations up to 2020 lead to further deterioration of the system and growing congestion unable to be addressed by system expansion.
- States seek innovative ways to deal with their most pressing transportation issues but are able to gain only enough public support to maintain the system at a minimal level.
- The situation is also complicated by high levels of state borrowing in the period between 2005 and 2015, precipitating further decline in service level in the absence of new revenue sources.

The scenario has the following implications for transportation in the post-reform period:

- With increased public trust, the door is open to federal leadership in significant expansion of tolling to the interstate system and ultimately to full network pricing.
- The initial motivation is the generation of sustainable revenue sources, but the incremental application of tolling across the system serves a demand management function in congested areas through variable pricing, thus reducing significant infrastructure expansion to meet demand.
- A new sustainable revenue source is available to invest in transit and alternative modes and support strategic capacity expansion for freight and alternative freight modes.
- Leading-edge vehicle technologies improve safety and reduce vehicle headway so that the system can be more efficiently operated.
- Privately administered payment mechanisms allow drivers to pay for road user fees while also paying for other services such as premium toll facilities, parking, navigation and location assistance with real-time traffic conditions, and pay-as-you-drive car insurance.

6.4 Bits over Buses

Table A.4 shows the key elements for this scenario.

Table A.4. Key Scenario Elements for Bits over Buses.

Scenario	Key Drivers	Scenario Kernel
Bits over Buses	Private funding Government role centralized High gas prices High information technology (IT)	A higher than expected increase in crude oil prices reduces the ability of ordinary people to travel as much as they used to. They turn instead to an expanded Internet, not only for communication but for most work and leisure activities that used to require physical movement.

Peak oil production had been discussed for decades, and now it was here. We were not running out of oil exactly, but we were running low on the cheap, easy stuff, at least. And then there was the Mideast war of 2016, in which Iran attacked Saudi oil facilities and the Saudis responded in kind, which jumped the price of oil to over $400 a barrel. The sudden jump reminded people of the 1970s—rationing, price controls, and long lines, but most of all the inability to drive anywhere you wanted because the price was simply too high. Wrenching the automobile from the fabric of American life was not just difficult; it was disastrous. People began the Post-War Era in love with their cars and all they stood for—mobility, freedom, and status. As a result, they approved the Interstate Highway System, the largest public-works project in history that had cost $1.5 trillion by 1991, 90 percent of which was funded by the federal government. And now the utility and the status of the American automobile were under pressure. They might be electric someday, but the infrastructure for electrifying and maintaining the fleet was not in place and would not be for a decade or more. Biofuels were still in their infancy as were fuel cells. No, the American public would have to do without their vehicles for the time being.

So what did they do? They jumped on the Internet for a solution. Not just to *search* for a solution but to actually use the Internet as *the* solution. Futurists had been talking about the Information Society for a long time, since Daniel Bell's *Commission on the Year 2000* and Alvin Toffler's *Future Shock* and *Third Wave* in the 1960s and '70s. Much progress had been made. The Internet had already transformed every institution in society, even schools eventually, but it was used along with physical mobility, not instead of it. Now it really had to perform. Modern society would become a true Information Society as it had become a true Automobile Society in the 1950s and '60s.

The first and easiest fix was for people to work from home rather than in the office. Almost 70 percent of households had broadband access by this time, and many people were already accessing their servers from home in the evenings and on the weekends. Smartphones had made remote access as common as, well, the automobile. So replacing physical with virtual presence in the office was not a technical problem, but it was a huge behavioral adjustment. Everyone from managers to teachers to health professionals to sales people were still used to doing most of their business face-to-face. And everyone still said that face-to-face was the best way to do business, but it was just too expensive except for the most critical interactions. So they had to learn to work together and be evaluated on outcomes rather than activities. Contract work took the place of full-time employment. People worked on their own time in their own way, and job satisfaction soared, particularly for those not spending the hours in traffic jams five days a week.

But not everyone had participated in the knowledge economy before the shock, and not everyone would do so afterwards. How many would be left out? And what would they do? It turned out better than the pessimists thought, but, of course, not as good as the optimists hoped. First of all, the education system had not prepared people for independent, self-managed work, so many struggled. The education system adjusted, literally by preparing people to work online by teaching them online. Still a sizable proportion of the population was not technically or emotionally fit to work this way. But what would they do in a society without easy access to transportation? The answer was staring us right in the face. Manual work still needed to be done—building, painting, fixing, and maintaining. The difference was that a few people in the neighborhood were good at that, so they became local contractors to the stay-at-home workforce. It was not a prosperous life, but it did earn the fixers, as they were called, a certain local respect because their skills improved as time went on.

Another big adjustment was commerce and trade. The cost of transportation in the Oil Era was a single-digit percent of the total cost of goods to the consumer. Hence, it paid to manufacture overseas, reaping a large decrease in labor cost for a modest increase in transportation cost. But that equation was now upside down. Buying local had been a mantra of the progressive class for a long time. Now business had to take up the refrain. Very low-volume manufacturing based on new materials helped, as did low-maintenance crops from the biotech sector for low-volume farmers. Of course, the ultimate in local was in the home, but that is not far off now with desktop manufacturing and urban farming both gaining ground.

After a while and with great reluctance, a person's enhanced capabilities and skills with remote communication changed personal relations as well. Families living across the country, initially separated by high gas prices, eventually moved closer together. You could work just as easily from Cleveland as from the suburbs. Parents were home with their children; neighbors became friends (and enemies!) again; folks used the new tools and sites for entertainment and even virtual travel. It was the rural village all over again, but this time connected to the world.

And since people were not driving anymore, revenues from the gas tax plummeted so much that the concept of the Highway Trust Fund was laughable. But that is where the private sector stepped in. Some transportation was still necessary, and business saw an investment opportunity there. Privately operated toll roads, of course, had experienced an on-and-off-again history. But that was easy to put back into place. With the cost of gasoline sky high, a few more dollars to get to your destination was not such a big deal, as long as you did not have to do it too often. The traffic was light, but then so were the maintenance costs on existing highways and toll roads. The real problem was streets and thoroughfares. You could not exactly toll the street in front of your house. But business got together and, with the blessing of state and city governments, created transportation cooperatives based on neighborhoods, similar to management districts that had been set up in the 1990s. The residents of an area would pay a flat fee to a private contractor to maintain the streets in that area at some level of performance, which was precisely specified. The higher the level, the higher the fee. However, residents in some areas chose not to set up the cooperative, or they could not afford the fee to do so. So roads in those areas had to be closed for lack of maintenance; that was considered a huge social problem at the outset, but even that turned out better than planners expected. The neighbors, through their own labor and with the help of the fixers, turned some streets into lanes for all manner of human-powered vehicles. The overall health of those populations even improved with exercise and with the inability to order takeout anymore. Local gardens flourished, and people returned to a more rural lifestyle even in the big cities. The system was called "pay as you go," so not owning an automobile became a real option for homeowners.

Potential Implications for Transportation

The Bits over Buses scenario has the following implications for transportation:

- The reduction in driving resulting from fuel prices leads to reductions in demand on the transportation system. Without revenues from the fuel tax that produce the resources for system expansion, available revenue levels dictate a focus on maintenance and preservation rather than expansion. Maintenance is supported by toll revenue on highways.
- Telecommuting and home-based work resulting from contract labor rather than traditional employment, in combination with fuel prices, leads to significant reductions in peak-period demand on the system.
- STAs turn over roads with local-access functionality to transportation cooperatives for maintenance and preservation.

6.5 Many Ways to Go

Table A.5 shows the key elements for this scenario.

Table A.5. Key Scenario Elements for Many Ways to Go.

Scenario	Key Drivers	Scenario Kernel
Many Ways to Go	Economic growth Funding amount Private funding Centralized government role Gas/carbon taxes High technology development Multimodal approaches	The government seeks new revenue in gas and carbon taxes, but rather than investing in the existing transportation system, it puts its money into new transport and information technology. This leads to a complex but efficient transportation system that includes significant shares of many different modes.

The Oil Era and hence the Automobile Era were over, for the time being at least, until a new transportation alternative could be found. Would it be the electric-, biofuel-, or fuel-cell-powered car that could use the existing road system? Or perhaps no cars at all, with the Internet as the highway of the future, as so many had dubbed it already. At least, the steep carbon tax made one of those much more likely before a return to the internal combustion engine, if ever.

The decision depended on the need for humans to have face-to-face interaction. The high-tech enthusiasts said that virtual interaction was just as good as face-to-face once you got the hang of it. Others disagreed. Social scientists arrayed themselves on all sides of the question, saying:

- People would get claustrophobic with such a small circle of face-to-face contacts.
- Aside from being a boon, parents at home with their children all day might actually narrow or even stifle their interpersonal growth.
- Neighbors who had enough face-to-face contact at work could easily avoid each other at home, but now they would crave the contact, even if it led to more neighborly conflict.
- The looser ties between employer and employee, between manager and worker, would lead to listlessness, lack of loyalty, and a churning labor force.

All of these arguments from psychologists, sociologists, teachers, and mental-health professionals convinced the business community in one medium-sized city to establish a unique private-public corporation called Ways to Go (WTG). WTG would invest in an ambitious experiment with an outrageous goal—to provide as much mobility to their residents as they had before, but without the automobile. (Earlier partnerships like this were called public-private partnerships, but this one was *private-public* because government was the minority partner here.) WTG could not bring the automobile back, at least not right away. And rather than try, it focused its talent and resources on a truly 21st century transportation system. That system would provide the same vehicles miles traveled (VMT) (vehicle miles *traveled,* not driven) at the same average speed and at comparable cost as the automobile had done when gasoline was $5 a gallon in 2017, but with less than 10 percent of the automobile miles as before. If the experiment succeeded, the investors would have a world market in designing and building similar multimodal transportation systems elsewhere.

It was expensive to drive these days because the higher fuel prices had been made even higher with a $40-per-ton carbon tax. Still many people were determined to drive. They had grown up in a world of autos, and they could not imagine life without them. So to get the automobiles off the road, WTG convinced the city and county to close many roads since they did not have the money to maintain them anyway. They imposed real-time congestion fees on those that stayed open and taxes to enter and drive in certain parts of the city, like what London did in the early 2000s. As a result, vehicle miles driven (VMD) went down to 7 percent of the level from 10 years before.

But that was the easy part. The promise was that people would travel the same amount with just as much convenience. And if people fell in love the WTG system, it could become a tourist attraction and the basis for a new economic cluster of advanced transportation systems.

WTG and city leaders sold the vision to the voters, who approved it by a fairly wide margin. So it was time to get to work. Money would come from:

- Private investment, which retained the rights to patents and trademarks on the new systems.
- A portion of the federal carbon tax that was set aside for innovative transportation systems.
- The new toll and congestion fees imposed by the city and county.
- Investments from large corporations like UPS for logistics, Siemens for advanced transportation technology, and Disney for people moving and entertainment.

People were excited. So what was the plan? The outcomes had already been set. What were the strategies?

- Obviously all modes of transportation would be considered, even some specialty automobiles.
- All modes would have to be operationally solvent. WTG would design, build, and operate the system. WTG would receive no public funds for operations, however, so the system had to have a good chance of at least breaking even on an operating basis.
- The nodes considered were:
  - **Trains:** Trains were employed sparingly and only between highly trafficked routes. Trains had become a showcase for a number of cities in the 1990s and through the 2020s, but most required huge subsidies to run. It was even possible that there would be no trains.
  - **Buses:** Buses would be the backbone of the public portion of the systems, but not buses like the population were used to. Traditionally, buses and most trains never paid for themselves because they competed with more convenient and comfortable automobiles. So they were used only by the bottom quarter of the population, people who could not afford an automobile. Now 80 percent of the population could not afford an automobile, so much of the stigma of traveling by bus was going away. Nevertheless, WTG launched a public-relations campaign to make bus riding more interesting, enjoyable, comfortable, and even cool. The buses would have been considered luxurious to a previous generation—electrical outlets, wireless internet, personal entertainment centers, and vending machines for drinks and snacks. The whole experience also had to be convenient. Routes were divided into super-trunk, trunk, local, and connector or jitney systems. The trunk buses traveled on the closed roads, so there was no stopping for lights or pedestrians—direct and non-stop. Transfers were walk-off/walk-on—timed and seamless, except for the jitneys, which operated on demand the way airport shuttles did in the old days. Systems in 2010 had already begun offering arrival information through smart phones at every stop. Now the city distributed an application that alerted the passenger to stop what they were doing and head to the corner to catch the next bus. The application was enormously popular because those who used it waited less than three minutes on average at the stop. Individuals could even reserve a seat on a particular bus through their phone for an additional charge.
  - **Walking and biking:** The city turned some of the smaller closed roads to hike and bike trails that crisscrossed the city. Walking and biking were much safer on these roads than on a busy street. WTG also launched another public-relations campaign on the health benefits of walking and biking, sponsored biking clubs and clinics, supported local bike shops, and received substantial contributions from bicycle manufacturers for the new concept of *active transportation*. As a result, the city was recognized as one of the nation's five healthiest cities.
  - **Autonomous vehicles:** The most innovative system, however, were the autonomous vehicles, first tested by Google in the 2000s. These driverless cars ran around the city, taking people to places for which the fixed transportation system was less convenient. An individual reserves the car or calls it in real time through an application on the phone. The car arrives, usually in less than five minutes, and drives the individual and

up to three other people to whatever destination they entered into the phone. The driverless cars avoid the need for large parking lots and garages where cars sit for hours waiting for a 20-minute drive. They are being used approximately 75 percent of the daylight hours, where the average utilization of personal vehicle is less than 5 percent. After all, the real purpose of transportation is mobility, getting from place to place, rather than necessarily owning the means to do so. We had learned the lesson from the Software as Service (SaS) movement in the 2010s. You did not have to own the software to get the processing service from the computing cloud.

The plan is in place. Funds from investment, taxes, and fees have been budgeted. It is now time to see if the system actually meets its goals

Potential Implications for Transportation

The Many Ways to Go scenario has the following implications for transportation:

- Funding revenues fragment as the fuel tax declines. A carbon tax offers the possibility of transportation funding.
- STA partnerships and advocacy campaigns encourage cultural transitions for demand-reduction strategies via telepresence alternatives to work and personal services (e.g., trips to the doctor and retail shopping).
- Federal, state, and local funding may shift to expand broadband access (urban/rural) that enables access to telepresence. The result could be less funding for transportation.
- Populist legislative efforts may reduce or suspend gasoline taxes to counter the rising costs of fuel.
- Agencies may use land (asset) sales or co-development of former road corridors that are now closed to traffic.
- General funding may decline as government dollars are allocated specifically toward new innovative transportation systems. This could impact general funds used in maintenance and revitalization of legacy assets.
- Freight and supply chain systems may shift, driven by advanced information technologies.
- The bus/jitney industry may fragment as new players compete for rising demand. This could lead to innovation driven by competition—or a negative consumer experience if the industry’s market structure does not allow for sustainable business models (e.g., hyper-competition leads to failed companies and abandoned routes).
- Agencies may manage (design and build) new transportation assets along highway systems (e.g., bike paths) used in active transportation.
- Autonomous vehicle fleets and transit partners may use new multimodal hubs along highways to bring last-mile services to suburban communities.

6.6 Escape to the Centers

Table A.6 shows the key elements for this scenario.

Table A.6. Key Scenario Elements for Escape to the Center.

Scenario	Key Drivers	Scenario Kernel
Escape to the Center	High population density Low mobility capacity Low security	The lack of mobility and increased threats to their well-being drive people out of the suburbs and into the city, reducing the demand for transportation—the arrival of the vision for the advocates of smart growth.

The end of the Automobile Era was difficult, but it provided lots of options for policy makers and the public alike. One of the most serious questions was about the form of the metro environment after the automobile. No one disputed the fact that, besides simple population growth, the high-rise structure and air conditioning for Southern cities, the automobile had done more to shape the form of the country's metropolitan areas than anything else. Cities in the Northeast and the industrial Midwest achieved their form before World War II. As a result, they are denser and have more transportation options. The rest of the cities are defined by their freeways rather than their rail lines. They are less dense because they were built for the automobile. With automobiles disappearing under the pressure of high gasoline prices and carbon taxes, will the population find another independent means of transport, build a complex (and expensive) multimodal transportation system, or give up on physical mobility altogether and retreat to the Internet? Of course, these options were not mutually exclusive, but one other choice remained. They could simply move. Pre-World War II populations had much more effective and robust transportation systems, but they also used them less than the generations who followed them. People lived closer to the factory and office and closer to family and friends. A short bus or train ride or even a short walk would get them to the places they needed to go, be it school, work, shopping, or entertainment. Of course, the automobile changed all that. They and the freeways they drove on gave rise to the sprawling suburbs, acres of shopping malls, and all the other amenities of metropolitan life.

So would that density continue with the automobile much less useful than it was before? If people did want to move, it would still take some time. Clustering around a company complex is not as easy as buying a home that one can afford and driving to wherever the work is. Real estate people in the 1990s said that distance to work was about the fifth most important consideration when people went to buy a home. Ahead of the commute were price, safety, education, and distance to amenities, in no particular order. Now, of course, distance to work was just as important, if not more important, than any of these. Nevertheless, it would take decades to reshape the cities, and even then the remnants of the automobile society would linger on, just like the form of the rail-city remains in New York, Boston, and Chicago.

Nevertheless, the advocates of what used to be called smart growth are cheering now that their dream might become a reality. Denser city living was a tough sell in the first quarter of the century when the automobile was still viable, particularly for families with children and for aging Boomers who want to be close to social services and cultural hubs. Now it might be thrust on a reluctant population by necessity. Of course, kids growing up in that environment would not know the difference. They did not remember square miles of quarter-acre plots with identical homes in rows. And even the adults will adapt because that is what we do. We may hanker for the suburbs, but one can only be nostalgic for so long. After a while, the urban environment becomes a way of life.

At the same time, the advocates of smart growth should not celebrate too soon. Just because people have to live closer to work does not mean that work has to be the central city at all. Rather than an overall increase in population density, those businesses might move to the suburbs where the people already are, rather than stay in the city. Suburban complexes are already quite common, such as Silicon Valley in California, Route 128 in Boston, and the Energy Corridor in Houston. People will still have to move to be closer to these relocated businesses. They cannot live just anywhere because they will not have the transportation they used to have to get to work. But they might move from one suburb to another, leaving the central city even less populated than it was. That form would create islands of density in an overall less dense metro area, much like Northern Virginia where business clusters around the metro stops.

However, it turns out that the automobile built the post-War city, and it will have a big effect when the city can no longer sustain that form. Nothing this substantial changes overnight, and remnants of the past remain, but the city of 2050 could well have a much denser feel than was true in the previous 100 years.

Potential Implications for Transportation

The Escape to the Center scenario has the following implications for transportation:

- Transportation agencies and engineering-solution providers shift toward place-based planning principles, taking a more holistic approach to multimodal systems.
- Incentives are created to cultivate market demand for high-density-based transportation systems among early adopters.
- STAs push for regulatory certainty on funding commitments to urban-based multimodal hubs. Constraints (e.g., fines and taxes) are placed on competing sprawl developments that might undermine efforts.
- STAs, transit providers, and real estate developers form stronger partnerships and may merge organizationally. This allows them to reduce overhead costs and leverage existing assets (e.g., highway lanes transformed into bus-only lanes or rail) to meet the needs of rising urban center demands.

6.7 Meltdown

Table A.7 shows the key elements for this scenario.

Table A.7. Key Scenario Elements for Meltdown.

Scenario	Key Drivers	Scenario Kernel
Meltdown	Climate change Environmental quality/sustainability Gas/carbon tax Government role Population density	The pessimistic scenarios for climate change ended up being more accurate than the optimistic ones. As a result, the most important priority for the next few decades was struggling with nature rather than growing the economy.

The debate over climate change is over. Abrupt climate change, a term coined in 2005, was now the new reality. The atmosphere contained a number of reinforcing feedback loops that, once started, had run out of control. The most obvious was the methane locked into the permafrost of the Arctic. Once the permafrost started to melt, it released methane into the atmosphere, which in turn increased the temperature and melted more permafrost, which released more methane, etc. The cycle was a runaway by 2025. Ice in Greenland and glaciers all over the world were melting at an increasing rate, and the breakup of the Ross ice shelf in Antarctica added meters to the sea level, inundating low-lying areas around the country and around the world. The East and Gulf Coasts were hit the hardest. Florida, Louisiana, and Texas lost valuable land. Millions were displaced, and whole industries, like the petrochemical industry in Houston and the tourist industry in Florida, relocated or simply closed. Transportation planners scrambled to rebuild roadways and train lines in more inland locations. In the end, adaptation, the incremental ability to protect society and its way of life from climate change, seemed an impossible venture for what would be required in the face of the actual emergency.

The new reality followed decades of wrangling about whether climate change was real or not or, at least, whether it was produced by emissions from human activity. The sensation produced by Al Gore's *An Inconvenient Truth* in 2006 did not last. In fact, people looked at record snowfalls and bitter winters in the early 2010s as evidence that the scientists were wrong or, even worse, that they had made up the whole thing to advance a pro-government, anti-capitalist agenda. But those who took the warnings seriously did not agree on what was to be done. The first response was to reduce the amount of carbon that people put into the atmosphere—the mitigation strategy. The Kyoto Protocol, negotiated by Gore when he was still vice president, was supposed to be the first step in that direction, but it was a feeble step—no enforcement, so almost no effect. And the big emitters, the United States and the large developing countries, were not even signatories. Emissions from emerging economies like India, Indonesia, and the newly industrialized resource-rich regions across Africa exceeded expectations. By 2020, the levels of greenhouse gases (GHGs), some of which would continue to warm the atmosphere for centuries, were so high that further reductions would not contain temperature increases in any meaningful way. The days for significant mitigation had passed.

But the public mood shifted rapidly once the runaway warming started. Legislation to control carbon was put into effect, even though scientists said that it could well be too little too late. The large carbon dioxide emitters were severely restricted by a carbon tax that would get close to $90 per ton—coal plants, manufacturing facilities such as petrochemicals and cement, and of course transportation. Farmers had to use less diesel and fertilizer, and some famines ensued. The construction industry had to get its material locally and cut down on waste altogether.

Societies and their transportation systems can undergo transformation for a number of reasons. Other triggers included loss of trust in and even the downright destruction of the Internet through the actions of hackers, terrorists, or nations engaged in cyber-warfare. As society became more dependent on the Internet for essential services like communications, power, coordination, and electronic commerce, it also became more vulnerable.

Another trigger, though on a more regional basis, were severe seismic event, much like the recent one in Fukushima, Japan. California and the whole West Coast were vulnerable to these seismic forces. Although the physical damage only affected a few states, the funds necessary to rebuild the infrastructure there were taken from states that were not affected.

The transition was brutal, but surprisingly people rallied to face the crisis together. Of course, there were disagreements on how and when things should be done, but the political fights for turf and political advantage were mostly gone. The United States, the most flexible (and some would say the most disorganized or even chaotic) society led the way. It implemented the draconian measures—not liking it but realizing that the threat existed.

It was a generation before life settled into a more local, more quiet, less hectic, and less stressful way of life. Some of the old-timers longed for the good old days of go-go and perpetual motion. Most, however, taught their children that the world they had grown up in was a unique historical moment, but that they were glad it was over. And their children looked back on the society of their grandparents and felt superior, as most generations are wont to do when they look to the past. They judged that their ancestors had done as well as they could under the circumstances, but that they, the present generation, had achieved a much better life. They saw the effects of the catastrophe as progress to them, as most generations are also wont to do.

In summary, the Meltdown scenario depicts a collapse of the transportation system as we know it, but that collapse can occur for any number of reasons.

Potential Implications for Transportation

The Meltdown scenario has the following implications for transportation:

- Government support and industry self-interest lead acceleration of vehicle electrification to respond to new demand (and public-relations battles of brands that are not transforming their fleets). Fuel-based revenues decline because of this.
- The need for maintenance dollars increases to repair roadways and railways impacted by rapid climate change (e.g., heat and rains/flooding).
- Coastal transportation infrastructure may be lost or need to be rerouted.
- Transportation may shift toward city-center-oriented transportation hubs
- Catastrophic events lead to resources totally diverted to repairing or rebuilding affected infrastructure to help revitalize the area impacted.

7.0 APPENDIX B - TRAFFIC SERVICES WHITE PAPER VISION

7.1 Description of Transportation Area: Traffic Services

The term *traffic services* describes the management and operation of traffic on a roadway using devices and technologies, including static and dynamic signs, signals, pavement markings, roadside lighting, and intelligent transportation systems (ITS). It includes the use of ITS to support the management of traffic flow in urban regions—in both recurring and nonrecurring congestion conditions—to maximize throughput and minimize the impacts to system reliability. Appendix B.1 provides more detailed information about different types of activities that the traffic services area covers.

The research team used the baseline scenario and selected three alternative scenarios that represented the most variability and had the greatest implication for the traffic services area from the baseline scenario. These scenarios were further developed into specific applications for the traffic services transportation area. These alternative scenarios include:

- "Back to the Future."
- "Escape to the Centers."
- "Meltdown."

The research team also identified the potential for new tools, technologies, and approaches for the baseline scenario and for each of the alternative scenarios.

7.2 Description of the Baseline Scenario: Managed Decline

In the baseline scenario, much of the future turns out as current trends project into the future. Potential implications of this scenario for traffic services are as follows:

- A reduction in funding for constructing new capacity limits expenditures on installation of new traffic control devices. However, funding shifts from new highway capacity to traffic operations supported by ITS, which plays a more significant role in managing and optimizing the system.
- Management and operations of traffic services shift from the public to the private sector in the face of public funding limitations.
- With per-capita vehicle miles traveled (VMT) declining, there is less pressure on growth in capacity. VMT growth is accommodated through technology-enabled mobility, which enhances both safety and efficiency.
- Increasing demand for road freight is supported through technology-enhanced mobility.
- The increasing sophistication of information technology (IT) speed and coverage puts traveler information and choices into drivers' hands. Without the direct public-sector provision of services, the role of STAs shifts from facilitator to end user of IT-generated data.

Under the baseline, "business-as-usual" scenario, five drivers impact the traffic services area the most in 2040–2060: the amount of funding, the proportion of private funding, the amount of demand for mobility, the amount and proportion of road freight, and the level of IT available.

Limited funding results in a reduction in new capacity, precipitating a shift in philosophy toward operations and a broadening scope for traffic services. Traffic operations, and ITS in particular, play a more significant role in managing and optimizing the system, both in terms of safety and efficiency. The traditional approach to capital investments initially leads STAs to focus on the development of IT software and hardware, vehicle-to-infrastructure (V2I)–based communications (illustrated in Figure B.1), hiring of employees capable of managing operations, etc. But this approach absorbs a significant amount of capital funds that have become increasingly unavailable. Further, reduced funding strains maintenance budgets for traffic control devices and ITS. Maintenance of outdated ITS systems in particular becomes problematic, given that IT systems become obsolete in a much shorter life cycle than other features of the highway infrastructure. Maintenance of V2I roadside readers, especially by local entities, proves difficult; the equipment requires rapid response to support high reliability for safety applications, and the agencies simply do not have the resources to provide the required level of attention. Materials used for signs and pavement markings undergo significant changes, particularly due to resins that were previously made with now-depleted natural resources.

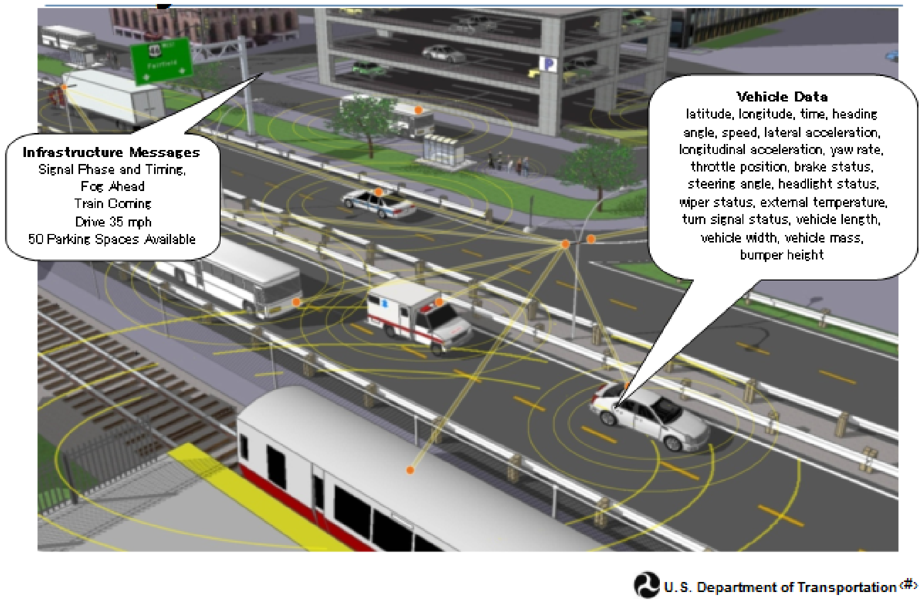


Figure B.1. Data and messaging available through vehicle-to-vehicle and vehicle-to-infrastructure connectivity (Source: http://www.its.dot.gov/presentations/trb_2013/Cronin_2013v2i_files/frame.htm).

Limited funding also puts increasing pressure on STAs to examine funding alternatives. Some states develop their own tolling programs, which help recoup costs for management and operations. But most public agency tolling applications continue to be led by regional or local tolling authorities working with STAs. Many states seek alternative funding methods and shift more of their dollars to privatizing the management, operation, and maintenance of traffic services. A new private-sector business model for funding emerges as the public recognizes the benefits of ITS and is willing to pay for services via private enterprise to gain time savings, reliable service, and enhanced quality of life. The shift to privatization additionally supports integration of private-sector data (location based and other) in operations, increasingly replacing public-sector-generated traffic data. The privatized model results in a scaled-back version of the

V2I vision, in that the roadside sensors and communications backbone are prioritized based on the market for services. And without research funding for STAs to address alternatives to traditional resins, breakthrough materials for traffic signing and markings are developed and marketed by the private sector until roadside information is conveyed through the vehicle.

In 2040–2060, total demand for mobility increases as the population grows. At the same time, per-capita demand for mobility decreases. The opportunity and real costs of travel increase, leading individuals to travel less. Technology and societal changes enable individuals to telecommute more easily, reducing the distance people travel. Communities are designed in a way that minimizes the need to travel long distances, through smart cities and careful urban planning. As a result, STAs put a lower priority on increasing capacity and instead focus on operating the system as efficiently as possible.

Demand for road freight increases in the 2040–2060 period. This increase in demand is accommodated through technology-enhanced mobility, and capital improvement activities are adjusted accordingly. STAs accommodate increased freight demand by deploying technology—initially themselves but increasingly by using the private sector—to improve the safe operating conditions for freight. For example, in 2012, current technology made operating larger loads and freight road trains impossible. Improved technologies allow states to loosen regulations and allow larger loads and road trains to operate on highways. This improves throughput and system efficiency. The increasing demand of road freight also pushes the limits on regulations, bringing safety and efficiency issues to the forefront. ITS safety applications also play a greater role.

Increased IT sophistication, including greater speed and coverage, puts traveler information and choices in the hands of drivers. Without the direct public-sector provision of services, the role for STAs shifts to being a facilitator and eventually end user of IT-generated data (i.e., the STAs initially collect the data and use the data to improve services; the private sector takes a larger role in collection over time). Private enterprise leads the advancement of vehicle technologies oriented toward consumer services (time savings, enhanced efficiency, improved safety, and better quality of life). Vehicle technology development, in-vehicle telematics, and transition to automated vehicles significantly reduce the need for roadside signing over time.

Traditional traffic control devices become increasingly adaptive as technology advances:

- Static STOP and YIELD signs become dynamic and adaptive to traffic flow patterns, and responsively display the appropriate message for the situation.
- Pavement markings “realign” for peak-period congestion, narrowing and adding lanes as needed.
- Roadside and overhead sign lighting is able to automatically dim based on need.

New materials improve driver and vehicle awareness of the boundaries and characteristics of the roads. As automated vehicles become commonplace, STAs and their private partners prioritize implementing limited applications of “smart” infrastructure to support the increasingly automated driving environment.

In summary, in the 2040–2060 period, most of what was predicted for funding and demand occurs, and STAs have to adapt to the conditions through alternative business models, supported by significant advances in technology.

7.3 First Alternative Scenario - Back to the Future

In the Back to the Future scenario, the economy returns to health, and transportation has the technology and resources to grow again. Potential implications of this scenario for transportation construction projects are as follows:

- Under this scenario, STAs spend less money on expanding capacity than in the present day.
- Instead, STAs focus on maximizing the usage of existing capacity through increasing the share of expenditures on operations and traffic services.
- Improved ITS and materials enable a safer and more efficient road network.

America is doing much better in this scenario than in the baseline. Unfortunately, economic growth and prosperity do not come without a cost. Overall demands for mobility have increased in comparison to the present day, but individuals are less free to travel than they were in the early days of the 21st century. More people wanting to travel and more goods being delivered create congestion on the existing road networks. Resources are more plentiful, but building more and more roads was quickly found to be an unsustainable model for facilitating growth.

Instead, Americans begin to put more faith in state and local governments to plan growth in a coordinated and thoughtful manner. Communities are set up to enable individuals to live their lives with a minimal impact on the transportation network: living in developments that centrally locate work, school, shopping, and other destinations. Transit and automated vehicles shepherd individuals and goods on the roads. Automated vehicles usher in a small revolution of their own but are insufficient to mitigate congestion independently. The roads and the vehicles work in tandem to prevent crashes and congestion, while more individuals work from home to minimize the amount of time they have to fight traffic.

STAs carefully regulate and coordinate development and growth with local governments. STAs have greater budgets but do not focus on building roads. Instead, they focus on creating the conditions that make roads operate smoothly. The earliest stages of this started with coordinating signal timing and optimizing traffic flows. As demands for mobility increased and the road networks could not keep up, STAs realized that they had to make the roads themselves more efficient, investing heavily in developing and implementing infrastructure and technologies—and the V2I vision in particular—that make the roads operate smoothly and safely. STAs hire employees capable of developing, implementing, and maintaining high-tech equipment. STAs take a lead role in facilitating the interoperability of disparate technologies, and leveraging their coordinated power to make the roads run as efficiently as possible. Capital project development includes both civil construction and IT design and implementation.

Cybersecurity becomes of utmost importance for STAs. Roadways, vehicles, and other equipment rapidly adopt ITS and integrate various connected technologies throughout the transportation network. Many aspects of the transportation network become interdependent and interconnected. Some of these technologies include connected vehicle sensors and infrastructure; near-ubiquitous dynamic message signs (and other tools that provide information to motorists); interconnected, smart traffic control devices; and many other technologies. As a result, technological vulnerabilities abound, and STAs hire employees to manage risks and prevent and deter hackers.

The demand for freight increases throughout this time period, and STAs take on new roles in developing strategies to handle the demand. States and STAs implement a variety of policies to handle the increased demand. Some states implement road pricing to shift demand away from urban corridors. Some devote highway lanes to move freight through congested areas, often coupled with additional road pricing. Road trains become legal and commonplace in less-populated parts of the country and under specialized circumstances. The overall road freight demand is slightly lower than it might have been, however, due to the advent, proliferation, and eventual successful commercialization of 3-D printing and alternative modes for freight delivery.

In summary, in the 2040–2060 time frame, advancements in technology and materials allow an actively managed and integrated system.

7.4 Second Alternative Scenario - Escape to the Centers

In the Escape to the Centers scenario, the lack of mobility and increased threats to individuals' well-being drive people out of the suburbs and into the city, reducing the demand for transportation—this is the vision of the advocates of smart growth. Potential implications of this scenario for transportation traffic services are as follows:

- STAs reduce capacity expenditures.
- They refocus efforts on maximizing the throughput of existing infrastructure.
- Improved ITS and materials create a safer and more efficient road network.

Under this scenario, Americans have found that living further and further out is an unsustainable life: the costs of congestion eventually put a limit on exurban growth, and life gradually creeps back into the cities. Density increases, and smart growth takes hold.

A shift in philosophy toward an operations emphasis in urban centers causes STAs to place less focus on building highways and additional roadway infrastructure. They begin instead to focus on maintaining and revitalizing the roadways in urban centers, bolstering multimodal transportation and expanding ITS to support the cross-modal user. Transit priority and bus rapid transit systems facilitated by the ITS infrastructure improve and create a seamless system.

Full pricing of the highway network supports the economic disincentives placed on dispersed development and the incentives for compact living and working. Technology standardization enables seamless fee collection across modes. The revenue generated in turn supports the integration of the urban highways into other modes with a "connected traveler" approach. Automated vehicles increasingly support an "auto use" model rather than an "auto ownership" model because the need for full availability of a car for all trips greatly diminishes as alternate modes thrive.

Advances in traveler information to include increasingly detailed and real-time traffic information drastically improve a variety of traffic operations, including transit arrival, various parking management systems, and general highway operations. The information quickly becomes accessible to commuters and travelers, safely integrated into the vehicles, and accessible through personal devices, enabling them to make efficient traveling choices based on real-time road conditions.

7.5 Third Alternative Scenario - Meltdown

In the Meltdown scenario, abrupt climate change shifts priorities from growing the economy to struggling with nature. Potential implications of the Meltdown scenario for transportation traffic services are as follows:

- Rapid climate change results in policies that dramatically change transportation in the United States.
- STAs and local governments focus on fostering the development of transportation modes that do not rely on carbon.
- STAs adopt smarter ITS and work to optimize all operations and monitor physical infrastructure status.
- Intelligent emergency evacuation systems are developed and implemented to ease mass people movement during the increasing number of emergencies.

Following years of severe droughts, wildfires, intense storms, sea-level rise, and other ill effects of climate change, the United States decides to focus efforts on decreasing carbon emissions. Among the policies implemented, pricing carbon has among the most dramatic effects on all of society. The transportation area is no exception.

Pricing carbon increases the costs of driving for all motorists, even those driving electric vehicles since most electricity is produced with carbon-based fuels. As a result, motorists finally bear the external costs of driving that had not been charged under previous pricing systems. The increased cost reduces VMT and creates strong incentives for motorists to use alternative transportation options. STAs and cities begin collaborating to make it easier for individuals to use modes other than the single-occupant vehicle to travel. STAs move toward exclusive use of alternative energy products, like solar energy, to power traffic service equipment.

VMT in rural areas dramatically drops off as STAs begin coordinating the development of intra-city transport that does not require large amounts of carbon. High-speed rail becomes the preferred way to move from one city to another. Because of the decreasing VMT, traditional rural traffic services become much less important, but those involving road-weather information and infrastructure status increase in use. These applications are needed to accelerate the process of alerting users of closures or dangers associated with severe weather events.

The emergence of frequent high-powered storms becomes an issue for STAs and emergency planners alike. Government agencies work in close coordination to develop better policies, procedures, and technologies to ease mass evacuations. Communicating with motorists becomes much easier as in-vehicle communications technologies enable emergency planners and STAs to quickly disseminate route and other pertinent information. The lynchpin of this effort is collaboration among disparate agencies. Police forces, local governments, STAs, and other agencies all struggle to integrate computer systems and easily share data.

Advances in traveler information to include increasingly detailed and real-time traffic information drastically improve a variety of traffic operations, including transit arrival, various parking management systems, and general highway operations. The information quickly becomes accessible to commuters and travelers, safely integrated into the vehicles and accessible through personal devices, enabling them to make efficient traveling choices based on real-time road conditions.

7.6 Identifying Potential for New Tools, Technology, and Approaches

After understanding the conditions and impacts, the next step was to identify the potential for new tools, technology, and approaches for each of the scenarios. Check marks in Table B.1 show how STAs may react to each scenario by adopting and/or developing new tools, technologies, and approaches. Visual assessment of Table B.1 shows a high concentration of tick marks under funding redistribution to operations, privatization, and workforce training. Accordingly, regardless of how the future turns out, these approaches have critical priority for STAs. Detailed examples for each column are provided as notes in the matrix of Table B.1.

Table B.1. Implications of the scenarios for STAs.

Multi-driver Scenarios	Tools		Technologies		Approaches		
	Traffic Control Device Materials	Data Management	V2I Integration	IT Integration and Standardization across Modes	Funding Allocation to Operations	Privatization	Workforce Training
Baseline (Managed Decline)					✓	✓	✓
Back to the Future		✓	✓		✓		✓
Escape to the Centers			✓	✓	✓	✓	✓
Meltdown	✓	✓		✓	✓	✓	✓

Notes:

- *Traffic control device materials* primarily refer to resins and other components of static signs and pavement markings that are required for durability and legibility. Current products are largely dependent on natural resources that are approaching depletion and contain hazardous byproducts.
- *Data management* includes the capabilities for securely storing, managing, accessing, and manipulating large traffic datasets to support operations.
- *V2I integration* refers to development and deployment of roadside infrastructure and backhaul communications for systems that support safety, mobility, and environmental applications.
- *IT integration and standardization across modes* include capabilities to integrate highway operations with transit, local, and regional operations.
- *Funding allocation to operations* covers new methods for increasing funding, including reallocating investments in construction of new facilities.
- *Privatization* refers to engaging the private sector in various business models to manage the development, deployment, operations, and/or maintenance of traffic services.
- *Workforce training* refers to the next generation of the workforce trained for performing sophisticated tasks involving new traffic service systems and delivery of those systems.

7.7 Implications for State Transportation Agencies

Several important themes arise following a review of the future scenarios and impacts for traffic services.

Funding Allocation to Operations

Future funding levels have a significant impact on the degree to which STAs will engage in the provision of traffic services. Current funding sources are unsustainable, resulting in a shift in available construction funds to traffic operations to gain additional efficiency in the system. Even under alternative scenarios with sufficient funding, expansion will continue to become increasingly expensive—particularly in urban environments—creating a greater need to focus on operations. This will necessitate a STA cultural change from "build it" to "operate it." However, low funding levels will be insufficient for STAs to have a significant role in enhancing operations and ensuring high levels of maintenance as technology advances.

Privatization

In the face of unsustainable funding, demand for services will require new business and funding models involving the private sector. Tolling authorities and the private sector will have important roles to play in the traffic services of the future. This is especially apparent when considering the current state of transportation operations technologies and maintenance requirements. Private-sector firms are already largely responsible for technological breakthroughs in transportation operations, most notably the auto manufacturers and suppliers involved in next-generation vehicle technologies, along with companies in areas such as traffic data and next-generation materials for traffic devices.

A concern for this burgeoning industry is the public's interests: At what level will STAs ensure that the broader public interests related to safety, mobility, and the environment are addressed through the consumer-oriented products that are under research, development, and deployment by private interests? Without sustainable funding, the traditional STA role may be diminished, resulting in the transportation system becoming a private enterprise with pay-for-use services.

Workforce Training

A STA cultural shift from "build it" to "operate it" will require expanded education and training to ensure that staff with the necessary expertise are available. New technological applications will require the development of new workforce skills to lead the public agency response. This is needed to ensure that the public interest, including stewardship of public funds, is effectively addressed. Skill sets involve IT integration, standardization, and data management. Changes in workforce skills will be needed to accommodate new partnering arrangements with the private sector, such as legal, financing, and contractual or innovative procurement expertise.

7.8 Appendix B.1—Traffic Services Activities

The term *traffic services* describes the management and operation of traffic on a roadway through devices and technologies, including static and dynamic signs, signals, pavement markings, roadside lighting, and ITS. It includes the use of ITS to support the management of traffic flow in urban regions—in both recurring and nonrecurring congestion conditions—to maximize throughput and minimize the impacts to system reliability. The following are some examples:

- Static signing—signs erected to provide information of a constant (i.e., unchanging) nature to road users.
- Dynamic signing—also known as changeable or variable signing; used to advise drivers of traffic or roadway conditions ahead and, in some cases, recommend alternate routes. Dynamic signing also reduces driver frustration by providing advance warning.
- Traffic signals—signaling devices positioned at road intersections, pedestrian crossings, and other locations to control competing flows of traffic.
- Pavement markings—markings set into the surface of, applied upon, or attached to the pavement to inform or guide traffic. Markings intended to guide traffic include striping, traffic buttons, raised pavement markers, and graphics.
- Roadside lighting—the placement of lighting within the right-of-way along a road for the purpose of illuminating the roadway.
- ITS—the application of technology to enhance the movement of people and goods, including:
    - Optimization of capacity through instrumentation and feedback.
    - New wireless systems and digital services along with distributed processing of the new traffic control systems.
    - Targeted information optimized according to accident-prone time periods and road surface conditions.
    - Use of cell phones and other advanced telecommunication tools to improve safety and mobility.

Other definitions include the following:

- Recurring congestion—traffic congestion that occurs in a regular pattern, such as congestion at rush hour or other regularly scheduled events.
- Nonrecurring congestion—traffic congestion created by activities such as individual incidents, temporary road closures, inclement weather, or special events.

7.9 Appendix B.2—Conditions and Impacts in the Baseline Scenario and Six Alternative Scenarios

Table B-1 summarizes the conditions in the six alternative scenarios. The reasoning was to understand the availability and level of funding to determine what activities or efforts STAs would focus on to provide the necessary level of service to the public. This condition determined the type of traffic service technologies and techniques that would be developed to support the traffic service activities in a safe and efficient way. The specific impacts that each condition would generate on individual scenarios are summarized in Table B-2. Finally, the development of new techniques and technology will be governed by other external conditions such as environmental concerns.

Table B-1. Summary of conditions in the baseline scenario and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	Meltdown
Funding and Focus	Emphasis on existing infrastructure operations. Growing involvement of private sector.	Some new construction due to availability of resources. Operations focus with government lead.	Some new construction due to availability of resources. Operations focus with government lead.	Emphasis on existing infrastructure operations. Growing involvement of private sector.	Construction of new transportation system as a result of economic growth and funding.	Less highway expansion. More focus on urban areas and integration with multiple modes.	Less highway expansion. More focus on urban areas and multiple modes.
Technology and Techniques	Technology-enhanced mobility but more private sector than public.	Realization of the roadside infrastructure vision (V2I). Strong STA role in facilitating technology.	Realization of the roadside infrastructure vision (V2I). Strong STA role in facilitating technology.	Technology-enhanced mobility but more private sector than public.	Widespread application of technologies across vehicles and personal devices to support travel needs.	Technology focused on urban travel.	Technology focused on optimizing operations and monitoring physical infrastructure status and hazards.
Proportion of Funding Private	Private-sector funding increases as a share of overall funding.	Private-sector funding increases as a share of overall funding.	Decreased private-sector funding as a share of overall funding.	Funding shifts to transportation cooperatives.	Private-sector funding increases as a share of overall funding.	Private-sector funding increases as a share of overall funding.	Private-sector funding increases as a share of overall funding.
Mobility Demand	Aggregate demand for mobility increases despite decreases in per-capita demand.	Aggregate demand for mobility increases.	Aggregate demand for mobility increases.	Decreased aggregate demand for mobility.	Increased aggregate demand for mobility.	Decreased aggregate demand for mobility.	Decreased aggregate demand for mobility, especially in rural areas.
Amount of Road Freight	Road freight increases.	Road freight increases.	Road freight increases.	Road freight increases.	Road freight increases.	Road freight increases.	Road freight decreases.

Table B-2. Summary of the impacts in the baseline and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	Disruptive Scenario (Meltdown)
Funding and Focus	Maintenance, operations, and renewal.	Capital projects oriented to operations.	Expansion, operations, and maintenance.	Maintenance, operations, and small demand for renewal.	Capital projects oriented to operations.	Capital projects oriented to operations in urban core. Ongoing maintenance.	Maintenance, operations, and renewal.
Technology and Techniques	Expertise in IT and procurement for private-sector implementation.	Development, implementation, and maintenance of extensive ITS infrastructure.	Development, implementation, and maintenance of extensive ITS infrastructure.	Expertise in IT and procurement for private-sector implementation	IT integration across multiple agencies and modes.	IT integration across multiple agencies and modes.	Expertise in emergency operations.
Proportion of Funding Private	Private-sector role increases in light of funding limitations and need for expertise. New models for partnerships emerge.	Private-sector role increases in light of funding limitations and need for expertise. New models for partnerships emerge.	Private-sector partnership in limited applications.	Funding shifts to transportation cooperatives.	Private-sector role increases in light of funding limitations and need for expertise. New models for partnerships emerge.	Private-sector role increases in light of funding limitations and need for expertise. New models for partnerships emerge.	Private-sector role increases in light of funding limitations and need for expertise. New models for partnerships emerge.
Mobility Demand	Increase in demand creates pressures to better operate the system.	Increase in demand creates pressures to better operate the system.	Increase in demand creates pressures to better operate the system.	Demand shifts to digital infrastructure. Reduced pressure on capacity but sustained focus on operations and maintenance.	Increase in demand creates pressures to better operate the system.	Demand shifts to local infrastructure.	Demand shifts to local infrastructure.

Driver	Baseline Scenario (Managed Decline)	Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	Disruptive Scenario (Meltdown)
Amount of Road Freight	Road freight increases supported through technology-enhanced mobility.	Road freight increases supported through technology-enhanced mobility.	Road freight increases supported through technology-enhanced mobility.	Road freight increases supported through technology-enhanced mobility.	Road freight increases supported through technology-enhanced mobility.	Road freight increases supported through technology-enhanced mobility.	No impact to traffic services.

7.10 Appendix B.3—Bibliography

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8.0 APPENDIX C - PAVEMENTS AND MATERIALS WHITE PAPER VISION

8.1 Description of Transportation Area: Pavements and Materials

The term *pavements and materials* describes the production of raw materials, use of recycled materials, pavement thickness design, materials selection, recycling, production of the finished material, pavement placement and compaction, and subsequent renewal, maintenance, and preservation activities. Currently, pavement activities occupy the greatest proportion of highway agency budgets in most states. Consequently, any scenario that would impact the use of roadways would have major implications for the funding, construction, and upkeep of pavements.

The research team used the baseline scenario and selected three alternative scenarios that represented the most variability and had the greatest implication for the pavements and materials area from the baseline scenario. These scenarios were further developed into specific applications for the pavements and materials transportation area. These alternative scenarios include:

- "Back to the Future."
- "Bits over Buses."
- "Meltdown."

The research team also identified the potential for new materials, tools, technologies, and approaches for the baseline scenario and for each of the alternative scenarios.

8.2 Description of the Baseline Scenario: Managed Decline

The baseline scenario calls for slow economic growth, more energy demand, more but slow technology development, and smaller government role in highways. Slow economic growth implies that funding for highways may not keep pace with the past expenditures. The result of this would be that only capital construction projects that are deemed critical (for instance, dedicated freight routes) would be built. Potential implications of this scenario for pavements and materials are as follows:

- The majority of emphasis for pavements is placed on preservation of existing structures using improved monitoring tools and longer-lasting materials.
- A higher demand for energy drives up construction costs and reinforces that only critical new highway projects are constructed and that pavement preservation is the main emphasis.
- Technology development leads to a more efficient workforce relying more heavily on automation, possibly through robotics, for construction operations to improve safety and potentially reduce costs by reducing lane closures and construction time.
- Longer-lasting materials include the use of alternate asphalt or cement binders and the use of nanotechnology to enhance performance. The use of advanced mechanistic approaches to design and evaluate pavement structures is made possible through improved modeling of pavement behavior and performance.
- A smaller government role results in the need to outsource many engineering and management functions to ensure project delivery. Local government and private investors replace traditional STA functionaries in infrastructure construction and operation.

Notable changes are made in materials, approaches, tools, and technologies. There is increasing pressure to use more economical and more environmentally friendly materials. This is accomplished through a combination of increased recycling of existing materials and the incorporation of new low-emissions binders and manufacturing and construction techniques, such as a 100 percent crushed concrete with a low-carbon cement binder. Mechanistic approaches to design continue to evolve and help avoid the gross overdesign resulting from the use of purely empirical pavement design methods used in the 2010s. This greater efficiency in design should substantially reduce the overall cost of pavement construction.

New binder materials are developed for roadway construction. In the 2000s and 2010s, there was a significant increase in the use of polymer-modified asphalt binders to improve pavement performance, especially in the surface course. The amount of polymer used in asphalt modification increased through the likes of high-polymer asphalts introduced to the market in 2012 by Kraton, Inc., as HiMA (Kraton, Inc., 2012). Alternate binders or binder replacements such as synthetic binders become more prevalent as petroleum prices increase and further research validates their performance. An example of this is Vegecol, a plant-based binder made in the 2010s by Colas, Inc., which can be transparent and produced at temperatures that are about 80° F cooler than typical asphalt mixes (Colas, Inc., 2005). Iowa State University researched the use of fast pyrolysis as a means of producing a binder extender from corn stover (Williams et al., 2011). Further asphalt binder substitutes become available from the farming and subsequent processing of certain strains of algae (King and King, 2009). New materials for construction require changes in specifications from current prescriptive specifications to performance-based or performance-related specifications. These changes entail the shift from recipe or volumetric requirements to performance specifications focused on the properties of asphalt and concrete mixtures.

In asphalt and concrete mixtures, efforts dramatically increase the amount of recycling and the use of additives to promote better performance. Complete reuse of asphalt mixtures is realized in the cold in-place recycling method, but such mixtures do not have the quality of plant-produced mixtures at higher temperatures that are typically used in surface courses. Work at Rutgers University aimed at producing high-quality asphalt mixtures with up to 100 percent recycled asphalt pavement (RAP) using rejuvenating agents (Bennert, 2012). Eco-friendly Portland cement substitutes were developed to go beyond the standard fly ash and blast furnace slag to include metakaolin, natural pozzolans, and limestone. Limestone cement production outpaced the production of Portland cement (Scrivener, 2010). By 2040, additives of nanoparticles are used to inhibit cracking or rutting in asphalt and cracking in concrete mixtures. Such additives are used in materials placed in critical locations in pavement structures where distresses are likely to originate. Again, changes in specifications and testing ensure that new technology can be accommodated.

Increased use of automation and innovation in the construction of pavements results in safer work zones by minimizing the number of workers exposed to traffic, and it appreciably speeds the construction process, thereby minimizing accidents. An example of innovations to speed the construction of pavements can be found in the Roads to the Future program sponsored by the Netherlands Department of Public Works and Water Management (Federal Highway Administration, 2005). In this effort, contractors submitted proposals to the department to construct the quietest possible road surface in the fastest possible time. Contractors submitting successful proposals were chosen to actually build sections. One example, called the "Rollable Road," is shown in Figure C.1 where the road surface is applied by means of a rolling dispenser and then adhered to the existing pavement by means of an infrared heater.

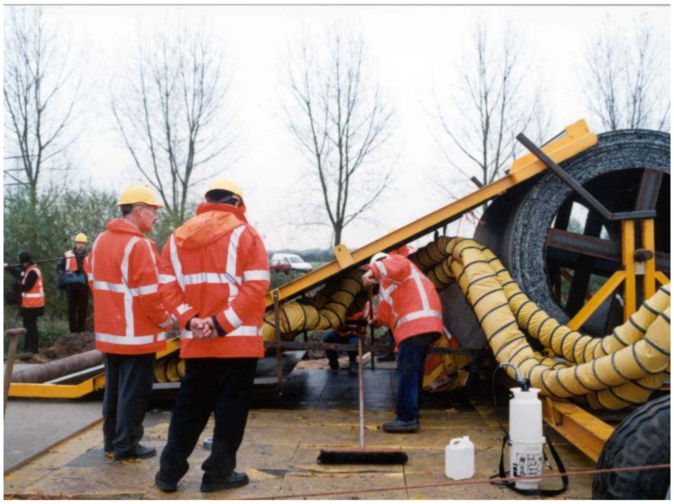

Figure C.1. The "Rollable Road" in the Netherlands (Federal Highway Administration, 2005).

Other technologies included modular concrete pavements and another rolled pavement surface placed with a microwave unit. Volvo developed specialized containers and a new paver called the Fenix system (Volvo Equipment Co., 2010). The concept is for modules of asphalt mix to be delivered in pods to the roadway and spaced at appropriate intervals. The paver picks up the module, places the mix, compacts it, and stripes the road. Empty modules are left on the road to be retrieved for transport back to the plant (Figure C.2). All this requires only one equipment operator.

Technologies such as these speed the construction process and allow greater flexibility to work around peak traffic flow than current construction methods. Global positioning system (GPS) units or total station surveying units are used to remotely direct construction equipment such as pavers and asphalt compactors. Such equipment was in use in the 2010s in the mining industry where driverless dump trucks were used to deliver aggregate or ore from the pit to the crusher. In order to take advantage of construction innovations such as these, it was necessary for agencies to allow contractors the flexibility to employ new technologies in construction as they became available. These construction techniques require different methods of quality control/quality assurance (QC/QA) testing and acceptance. Such methods check uniformity in placement and provide for automated data collection, analysis, and system feedback to adjust production and paving.

Figure C.2. "Fenix" paving system as envisioned by Volvo (Volvo Equipment Co., 2010).

Testing of pavements and pavement materials employs nondestructive and rapid methods. For example, the full spectrum of electromagnetic energy is used, including ultraviolet, visible, and infrared light frequencies (Figure C.3). Ultraviolet light is used to investigate the durability of asphalt mixes, and visible light is used in distress measurements. Enhancements to automated means of making and interpreting these surveys make them even more powerful. Until 2010, infrared measurements were performed on a limited basis behind asphalt pavers to ascertain the uniformity of the material. This practice expands in the 2040–2060 time frame, and is tied into a communications network that tells the paving crew and plant how to make appropriate adjustments to the process or the materials in real time. In addition, ground-penetrating radar, as featured in the Strategic Highway Research Program 2, is also used to examine the uniformity and moisture content of the layers underneath the pavement, identifying potential weak spots that could be prone to delamination. In-situ monitoring devices such as strain gauges and piezoelectric sensors are used to provide real-time indications of structural health in pavements. Before visible distresses occur in the surface, such sensors can alert agencies to perform preservation treatments to extend pavement life. This saves the agency time and money in maintaining roadways. Other technology is also brought to bear in the evaluation of materials, such as nuclear magnetic resonance, which may be useful in ascertaining the degree of aging in pavement materials.

(a) Ultraviolet (b) Visible (c) Infrared

Figure C.3. Pavement testing and monitoring nondestructive techniques employing full light spectrum.

In the 2040–2060 time frame, pavement design methods grow in the complexity of their analysis, but they also become more user friendly. In place of the linear elastic methods used up to the early 2010s for both asphalt and concrete pavement design, visco-elastic-plastic models capable of handling much more sophisticated structures are developed. In the 2040–2060 time frame, choices for pavements are not limited to concrete or asphalt but rather include what combination of concrete, asphalt, or both materials should be used for a given set of traffic and climatic conditions. However, the inputs for determining the combination proportion is reduced to a relatively few, easy-to-determine parameters. Designs are more efficient as the engineering of materials for specific functions within the structure becomes more fine-tuned. Also, compared with the 2010s, a wider range of conditions, such as the generation of roadway noise in urban areas, the need for fully drainable (permeable) pavements to mitigate run-off problems, and frictional properties of the surface for increased safety, are considered during pavement design. In the 2040–2060 time frame, pavement design methods are more encompassing, flexible, powerful, and user friendly than what had been used up to the early 2010s.

In the 2040–2060 time frame, agencies outsource more functions. This is necessary because operations budgets continued to decrease, and project delivery demands continued. Consultants are employed in the design, construction management, and materials-testing functions within STAs. This necessitates consultant certification in pavements and materials technologies. Such certifications were already being used in early 2010s to qualify materials sampling and testing technicians. Due to the innovations possible in materials and construction, more agencies employ warranties for the performance of roadways rather than use prescriptive specifications. Contractors need to become more involved in the development of technology that allows them the capability to rapidly build pavements and ensure their performance.

Although the baseline scenario calls for relatively slow development of technology, a number of developments encourage innovation on certain issues. These issues are economic and environmental pressures, agency downsizing, the availability of new technologies, and innovative construction techniques employed for safety, product quality, and traffic congestion mitigation.

With the baseline defined, some alternative futures will now be examined with respect to their impacts.

8.3 First Alternative Scenario - Back to the Future

In the Back to the Future scenario, the economy is healthy, and there is plentiful funding for infrastructure. Potential implications of this scenario for pavements and materials are as follows:

- A healthy economy means a return to higher energy costs, which impacts both concrete and asphalt costs.
- Material shortages and labor shortages occur due to higher competition for resources driving up costs.
- Because larger projects are feasible, renewal funding overshadows preservation and maintenance.
- There is less innovation and technology implementation on the design and materials portion of projects because with adequate funding there is little need to change the way things are done.
- In spite of the relatively slow rate of innovation and implementation, improvements have been made in pavement construction efficiency and work zone safety.

As was seen in the early 20th century, a healthier economy means a higher demand for both energy and construction materials. Figure C.4 and Figure C.5 illustrate this point for both Portland cement and asphalt cement, respectively. Because the economy was at a peak in 2008, prices for both of these commodities peaked. As the economy began a rapid decline, prices for both materials fell. This was partially due to the relationship between these binders and energy costs, but it was also due to global competition from expanding economies in countries such as China and India. China ranks first among nations in the consumption of cement, using over 50 percent of the world's supply, and India is a distant second. As the world economy recovers, there is greater demand from other countries such as Brazil, Australia, and Nigeria.

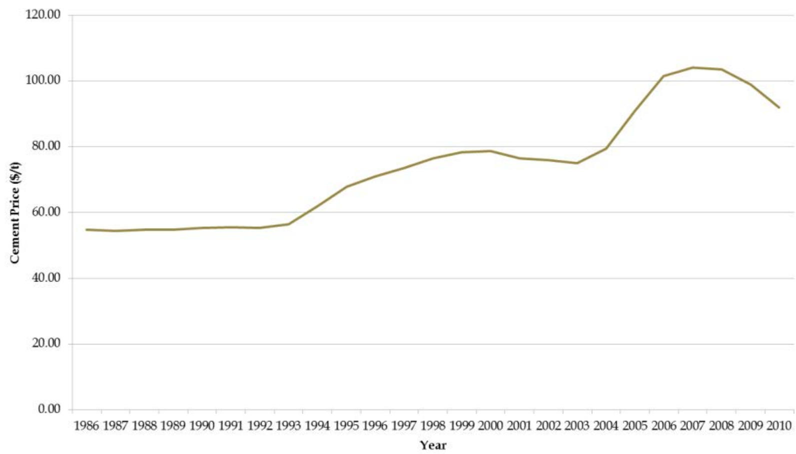

Figure C.4. Changes in cement prices, 1986–2010.

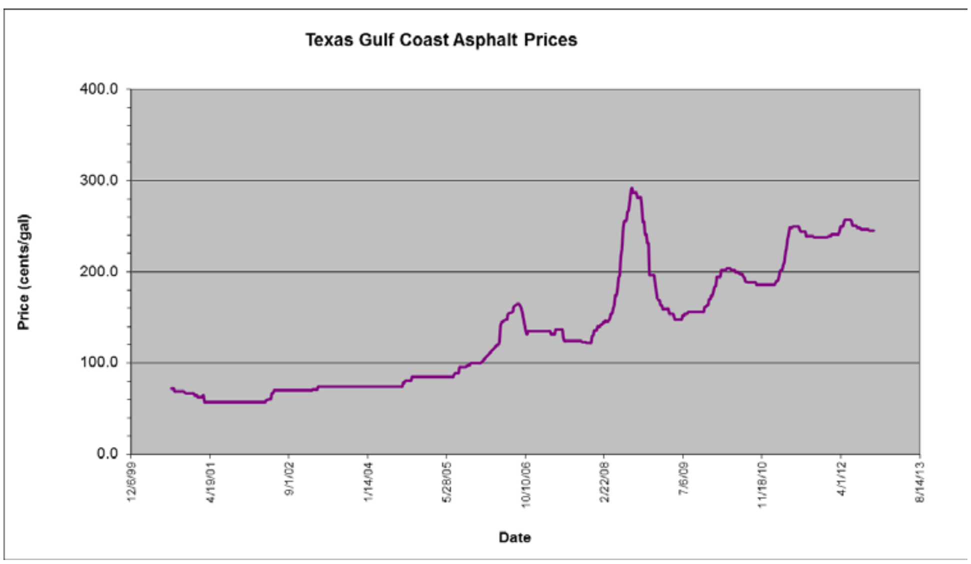

Figure C.5. Changes in liquid asphalt prices, 2000–2012.

Other effects of a strong economy are shortages in materials and labor. High demand for cement in 2005 led to spot shortages in the United States because production could not keep up with global demand. Also, as demand for transportation related fuel increased in 2008, refineries began installing coking units to convert asphalt to usable fuel stock. Although not related to the world economy, 2008 also saw a shortage of styrene-butadiene-styrene (SBS) block co-polymer, which is often used in asphalt modification required for high-volume roadways. This particular shortage occurred as a result of modifications being made to SBS production facilities in Asia. One of the important aspects of the oil boom in Texas in the 2010s was a shortage of truck drivers due to the demand for this skilled labor set in the hydraulic fracturing (fracking) process. In the 2040–2060 time frame, as commercial and residential construction make a comeback, the available pool of trained construction workers for highways dwindles. Wages and the demand for training subsequently increase.

Since funding is readily available, STAs concentrate on larger projects, and the emphasis on maintenance and pavement preservation decreases. Many of these capital projects had been deferred, and the opportunity to finally address added capacity and other waiting upgrades is very attractive to agencies. As a result, maintenance and pavement preservation, although still practiced, is not a large percent of the total budget, as they were early in the century when agencies were scrambling for band-aids to hold their road systems together.

While innovation is available for the design and materials selection phases of projects, there is only modest interest in pursuing them because agency engineers focus on project delivery. Mechanistic design evolves over the years, and its application becomes more universal, and performance testing of materials is on the rise. With the increase in materials prices, there is renewed interest in finding alternatives to using the past standards. Increased recycling, bio-based binders, and mineral substitutes are in greater use.

On the construction side, contractors are eager to take advantage of technology to make up for labor shortages and speed the delivery of projects. Automation in materials production, paving, and quality control/quality assurance enhances the ability of contractors to produce pavements faster and with greater consistency. Also, reducing the number of workers and improving work zone crash countermeasures gives the industry a much safer environment in which to build roads.

In the end, the Back to the Future scenario has many positive features for the improvement of roadways and the health of the contracting industry. It also means reducing maintenance and preservation efforts in favor of concentrating on deferred construction projects. There are implications in terms of the cost and availability of materials and labor, some of which is mitigated through the use of alternative materials and automated construction processes.

8.4 Second Alternative Scenario - Bits over Buses

In Bits over Buses, the price of crude oil rises much faster than expected. As a result, fewer people are using traditional transportation in lieu of conducting business and leisure activities using the Internet through networks provided by the government. Thus, “ordinary” travel is greatly diminished, leaving roadways available for more crucial items such as essential trips and the efficient movement of goods and services. As a result, the materials and pavements aspects of transportation are affected as follows:

- Construction costs are much higher due to higher energy costs. Asphalt is dependent upon oil for binder, concrete is dependent upon energy-intensive cement, and fuel affects all construction operations. The high costs of virgin materials force a greater level of recycling for all materials and more growth in markets for alternative binders.

- Competition for projects is fierce because there are much fewer construction projects due to much higher costs and a sharp decline in demand. Some contractors are forced out of business, and those that remain are vertically integrated and use advances in technology to remain nimble.
- More technology is being employed in material production and placement practices. Contractors must gain efficiencies because of the increased competition for fewer projects and the need to minimize fuel consumption during construction, maintenance, and preservation activities.
- The focus for agencies is on maintaining the critical components of the existing system. They give more attention to maintenance and preservation because the construction of new facilities is not necessary. Many low-volume rural roads are allowed to degrade to an unsurfaced state.

The price of fuel increases dramatically in 2040 in this scenario, and the production of materials is an energy-intensive activity. Since asphalt is derived from petroleum, any increase in crude oil price is automatically reflected in the cost of asphalt binder. Recycling asphalt back into mixtures generally results in about a 9 percent cost savings for each 10 percent of RAP used in the mix. Up to the 2010s, Portland cement concrete was recycled as aggregate in either granular base courses or in concrete mixtures as coarse aggregate. In the 2040–2060 time frame, the use of bio-based asphalt binder substitutes and mineral extenders such as sulfur is more prevalent as asphalt becomes much more expensive. While these actions are stirred by economic concerns, they have an environmentally friendly outcome in consuming fewer resources.

The competition for construction projects becomes fierce due to the paucity of available jobs. With the fuel tax revenue falling due to declining use of vehicles, the available capital must be spent on preserving as much of the existing system as possible, and the few critical construction projects are focused on renewal. Successful contractors stay in business by being vertically integrated and having the ability to provide a wide variety of services including construction, maintenance, pavement preservation, pavement evaluation, structural design, and materials evaluation. They employ systems that rely on automation and feedback to reduce labor costs and gain efficiencies. They frequently have long-term contracts to provide system services for local governments. However, smaller contractors have to either exit the market completely or relegate themselves to specialty work such as parking lots. Thus, in the end, the market is dominated by a few very large contractors.

Innovation and technology are tools employed by contractors to gain efficiencies and attract customers. Technology such as infrared monitoring of asphalt mixtures during placement and intelligent compaction is common and focuses on making construction as efficient as possible by ensuring that equipment spends no more time than necessary to construct a quality pavement. Nondestructive testing is employed to monitor as much of the delivered project as possible to ensure long-term performance. Because the contractor is responsible for the roadway over its entire life in many cases, all possible means are used to reduce maintenance and rehabilitation, not only because of the tangible costs but also to reduce roadway user costs, because agencies hold contractors responsible for any congestion.

Reduction in revenues forces agencies to downsize their systems in order to focus their scarce resources in a manageable way. Part of that downsizing is STAs shifting responsibility for certain roads to counties, and counties to cities and townships. It also means an increased number of public-private partnerships (PPPs) to run and maintain critical toll roads. In some cases, right-of-way is given back to landowners. Some low-volume roads that had hard surfaces are allowed to revert to unsurfaced facilities. While this does not relieve the agency of maintenance for the roadway, it does reduce the amount of expensive binder being used for patching and overlays. Existing facilities are watched closely to monitor the proper timing for pavement preservation activities. Keeping these facilities healthy is of prime importance for critical transportation needs and movement of goods.

This scenario forces hard choices for both the agencies and industry. Lower revenues mean decreased work but greater competition to win it. Agencies downsize their system and their personnel to deal with the harsh realities. Successful contractors adapt to the shifting market rapidly by expanding their capabilities and becoming more self-reliant. Pavements continue to exist, but they need to last longer with fewer repairs.

8.5 Third Alternative Scenario - Meltdown

There is a wholesale change in government as the focus of society changes from economic growth to environmental improvement. Changes in the laws require transportation agencies to provide monitoring and regulation of activities affecting the environment. Potential implications of the Meltdown scenario for pavements and materials are as follows:

- "Green" construction guidelines and metrics are developed and enforced by a conflicting and confusing array of government agencies. At the federal level, the U.S. Environmental Protection Agency and U.S. Department of Transportation have politically mandated guidelines for green construction and monitoring. These are often at odds with state and local requirements that have proliferated in the wake of the green movement.
- Pavement construction methods are geared toward greatly reducing carbon emissions and speeding construction to reduce or eliminate congestion.
- Maintenance and pavement preservation of critical roadways become the primary focus of transportation agencies. Beyond a few improvements and realignments of roads near ocean fronts, there is very little new construction.
- The use of recycling and alternative binders increases exponentially, almost at a rate where contractors and agencies cannot track their development. New mixture design methods must be developed for these new materials, and new pavement design methods must be developed for a new generation of highway vehicles.
- As people are drawn to population centers, rural roads become neglected, and many revert to unsurfaced conditions.

In the 2040–2060 time frame, necessity becomes the mother of invention, and necessity reveals itself in the form of many laws and regulations that rapidly proliferate and are enforced. Although there is a great deal of confusion and legal positioning that result at the federal, state, and local levels, it is clear that construction practices must be amended to reduce greenhouse gas emissions and consider the cradle-to-grave implications of the materials, machinery, and design used for roadways. Ratings systems such as Greenroads are required on all roadway construction projects although the metrics vary widely among jurisdictions. Eventually, jurisdictional authority and rating systems become more uniform, and the requirements are somewhat harmonized.

Pavement construction practices, for the few realignment and critical projects that exist, seek to minimize the generation of greenhouse gases through the selection of raw materials, design practices, construction equipment, and production and placement of finished materials. Raw materials that require energy-intensive, carbon dioxide–producing techniques are obsolete. New low-carbon Portland cement and bio-based binders have increased market share. Cold processes used for making asphalt mixtures improve to the point that hot-mix plants are no longer needed. Long-life pavement design is no longer optional; it is mandated as a way to reduce traffic congestion. Construction equipment runs on cleaner fuels that provide more energy for fewer emissions.

Since new roads are not being constructed and renewal projects are few and far between, it is necessary to employ maintenance and pavement preservation to keep the critical components of the existing system in working order. Although it is largely banned, all use of asphalt cut-backs is replaced with the use of asphalt emulsions to reduce emissions. Long-lasting seal coat binders are developed using bio-based and mineral-based extenders. The reduced number of roads is kept in very smooth condition to reduce emissions associated with greater energy consumption due to rough roads. Hot processes normally associated with maintenance and preservation activities are replaced with more expensive but environmentally friendlier cold processes.

The use of recycling increases exponentially with technology that allows 80 to 100 percent of the old material to be used. In fact, RAP becomes a highly traded construction commodity in an effort to avoid paying carbon tax on virgin materials. The use of RAP materials stiffens asphalt mixtures, leading to performance suited to the hotter environment. Other materials such as polymer modifiers in asphalt become more prevalent to resist rutting and shoving in high temperatures. Concrete mixtures are modified with set-retarder admixtures so that hydration of the cement is maintained at the proper rate. Battery-operated electrical vehicles, while being cleaner, are heavier, and the payloads they carry are heavier to make the expenditure of fuel more efficient. Upgrading of pavements to withstand higher loads includes the design of long-life pavements during rehabilitation. This requires new approaches to pavement design to ensure long life and low environmental cost by reducing congestion during maintenance and renewal.

People are attracted to population centers, and the rural areas see their population density become even thinner. While individual farmers are able to care for greater acreage due to technological improvements in agriculture, they find that many of the roads they depend on to move goods have either fallen into severe disrepair or are abandoned altogether. Thus, a far smaller network of critical farm-to-market roads is kept in adequate condition to move food from rural areas to metropolitan areas.

8.6 Identifying Potential for New Materials, Tools, Technology, and Approaches

After understanding the conditions and impacts, the next step was to identify the potential for new materials, tools, technology, and approaches for each of the scenarios. Check marks in Table C.1 show how STAs may react to each scenario by adopting and/or developing new materials, tools, technologies, and approaches. For example, environmental concerns associated with transportation construction projects make sustainability of construction approaches a critical priority for addressing challenges related to abrupt climate change in the Meltdown scenario. On the other hand, because in the Many Ways to Go scenario there is little need for new construction, there is low priority for investing in developing robotic equipment.

Visual assessment of Table C.1 shows a high concentration of tick marks under workforce training. Sensor deployment is considered a priority in scenarios involving a declining operating budget for STAs. Efficient construction, recycling, mechanistic design, automated QC/QA, and intelligent construction are important to any scenario involving more infrastructure construction or catastrophic events requiring much greater innovation. Accordingly, regardless of how the future turns out, these materials, tools, technologies, and approaches have critical priority for STAs. Detailed examples for each column are provided as notes in the matrix of Table C.1.

Table C.1. Implications of the scenarios for STAs.

Multi-driver Scenarios	**Materials**			**Tools**		**Technologies**			**Approaches**		
	Effective Design	Efficient Construction	Recycling	Mechanistic Design	Automated QC/QA	Intelligent Construction	Intelligent Production	Robotics	Sustainability	Sensor Deployment	Workforce Training
Baseline (Managed Decline)	✓	✓	✓	✓	✓	✓	✓	✓			✓
Back to the Future		✓	✓	✓	✓	✓				✓	✓
Bits over Buses									✓	✓	✓
Meltdown	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes:

- *Effective design* includes long-lasting pavement design and materials selection to reduce congestion due to work zones during the pavement life.
- *Efficient construction* includes all equipment and techniques needed to complete construction, renewal, maintenance, and pavement preservation in such a manner as to minimize traffic disruption.
- *Recycling* includes the reuse of any pavement materials including Portland cement, asphalt cement, and aggregate base.
- *Mechanistic design* includes all pavement design and materials selection criteria used in rationally designing pavements using the principles of mechanics.
- *Automated QC/QA* includes all the activities involved in sampling, tracking, testing, data recording, data analysis, feedback, and process adjustments involved in evaluating materials and finished products.
- *Intelligent construction* involves all technology associated with roadway activities such as milling, paving, sealing, and compacting the surface.
- *Intelligent production* includes all processes involved at the plant from receiving raw materials, processing raw materials, and realizing a final product to ship to the roadway.
- *Robotics* includes all activities associated with the production and placement of materials that have been traditionally controlled by human operators.
- *Sustainability* covers topics such as the use of bio-based binders, mineral extenders, or recycled content paving materials and greener production and paving methods.

- *Sensor deployment* refers to the use of devices to monitor the health of pavement systems by tracking responses to loads and environment and alerting agencies when problems may be forthcoming.
- *Workforce training* refers to the next generation of the workforce trained for performing sophisticated tasks involving new systems, equipment, and materials.

Note that for the pavements and materials area, potential construction techniques could have an effect on the materials used with new approaches or tools.

8.7 Implications for State Transportation Agencies

Table C.1 shows that agencies will need to adjust their operations and priorities with respect to pavements and materials according to specific conditions. Certain areas will be important almost regardless of the scenario. It is interesting to note that most of the changes in pavements and materials occur in the Meltdown scenario because the wholesale environmental change and societal reaction will require great innovation on the part of agencies merely to remain in business.

Sustainability

Sustainability will be more important in the future and especially in scenarios where environmental concerns dictate the use of green construction practices. Efficient design will be important in order to avoid overdesigning pavement structures and wasting money that could be going to other projects or programs, or to improve the environmental friendliness of pavements. Agencies will need to adopt long-life pavement design and rehabilitation strategies to reduce costs and environmental impacts. This will be especially important in handling heavier vehicle loads. Porous pavements will be increasingly used to mitigate stormwater runoff and recharge aquifers. Recycling will be important in any scenario involving large-scale construction or an environmental emphasis. Agency-led research will need to support increasing use of recycled materials, and permissive specifications will need to be developed to allow larger quantities of recycled materials.

Efficient Construction, Automated QC/QA, and Intelligent Construction

Automation in construction and production will be important in any scenario involving construction due to the need for contractors to be more competitive. This will drive agencies to find ways to accommodate automation by making their specifications more flexible. Rapid construction practices will take on greater importance in some scenarios than in others, but it will be an area that will continue to evolve under all of them. The institution of performance specifications will be completed.

Workforce Training

Training for both agencies and contractors will always be important regardless of the scenario as processes evolve in which feedback from sensors is used to make real-time decisions during construction or maintenance activities. This will also be true as more equipment is operated remotely from the roadside rather than in the roadway.

8.8 Appendix C.1 - Conditions and Impacts in the Baseline Scenario and Six Alternative Scenarios

Table C.1.1 summarizes the conditions in the six alternative scenarios. The reasoning was to determine what activities or efforts STAs could focus on to provide the necessary level of service to the public under certain funding constraints. This determined the types of materials, tools, technologies, and approaches that would be developed to provide pavement infrastructure as efficiently as possible. The specific impacts that each condition would generate on individual scenarios are given in Table C.1.2. Finally, the development of new techniques and technology will be governed by other external conditions such as environmental concerns.

Table C.1.1. Summary of conditions in the baseline scenario and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Higher Resource Scenarios		Lower Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Economic Growth	More emphasis on maintenance and preservation. Only critical capital construction built.	More construction. Renewal dominates preservation. Larger projects.	More construction of larger projects, maintenance, and preservation.	Much less capital construction. Preservation and maintenance on high volume only.	More emphasis on preservation of existing high-volume roads to ensure delivery of goods and providing essential services.	More emphasis on preservation of existing high-volume roads to ensure delivery of goods, and providing essential services and mass evacuation routes.	More emphasis on preservation of existing high-volume roads to ensure delivery of goods and providing essential services.
Govern-ment Role	Reduced STA operating budgets including personnel.	Operating budgets do not increase. Project delivery demands increase.	STA operating budgets restored, and more functions return to STA.	Lower operating budgets mean fewer STA personnel. More private and public-private toll roads. More roads turned back to local authorities.	Reduced operating budgets and overall lower usage of roads.	Reduced operating budgets and overall lower usage of roads.	Reduced highway usage reduces need for pavements and bridges.
Resources/ Energy—Demand	More emphasis on maintenance and preservation. Only critical capital construction built.	Material shortages due to competition. Higher material costs due to high transportation costs. Higher energy consumption. Personnel shortages.	Greater use of materials creates shortages. More emphasis on recycling.	Energy is expensive. Higher materials costs. Long-lasting designs and materials used on high-volume roads.	Lack of work means more competition for preservation work. Highway contractors go out of business.	Lack of work means more competition for preservation work. Highway contractors go out of business.	More emphasis on recycling and improved materials to reduce carbon footprint.
Technology—Physical and Fixed	More efficient design, testing, and construction. Use of long-lasting materials and mechanistic design.	Technology focused more on how to get more delivery, not on efficiency of materials or structures.	Technology focused more on how to get more delivery, not on efficiency of materials or structures.	Technology used to improve preservation/ maintenance treatments.	Less need for technology because there is reduced funding and interest in roads. Innovation goes elsewhere.	Less need for technology because there is reduced funding and interest in roads. Innovation goes elsewhere.	Technology focuses on more efficient, greener designs and greener construction practices.

Table C.1.2. Summary of the impacts in the baseline and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Higher Resources Scenario		Reduced Demand Scenario			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Economic Growth	Roads maintained in marginal condition.	Labor. Higher costs. Less innovation (no need to change).	Road conditions improve in both rural and urban areas. Greater usage of materials results in shortages.	Decline in funding for rural roads. More turn-backs to local governments. More reversion to gravel roads.	Decline in funding for rural roads. More turn-backs to local governments. More reversion to gravel roads.	Decline in funding for rural roads. More turn-backs to local governments. More reversion to gravel roads.	Decline in funding for rural roads. More turn-backs to local governments. More reversion to gravel roads.
Government Role	More outsourcing functions to consultants. Local government and private investors take prominent role.	Increased project delivery requires greater use of consultants. Private investment in toll roads grows.	More functions performed by STAs. Slowdown in development of toll roads. Fewer PPPs.	Lower operating budgets mean smaller STAs, but outsourcing does not increase because the work is not there. Fewer PPP projects. Shift responsibility to local government.	Lower operating budgets mean smaller STAs, but outsourcing does not increase because the work is not there. Fewer PPP projects. Shift responsibility to local government.	Lower operating budgets mean smaller STAs, but outsourcing does not increase because the work is not there. Fewer PPP projects. Shift responsibility to local government.	Government switches from “highway” departments to more “holistic” agencies. Results in less emphasis on constructing and maintaining roads. Fewer PPP projects. Shift responsibility to local government.
Resources/ Energy—Demand	Materials production keeps up with demand. Energy available.	Higher material and energy costs. Possible material shortages. Labor shortages. High transportation costs.	Higher material costs due to higher demand. Possible shortages of materials. Labor shortages. High transportation costs.	Cost of construction, preservation, and maintenance increases. Focus on getting longer life out of materials.	Greater competition for less available work. Materials remain at reasonable cost—not much demand. Fuel expensive.	Greater competition for less available work. Materials remain at reasonable cost—not much demand. Fuel expensive.	Much higher costs for materials and energy result in more efficient design and construction.
Technology—Physical and Fixed	Workforce more efficient. Reduced construction time. Better pavement performance.	STAs and engineers have little cause to improve structures or materials. Plenty of money.	STAs reluctant to take risks with innovation and implementation.	Improved recycling techniques, longer lasting materials, and energy-efficient construction all required.	Pavement and materials technology development almost nonexistent. Without a market, innovators look elsewhere.	Pavement and materials technology development almost nonexistent. Without a market, innovators look elsewhere.	More innovation in design to find greener ways of building and maintaining the remaining roads.

8.9 Appendix C.2—Bibliography

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9.0 APPENDIX D - CONSTRUCTION WHITE PAPER VISION

9.1 Description of Transportation Area: Construction

Construction in this study focuses on any transportation predesign, design, building, and assembly services and the means and methods related to delivering new and maintaining existing roadways and infrastructures. Construction services and activities cover a wide range of operations related to earthwork, such as subgrade preparation, foundation courses, base courses, shoulder construction, and gravel surfacing; installation of lighting, signs, and traffic control devices; laying of pavements; erection of bridges and culverts; and roadside development and erosion control. Appendix D.1 provides more detailed information about different types of activities that the construction area covers.

The research team used the baseline scenario and selected three alternative scenarios that represented the most variability and had the greatest implication for the construction area from the baseline scenario. These scenarios were further developed into specific applications for the construction transportation area. These alternative scenarios include:

- "Back to the Future."
- "Many Ways to Go."
- "Meltdown."

The research team also identified the potential for new materials, tools, technologies, and approaches for the baseline scenario and for each of the alternative scenarios.

9.2 Description of the Baseline Scenario: Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for transportation construction projects are as follows:

- Challenges remain in the maintenance and renewal of the existing infrastructure, and there is less emphasis on new capital projects.
- More dependence on public transit system leads to construction and maintenance activities that support innovative public transit systems.
- More private execution of design and construction processes leads to modest increase in innovation and faster project delivery. Hence, increased involvement of the private sector results in innovative project delivery and contracting methods.
- Development in information technology (IT) allows for the development of semi-autonomous heavy construction equipment, yet human interaction is still an integral part of construction.
- Concern for sustainability leads to heavy construction equipment that is fuel efficient and designed for human ergonomics.
- The construction workforce becomes more sophisticated.

In the baseline scenario, much of the STAs' effort focuses on maintenance rather than the addition of new capacity because of the expected constraints on funding. Higher fuel prices encourage people to drive less and make alternative travel arrangements such as carpooling and ridesharing. STAs are continuously faced with enormous challenges to simply maintain and rehabilitate existing highway infrastructure. Fortunately, with time this is somewhat alleviated by faster delivery and innovative contracting methods. In turn, preservation and renewal of facilities start to occur faster while maintaining an acceptable level of quality.

The main difference from 2013's construction activities is that there are more semi-automated technologies that can support efficient construction and simulation models that support effective maintenance processes. Although government funding has decreased, public-private partnerships (PPPs) and congestion pricing have reduced congestion in some areas and have driven innovation and modest technological advancements. Efficient construction means less downtime and errors, along with faster delivery. Simulation models assist planners in expending the limited funds for maximum benefit.

In the 2040–2060 time frame, the rise in public transit increases dramatically, and transit becomes the critical mode of transportation for many people. The growing senior population also relies heavily on the public transit system for independence, mobility, and accessibility.

The need to address the transit infrastructure has been an issue of national importance since the early 2000s. For example, in 2012, the Chicago Metropolitan Agency for Planning published a comprehensive regional plan, projected to 2040, to assist communities planning for sustainable prosperity. The argument was that an increase in the public transit system is far cheaper, leads to reduced congestion, and is better for the environment. And in support of this conclusion, the agency asserted that agencies should prioritize investment based on performance-driven criteria and that regions should plan to modernize existing assets rather than expand the system.

Consequently, in the 2040–2060 time frame, the multimodal approach considering transit users, bicyclists, and pedestrians receives the highest priority. Many of the existing public transit system are returning to better conditions, which results in reduced delays and increased reliability. This is also beneficial for the construction workforce. Far more money is spent on actually building a system rather than acquiring land, and the approach requires more diverse skills than just highway construction.

To further increase the efficiency of project delivery processes, state agencies use innovative contracting methods such as hiring a contractor to provide feedback during the design phase before the start of construction. In this process, a project is broken down into two contract phases, namely the design phase and the construction phase. The first contract phase, the design phase, allows the contractor to work with the designer and identify risks, provide costs estimates, and refine the project schedule. Moreover, state agencies use the design-build (DB) delivery approach, in which they select a DB team to assume the risk and responsibility for the design and construction phases. With DBs, STAs generally have the option of selecting a DB team based on a best-value basis, allowing STAs to consider other factors beyond lowest price. In general, innovative delivery approaches increase the direct interaction of clients with STAs, accelerate project delivery, lower project costs, and improve project quality.

Heavy-equipment manufacturers have developed machines that require software-driven platforms to support complex operations, such as global positioning systems (GPS), geographical information systems (GIS), and radio-frequency identification (RFID). For example, beginning in 1998, the Construction Industry Institute started researching the possible uses of RFID and GPS in construction for materials tracking and inventory management, and successfully used these technologies for improving the efficiency of activities. New emission regulations also changed the design and specification of heavy-equipment machinery. Indeed, green technology required equipment manufacturers to deliver increasingly fuel-efficient engines and designs that considered human ergonomics for greater worker safety.

Even in the 2040–2060 time frame, construction activities are still somewhat labor intensive. Many workers report musculoskeletal disorders from job activities such as lifting, making repetitive motions, working in confined spaces, carrying heavy loads, and using tools and equipment that vibrate. While these injuries have always been common in these dangerous occupations, the public and hence the government are less tolerant of work-related injuries that can be prevented by ergonomic measures. The increasing cost of health care also makes prevention a better long-term investment. Ergonomics typically involve changing tools, equipment, materials, and work methods. Most construction equipment is designed with flexibility to accommodate the individual operator's physical dimensions and strength. Sophisticated auditory and visual systems increase the safety of machines and workers. Nonvibrating tools replace vibrating tools, and many nondestructive tools are used to increase the quality of the work and also reduce unnecessary repairs.

Beginning in 2011, the Environmental Protection Agency Tier 4 emissions requirement called for a more aggressive 50–90 percent reduction in particulate matter emissions and up to 90 percent reduction in emissions of oxides of nitrogen depending on the kilowatt rating of the engine/generator set. Looking ahead to heavy-equipment innovation in the future, the industry expected innovation in green technology, an increase in power and performance of construction equipment, increases in versatility and value, and reduced operational cost by increased accuracy of GPS guidance and remote monitoring of machine operation.

Up to the early 2000s, the primary focus of visualization techniques had been on constructing buildings rather than highways. Yet, beginning in the late 2000s, a number of investigations looked into the benefits of four-dimensional (4D) computer-aided design (CAD) for highway construction as well. As a result, conventional visualization methods, such as illustrations, photo simulation, photorealistic three-dimensional (3D) CAD, multimedia animations, and GIS dominated highway projects in the 2040–2060 time frame.

Technologies such as GPS, GIS, and RFID that give early warning signs of trouble have been implemented in siting materials, aiding equipment operations, and monitoring real-time safety management. These technologies eliminate some human interactions and minimize others, thereby reducing human errors and construction-related accidents.

Technology also requires a more sophisticated construction workforce. Universities or colleges that offer construction programs have become more integrated with manufacturers and vendors to prepare the industry for the next generation of workers.

Until 2010, the application of automation and robotic technology in construction had been limited to processing raw materials and producing building parts and modules. Using autonomous humanoids or service robots in the unstructured and nonstandardized environments of the construction site was difficult. Despite these limitations, beginning in the early 2010s, several projects applied robotic technologies to highway construction and maintenance. For example, remotely driven dump trucks were used as a barrier during slow-moving maintenance operations. Other technologies such as automated paving machines, robotic paint-removal systems, laser-guided lane stripe painting machines, industrial and mobile robots for roadway crack sealing, and tele-operated aerial systems for bridge inspection were used in several projects. There were also several cases of automated placement of highway safety devices and application of sensor-based guidance of road pavers, control of excavators, tunnel boring, and infrastructure inspection.

In summary, in the 2040–2060 time frame, most of what was predicted has occurred and has continued to develop to meet the future demand and market.

9.3 First Alternative Scenario - Back to the Future

In the Back to the Future scenario, the economy returned to health, and transportation had the technology and resources to grow again. Potential implications of this scenario for transportation construction projects are as follows:

- Advancements in IT have provided opportunities for using ubiquitous sensor networks, voice recognition, natural language processing, huge databases, and apparently intelligent responses and actions to most queries or commands. These technologies allow for totally autonomous construction equipment, which can be programmed in advance requiring no real-time human interaction.
- In terms of project delivery, visualization and an immersive environment during design lead to paperless construction execution (no hard copy plans and specifications). Agency and private organizations work together, beginning with project scoping and continuing throughout the design and construction process (integrated project teams).
- Negotiated design and construction contracts have a high level of incentives.
- Advanced IT also means superior working conditions for construction workers and equipment operators.
- Development of sustainable materials allows for new and innovative road systems such as glass roads. Glass roads allow harvesting energy, melting snow, and recharging electrical vehicles.

In the 2040–2060 time frame, rapid development in computing, sensing, and control makes highway construction activities faster and safer. Industrial robots perform well-defined repetitive tasks in carefully controlled environments, such as during the prefabrication process. In the construction site, multiple mobile robots are capable of operating in dynamic environments without interfering with each other. Robots have the intelligence to know when a part made of smart materials is being placed correctly.

In this future, advanced visualization techniques play an important role for highway project development, planning, engineering, and public communications. Data from GIS databases are used to build a digital site model representing the terrain contours and existing highway features in the proposed project area. Parametric 3D solids are used to model the existing structures, the temporary structures during construction, and the finished structures upon completion. Highway elements, including railings, barriers, medians, curbs, common traffic control structures, and the like, are added to the model. Each element has a unique identification number that is stored in a separate database. Once the 3D graphical framework is defined, 4D CAD-based animations (3D CAD plus time) are used to link geometry with the construction schedule and traffic planning. 4D animations are used for showing changing traffic control measures to drivers during the construction process. In this system, the information is displayed as a photorealistic animation along the drivers' path using their vehicle-based heads-up displays. The animation shows changing traffic conditions and construction activity along the route, alerting drivers to the real-time conditions and helping them anticipate changes in traffic patterns.

Robotic total stations commonly track construction equipment and transmit that data to the equipment control station using a wireless network. Thus, equipment operation is immediate, using real-time data.

Drones such as small remote-controlled helicopters, shown in Figure D.1, capture project information and identify issues that need to be resolved to ensure smooth project completion. These aerial vehicles are equipped with high-resolution still cameras (with remote zoom, shutter control, and tilt), high-definition video, low-light black-and-white video, and infrared cameras. With a live video feed to the operator or other observers, project engineers obtain the information they need to make accurate assessments using the live video feed. The small profile of these devices increases maneuverability and helps building in confined spaces. Additionally, the low noise level reduces the disturbance from construction activities to communities.

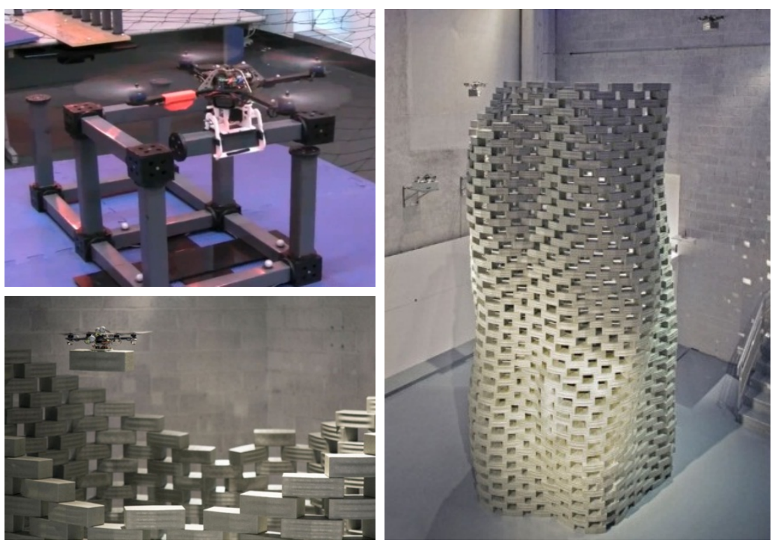

Figure D.1. Groups of miniature, autonomous drones have been used in the laboratory settings for performing light construction activities (Sources: http://blogs.smithsonianmag.com/design/2013/02/the-drones-of-the-future-may-build-skyscrapers/ and http://www.constructionweekonline.com/article-11137-in-video-flying-robots-build-future-construction/#.UTFX9cWByLA).

Sophisticated use of drones for military use was not uncommon even in the 2010s. As early as 2014, 30 percent of Air Force pilots flew unmanned planes. Pilots sat in a command post remotely flying the drones. This required a lot of re-engineering from the Air Force training program. And, as much as the military tried to make the operation flawless, human error posed fatal problems for mission-critical events: the human eye had trouble adjusting to a screen with a narrow field of vision, and human reactions had trouble adjusting to the short delay of transmission of information to the screen. This was less of a problem for the construction industry. Most construction activities did not deal with moving targets. Rather, most construction tasks required activities that were stationary and could tolerate the few-second delay in relaying information. Using drones was particularly effective for maintenance activities such as pavement crack detection. Nevertheless, construction operators had to be fully trained to operate the drones to avoid costly mistakes. Common mistakes included accidently knocking off a part of a structure, misaligning structures, forgetting to calibrate the equipment, and programming the wrong task.

Tele-operation construction techniques, investigated by the National Aeronautics and Space Administration (NASA), were applied to highway construction. Figure D.2 shows an example of such techniques. In 2012, NASA improved remote and autonomous operation as a part of its Vision for Space Exploration. Autonomous operations were initially developed for Mars spacecraft because of the high latency for messages to and from Mars. In autonomous operations, engineers program the desired work and offload it onto the machine, and then the machine carries out the work without anyone interfacing with the machine, either remotely or directly. The machine reads the program at the site and positions itself—all the time avoiding rocks or other objects that might be in the way. The enhanced accuracy and precision of GPS devices made it possible to make sure autonomous robots stayed on the preplanned path programmed into their onboard computers. With autonomous robots, part of highway construction operations such as excavation and paving could be safely conducted in hazardous environments.

Figure D.2. NASA and Caterpillar collaborated to augment existing earth-moving equipment with sensors and onboard processors to provide time-delayed tele-operational control (Source: http://www.universetoday.com/12234/heavy-construction-on-the-moon).

Highway construction also takes advantage of advancements in IT, such as mixed reality (MR) and augmented reality (AR). MR-based human-machine interfaces provide an immersive and compelling way to view the world, and AR increases worker safety. AR allows the workforce to work in a real-world environment while visually receiving additional computer-generated or modeled information to support and make decisions while performing tasks. Field superintendents use AR applications to verify the design and identify, process, and resolve its discrepancies with reality before carrying out the construction activity. For example, Figure D.3 illustrates utility contactors using georeferenced visualization of subsurface utilities for determining the location of underground utilities before excavation.

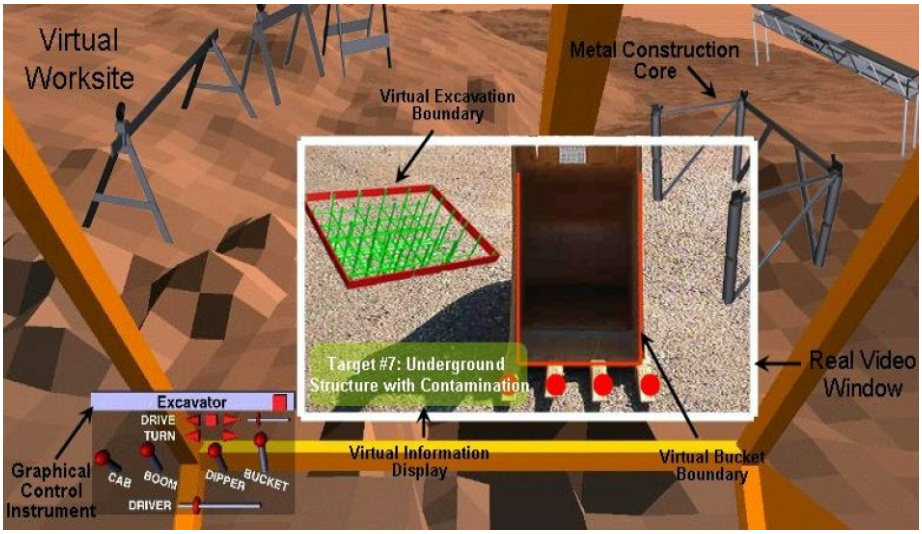

Figure D.3. A sample display screen for tele-operated excavation using mixed AR and AV techniques (Source: Wang, X., and Dunston, P. [2006]).

In addition to improving the safety and efficiency of construction activities, use of advance IT platforms also improves integration of project teams and wider adoption of team work and partnering. Advances in analysis and visualization techniques improve integration of project processes by intelligent integration of any digital project information using 3D computer modeling, interactive scheduling, project controls, analytical simulation, spatial databases, real-time visualization, and virtual reality.

In addition to advance technologies, state agencies adopt integrated project delivery approaches to give all parties a vote in the final contract terms, share decision making, pool contingencies, and provide incentives for team performance. Integrated project delivery is supported with the use of relational contracts, in which one agreement is signed by the owner, engineer, and contractor.

Use of sustainable materials changes how the United States builds roads. In early 2010, Solar Roadways proposed a new and innovative way to reduce dependency on fossil fuels by developing and testing solar road panels. As Figure D.4 shows, the glass pavement is embedded with solar cells that generate power from the sun and store it in batteries that can be used at night. Solar roadways also offer embedded light-emitting diodes (LEDs) to illuminate the road and display information on current traffic conditions. High-strength glass allows tires to grip and water to run off as well. Although this approach did not replace all of the existing roadway systems, some segments of the country implement and benefit from the use of solar roads.

In summary, in the 2040–2060 time frame, advancements in technology and materials allow complete automation of construction and innovative road systems.

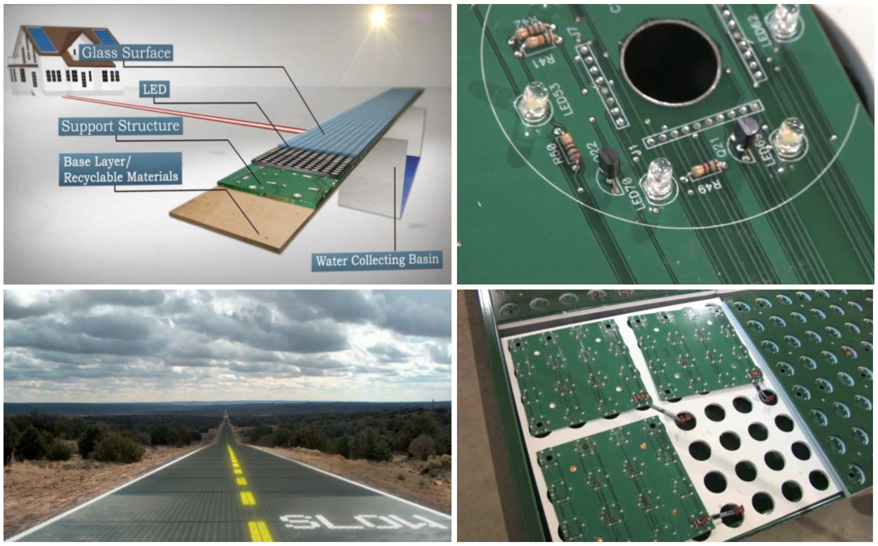

Figure D.4. Developing and testing solar road panels can help reduce dependency on fossil fuels (Source: http://solarroadways.com/intro.shtml).

9.4 Second Alternative Scenario—Scenario 4: Many Ways to Go

In the Many Ways to Go scenario, the government invests in new transport and information technology that includes significant shares of many different transportation modes. Potential implications of this scenario for transportation construction projects are as follows:

- Construction of new transportation systems brings various challenges (staging multiple systems and the integration of systems) and leads to the development of modular and prefabrication techniques.
- There is a substantial shift to the private sector for project scoping, design, and construction with much less agency involvement (e.g., performance-based contracting). Different types of skill sets emerge and are furnished by the private sector.
- As construction execution and quality control become complex, there is a demand for skilled construction managers to perform the project in a safe and timely manner.
- Existing highways that are obsolete need to be disposed of or reconfigured for alternative use in a sustainable manner.
- Construction efforts increase for soil treatment and revegetation, development of stormwater runoff systems, and paving of bike paths and walkways.
- Maintenance activities increase in landscape preservation.
- Deconstruction techniques advance, and there are innovations in recycling of construction materials. As a result, new infrastructure is designed with disassembly in mind.

In the 2040–2060 time frame, the construction workforce becomes more sophisticated to support development and construction of new and innovative transportation systems. Moreover, development of new and advanced transportation systems and IT leads to convenience in traveling. Funding comes from a variety of sources including private investment, taxes, and user fees.

Integration of multiple systems and the staging of construction lead to innovation in development of modular and prefabrication techniques. In fact, in 2009, according to the National Institute of Standards and Technology and National Research Council, there were five breakthroughs to improve the efficiency and productivity of the construction industry; modularization and prefabrication were one of these breakthroughs. Modularization and prefabrication lead to lower project costs, shorter schedules, and enhanced quality. In the 2040–2060 time frame, modularization also has a positive impact on roadwork in congested areas by facilitating prefabrication. To decrease congestion and traffic delays caused by roadway renewal and maintenance, new approaches for performing activities are developed to make the construction process safer and more efficient. Also, to reduce the need for roadway closures, roadwork in high-density urban areas requires performing roadwork during off-peak hours. To accomplish this objective, modular systems receive attention from STAs as an alternative construction technique over traditional cast-in-place construction. Figure D.5 illustrates the application of prefabrication techniques in urban construction projects.

Figure D.5. Precast modular concrete panels formed at an offsite location and installed during off-peak travel times have been used in several transportation projects in high-density areas to reduce traffic congestion and speed project completion (Source: http://www.fhwa.dot.gov/hfl/innovations/precast.cfm).

By 2010, several projects in high-density urban areas had used precast modular concrete panels formed at an offsite location and installed during off-peak travel times. Installing precast panels with built-in scales for weigh-in-motion sites is another area in which precast panels offer advantages over cast-in-place methods. In addition to making the construction process safer and more efficient, precast modular concrete panels provide additional advantages over traditional construction methods, including higher quality and greater durability. Precast concrete panels are subject to higher quality control standards during fabrication. Accordingly, roadways built using modular precast panels last longer before needing replacement and costly repairs due to fabrication in a controlled environment. In addition, with construction of large bridge superstructures, advances in methods for system moves include use of lateral slide and self-propelled modular transporters. Other techniques such as incremental launching methods become more popular. Incremental launching methods allow preassembling bridge elements and systems, and lifting and/or pushing longitudinally into final position. According to an American Association of State Highway and Transportation Officials study, these techniques require significant expertise and specialized equipment. Since the building of the whole transportation system requires techniques such as modularization, prefabrication, and placement of large preassembled structures, the implication for construction in the 2040–2060 time frame is that using this technique requires a significant amount of structural and construction monitoring during the assembly and construction process. Construction managers with advanced knowledge in these areas are in high demand for quality control and good project execution. Increased use of virtual teams and visualization technology during project scoping and design leads to increased innovation of these processes.

As use of technology in construction projects increases, state agencies outsource many of their in-house activities, including maintenance operations. To guarantee the quality of such services, agencies use new approaches to pay service providers and contractors based on the results achieved, not on the methods for performing the work. This approach, known as performance-based contracting, provides disincentives, incentives, or both to the contractor to achieve performance standards or targets for measurable outcomes and sometimes outputs. A variety of methods for undertaking performance-based contracting has been developed, such as total asset management and performance-specified maintenance contracts. Disincentives or incentives used in these projects include liquidated damages for failing to satisfy a contract provision, an award fee for satisfying qualitative criteria, and a contract extension if the contractor performs well.

Because many other transportation options are available for the general public and for movement of goods, STAs close some of the obsolete road corridors and repurpose them for other uses. In essence, the surplus vacant lands provide new opportunities. These lands are sometimes sold off for a profit, co-developed with the private sector, repurposed as green belts, or repurposed for growing food and even for generating alternative energy. Since sustainability is an issue, STAs and the government can use the surplus real estate to develop green infrastructures such as areas to manage (hold and filter) stormwater runoff and recover the damaged ecosystem. Construction activities related to repurposing include soil treatment and revegetation, development of stormwater runoff systems, and paving of bike paths and walkways. More landscape maintenance activities grow out of these transformations.

Removal and reuse of construction materials become important as more reconfiguration activities grow and new transportation systems are integrated into the existing infrastructure. Using recycled highway materials in pavement construction becomes a common practice to preserve the natural environment, reduce waste, and provide a cost-effective material for reconfiguration activities. Waste and byproduct materials are used in several construction applications including asphalt concrete, granular base, embankment or fill, stabilized base, and flowable fill. State and research agencies develop a mix design and analysis procedure for high reclaimed asphalt pavement content that allows using a higher percentage of reclaimed asphalt and provides satisfactory long-term performance. As in the building industry, the new systems are designed with disassembly in mind. More materials are recycled and reused in multiple sites rather than consuming raw materials. Demolishing existing roadways also includes careful removal of materials and resorting to transporting the materials to appropriate facilities.

In summary, in the 2040–2060 time frame, the country develops a new, innovative, and sustainable transportation system that provides many alternative ways that people can travel. In the process, obsolete and cost-prohibitive transportation infrastructure is repurposed with sustainability in mind. Construction techniques to support complex systems are developed, and advanced construction management skills are highly desired to support building multimodal transportation systems.

9.5 Third Alternative Scenario - Meltdown

In the Meltdown scenario, abrupt climate change shifts priorities from growing the economy to struggling with nature. Potential implications of the Meltdown scenario for transportation construction projects are as follows:

- Rapid climate change requires a strict policy on reducing greenhouse gas (GHG) emissions.
- Climate change impacts current design standards and approaches to emergency preparedness. Maintenance activities increase due to rapid climate change.
- Transportation shifts toward metropolitan transportation hubs.
- The construction industry develops technologies to support modularization, efficient construction, and green construction to meet aggressive GHG policy requirements.
- Construction methodology improves to support city-center-oriented transportation hubs.
- Highway contractors reduce emissions by cutting fuel use by improving efficiency, reducing idling time, performing better equipment maintenance, and using alternative fuels in the field.
- Green construction in transportation becomes the norm, and recycling of construction and demolition debris leads to further reducing GHG emissions.
- Agencies take on more project development and delivery with less outsourcing to the private sector.
- The government starts supporting labor-intensive public works programs as an economic policy tool to create employment and mitigate the economic downturn resulting from the GHG policies.

In the 2040–2060 time frame, abrupt climate change and rising sea level bring faster deterioration of the existing highway infrastructure. The network requires more maintenance in more efficient ways without further affecting the environment. The government sets out a strict GHG limit in an effort to reduce GHG emissions. Contractors and STAs therefore have to use more fuel-efficient heavy equipment and fleets. It also means that contractors have to reduce idling time, right-size the equipment, and institute better equipment maintenance practices.

Many elements of bridges and structures are built and prefabricated off-site because extreme weather conditions, such as high winds, extreme heat, and heavy rains, directly affect worker productivity and safety. Use of modularization and prefabrication help improve efficiency by saving time and resources and in turn contributing to a greener process.

In the 2040–2060 time frame, policy makers adopt approaches for improving emergency planning and preparedness in an attempt to minimize the possible effects of disruptions caused by major incidents. Many organizations invest in developing and using advanced damage assessment models for assessing the resilience of existing structures and identifying required improvements. In addition to preventive approaches, policy makers also focus on post-disaster rehabilitation and recovery. The high likelihood of natural disasters reveals the critical need for a quick response and the ability to get contractors, materials, and equipment to impacted areas in a timely manner. Modularization and prefabrication significantly improve the efficiency of construction activities related to rehabilitation recovery, such as repairing bridges, clearing debris, and restoring utilities, water, and communication services. To make rapid response possible in emergency situations, federal and local agencies create new contracting regulations that provide flexibility in emergency situations. As a part of their emergency response system, construction companies develop new systems for quick communication between project personnel during emergency situations. Reliable communication equipment and emergency response procedures and training for personnel become a standard safety practice in construction projects.

Renewal and maintenance of roadways in the limited space available in populated areas lead to the development of a new generation of equipment and machinery that are smaller, more maneuverable, and easier to transport. Prefabrication technology increases the demand for versatile, transportable cranes capable of handling concrete panels. New construction machinery is also capable of assessing quality during construction. Instant quality assessment makes the real-time correction of quality issues possible, providing more durable transportation facilities and lengthening the rehabilitation cycle. Additionally, the use of positioning systems in construction machinery reduces the time needed to prepare for construction operations like surveying.

Green construction in transportation becomes the norm. In the early 2010s, many organizations started to develop self-evaluation tools to help state and local agencies design, build, and maintain sustainable highways. For the Federal Highway Administration (FHWA), a sustainable approach to highways meant “access, movement of people and goods, and provision of transportation choices, such as safe and comfortable routes for walking, bicycling, and transit” (http://www.sustainablehighways.dot.gov/overview.aspx). Organizations such as FHWA introduced INVEST, Greenroads developed the Greenroads Rating System, and the Institute of Sustainable Infrastructure in collaboration with Harvard University created Envision. These tools were voluntary and provided a framework for assessing the economic, environmental, and social benefits throughout a highway’s entire life cycle. In 2040–2060, these rating tools are combined to form national standards and are enforced by the government. The resulting total quality management plan includes safety and training of workers; energy-efficient fleets, vehicles, and equipment; Energy Star–rated office equipment; a stormwater management plan; and a recycling plan.

Preventing abrupt climate change makes environmental preservation the most important priority rather than growing the economy. To maintain the required physical infrastructure and preserve jobs, the federal government uses labor-intensive methods as an economic policy; labor is already the dominant resource for carrying out work. States direct funding sources to projects proposed by local communities and make policies to encourage execution of projects by the local population. These local labor-intensive projects serve both as a fiscal measure to expand public spending and as a short-term measure to alleviate unemployment. In comparison to conventional capital-intensive methods, labor-intensive maintenance results in the generation of a significant increase in employment opportunities per unit of expenditure. Consequently, labor-intensive maintenance projects help the government prevent an increase in the unemployment rate. In addition to lowering project costs and creating jobs, the involvement of the local community ensures that people view the projects as their own and so pay more attention to maintaining the infrastructures.

9.6 Identifying Potential for New Materials, Tools, Technology, and Approaches

After understanding the conditions and impacts, the next step was to identify the potential for new materials, tools, technology, and approaches for each of the scenarios. Check marks in D.1 show how STAs may respond to each scenario by adopting and/or developing new materials, tools, technologies, and approaches. For example, environmental concerns associated with transportation construction projects make sustainability of construction approaches a key priority for addressing challenges related to abrupt climate change in the Meltdown scenario. On the other hand, because in the Many Ways to Go scenario there is little need for new construction, outsourcing heavy-duty and specialized equipment is not a key priority. Note that there is a key priority for developing light equipment in this scenario because it is needed for maintaining the existing network and infrastructure.

Visual assessment of Table D.1 shows a high concentration of tick marks under sustainability, innovative financing, and workforce training. Accordingly, regardless of how the future turns out, sustainability, innovative financing, and workforce training have critical priority for STAs. Detailed examples for each column are provided as notes in the matrix of Table D.1.

Table D.1. Implications of the scenarios for STAs.

Multi-driver Scenarios	Materials	Tools		Technologies		Approaches			
	Innovative Materials	Light and Medium-Duty Equipment	Models and Simulations	Wireless Communication	Visualization	Sustainability	Innovative Financing	Workforce Training	Outsourcing Heavy-Duty and Specialized Equipment
Baseline (Managed Decline)						✓	✓		
Back to the Future	✓		✓		✓	✓		✓	
Many Ways to Go	✓	✓		✓	✓	✓	✓	✓	
Meltdown			✓			✓	✓	✓	✓

Notes:

- *Innovative materials* include using solar road panels and recycle content materials for improving the durability of pavement and reducing its weight.
- *Light and medium-duty equipment* are normally used in maintenance operations and include chainsaws, grass trimmers, lawnmowers, plows, salt and sand spreaders, light pickup trucks, light trucks, heavy pickups, medium dump trucks, nondestructive testing methods, small robots, pavement marking equipment, quadrotors,

integrated quality control capabilities, and automated equipment (see Appendix D.3 for equipment classification).

- *Models and simulations* include computer-integrated platforms for optimization, integrated project delivery, lean construction, asset management, and the like.
- *Wireless communication* includes using sensors, RFID, and GPS tools.
- *Visualization* includes using 3D, 4D, five-dimensional, and building information modeling.
- *Sustainability* covers topics such as using low-algae materials, recycled content materials, glass roads, solar panels, silent equipment, and low-impact construction methods including prefabrication.
- *Innovative financing* refers to alternative funding mechanisms, community buy-in, and use of the local workforce.
- *Workforce training* refers to the next generation of the workforce trained for performing sophisticated tasks involving new systems, equipment, and materials.
- *Outsourcing heavy-duty and specialized equipment* is normally used in new construction or deconstruction operations and includes heavy trucks, tractors, loaders, graders, backhoes, oil spreaders, paving equipment, cranes, deconstruction equipment, integrated quality control capabilities, and automated equipment (see Appendix D.3 for equipment classification). State agencies do not own and operate this type of equipment, and services involving usage of such equipment are performed by contractors. Scenarios in which intensive use of heavy equipment is needed require STAs to develop innovative contractual agreements with contractors of transportation projects to guarantee the efficient used of heavy duty and specialized equipment.

9.7 Implications for State Transportation Agencies

In general, one of the main concerns for the U.S. transportation industry is that the highway system is aging, and state agencies need to maintain, preserve, or rehabilitate existing highway infrastructure. In the meantime, concerns for adverse societal and environmental impacts of transportation construction projects are one of the most critical priorities that influence the future of transportation-related construction. This influence covers a wide range of topics including tools (e.g., sensor and wireless technology for real-time transfer of construction activities to the surrounding traffic), equipment (e.g., silent and low-emitting equipment), materials (e.g., recycled content pavement materials and glass panels as pavement to harness solar energy), and construction methods (e.g., modularization and prefabrication).

Sustainability

Addressing societal and environmental impacts will stir the development and use of innovative materials, tools, equipment, materials, and methods. Particularly, state transportation agencies should work with legislators to facilitate offering incentives for encouraging the construction of sustainably built highways and infrastructures. Incentive programs may include rebates on permits for contractors that use recycled content pavement materials and materials with industrial byproducts as substitutions for raw materials during construction. Incentive programs should also encourage fuel-efficient, low-emitting equipment. Moreover, state agencies need to gain capabilities for rigorous application of visualization techniques and simulation methods. Using these techniques will be necessary for improving construction productivity by lowering downtime and detecting errors early, as well as improving the efficiency of maintenance processes. Consequently, the level of knowledge, skill, and capability required to operate high-tech tools and equipment and perform sophisticated tasks involving new materials and methods will necessitate workforce training.

Innovative Financing

To address these issues, STAs need to find sustainable funding mechanisms that will allow adequate investment. Public-private partnership is one such approach that promises great potential in transportation projects. Early involvement of the private sector brings the necessary capital, creativity, and efficiency to address complex transportation problems. State agencies need to improve capacity to support considerations of PPP projects and clarify the degree to which the private sector assumes responsibility, including financial risk. Additionally, requirements of PPP projects for capital projects versus operation or expansion of existing assets need to be clarified. Involvement of the private sector equipped with cutting-edge knowledge and technology, including automation and robotic techniques combined with GPS guidance and remote monitoring of equipment operation, will be necessary for maximum benefit.

Workforce Training

Training the construction workforce, and securing sustainable funding for long-term training programs, is an emerging trend in the future of transportation construction projects across all six alternative scenarios. Moreover, the intense use of high-tech equipment and tools will require attention to health and safety of the state transportation agency’s workforce, including ergonomic measures of the work environment. Proper planning among the state transportation agencies, industry, and education may reduce the potential skill shortages in the 2040–2060 times frame. For example, state transportation agencies should collaborate closely with academia to produce graduates with relevant skills prior to working on the job. Programs such as one-on-one mentoring can lead to smoother transition from educational institution to long-term employment positions. In addition, state transportation agencies should be disciplined about workforce planning and continuously research and develop training programs to recruit, retain, and strengthen the current talents within the organization.

9.8 Appendix D.1—Construction and Maintenance Activities

The following are some construction and maintenance activity products:

- Earthwork including clearing and grubbing, removal of structures and obstructions, excavation and embankment, subgrade preparation, erosion and sediment control, and salvaging and placing of topsoil.
- Base courses including aggregate base course, subgrade modification, and reconditioned existing base and surface.
- Flexible pavement (asphalt pavement) including tack coat, prime coat, chip seal, microsurfacing, surface recycling, and fabric reinforcement.
- Rigid pavement (Portland cement concrete pavement) including jacking, subsealing and stabilizing, resealing joints, sealing cracks, patching, grooving, grinding, milling, recycling, cracking, and seating.
- Miscellaneous construction including concrete barriers, culverts and storm drains, underdrains, guardrails, fences, sidewalks, curbs and gutters, paved ditches and paved flumes, turf establishment, and provision of trees, shrubs, vines, and ground covers.
- Systems operations including traffic incident management, safety service patrols, surveillance and detection, traveler information and dynamic message signs, road weather information systems, work zone management systems, ramp metering systems, traffic signal optimization/retiming, traffic adaptive signal control, electronic toll systems, electronic border crossing systems, commercial vehicle information systems, bus rapid transit, transit signal priority, parking management systems, transit automated vehicle locator/computer-aided dispatch, and high-occupancy toll facilities.

9.9 Appendix D.2—Conditions and Impacts in the Baseline Scenario and Six Alternative Scenarios

Table D.2.1 summarizes the conditions in the six alternative scenarios. The reasoning was to understand the availability and level of funding to determine what activities or efforts STAs would focus on to provide the necessary level of service to the public. This condition determined the type of construction technologies and techniques that would be developed to support the construction activities in a safe and efficient way. The specific impacts that each condition would generate on individual scenarios is summarized in Table D.2.2.

For example, in the Back to the Future scenario, the economy returns to health, and transportation has the technology and resources to grow again. Accordingly, as Table D.2.1 shows, technology, and more specifically information technology capabilities, continue to grow and are adopted in almost all facets of construction and maintenance activities in transportation projects. As Table D.2.2 shows, adaptation of information technology increases the precision and reliability of operations performed by equipment and improves worker safety by reducing the likelihood of construction accidents. Concurrently, equipment operators and field engineers are equipped with a new set of knowledge, skills, and abilities to operate the equipment in a safe and efficient way.

Table D.2.1. Summary of conditions in the baseline scenario and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Higher Resource Scenarios		Lower Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Funding (and Focus)	Innovative financing available from PPP and congestion pricing. Construction focuses on existing infrastructure due to slow growth in technology and limited resources.	Construction focuses on capital projects (new construction) due to availability of technology and resources to grow.	Significant rise in tolling and network pricing and variable pricing, plus more traditional sources such as higher fuel taxes, provide necessary funding for government to expand the network and maintain existing infrastructure.	Decrease in fuel tax leads to lack of funding for system expansion. Construction focuses on maintenance of existing infrastructure.	General funding shifts toward new and innovative transportation systems. Construction focuses on both new transportation system and maintenance and revitalization of existing assets.	Funding commitments for urban-based transportation with focus on street rather than highway because of denser settlement pattern. Construction focuses on repurposing existing assets and transportation systems for urban areas with high-density.	To maintain emergency preparedness, need for maintenance dollars increases. Construction focuses on maintenance activities and adaptation to significantly different environmental conditions due to rapid climate change and urbanization.
Construction Technology and Techniques	Moderate adoption of information technology in construction.	Moderate adoption of information technology imported from elsewhere in all aspects of construction, with little need for true innovation.	Rigorous application of technology for minimizing disturbance of construction projects on current traffic with emphasis on safety.	Low to moderate application of new technology in construction and maintenance.	Rigorous application of information technology in all aspects of construction, in response to challenges associated with staging multiple systems and integration of systems.	Moderate application of new technology in construction equipment for building in urban areas.	Moderate application of information technology in construction equipment, as well as new technologies for increased energy and materials efficiency.
Environmental Concerns	Overall concern for sustainability.	Modest concern for sustainable materials.	Modest concern for context-sensitive design and construction.	Reduced concern for sustainability because of low demand for new construction.	Concern for disposal of or reconfiguration of existing highways that are obsolete.	Concern for construction methods with low impact on environment and public well-being.	Sustainability is the top priority. Concern for construction methods with low impact on environment and public well-being.

Table D.2.2. Summary of the impacts in the baseline and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Higher Resource Scenarios		Lower Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Funding (and Focus)	Maintenance and renewal.	Capital projects.	Expansion and maintenance.	Maintenance and small demand for renewal.	Repurposing right of way in order to construct multimodal systems.	New construction, maintenance, and renewal in urban areas.	Maintenance, renewal, and adaptation.
Construction Technology and Techniques	Semi-autonomous heavy construction equipment. Sophisticated construction workforce.	Sophisticated but safer work environment. Totally autonomous construction equipment.	Real-time transfer of construction project information to reroute or direct traffic flow to safe alternative routes.	Semi-autonomous maintenance equipment. Versatile construction equipment with higher maneuver-ability.	Construction execution and quality control become complex, demanding skilled workers to perform the project in safe and timely manner. Techniques and technologies to support modularization and deconstruction techniques.	Techniques and technologies to support modularization and pre-fabrication. Versatile construction equipment with higher maneuverability.	To create employment and prevent economic downturn, the government starts supporting labor-intensive public work programs as an economic policy tool. Versatile construction equipment with higher maneuverability.
Environmental Concerns	Heavy construction equipment is fuel efficient and designed for human ergonomics.	Innovative road systems such as glass roads allow harvesting energy, snow melting, and recharged electrical vehicles.	Heavy construction equipment is fuel efficient and designed for human ergonomics (similar to baseline).	Maintenance equipment is fuel efficient and designed for human ergonomics.	Innovation in recycling of construction materials. New infrastructures designed with disassembly in consideration.	Construction equipment is fuel efficient, emits less GHG, and is quiet and designed for human ergonomics.	Climate change impacts current design standards and reduces worker productivity, efficient equipment, and green construction.

9.10 Appendix D.3—Equipment Classification

State transportation agencies operate a wide variety of vehicles and equipment, ranging from light-, medium-, and heavy-duty vehicles to specialized equipment, small-engine equipment, and seasonal vehicle attachments. As proposed by the National Association of Fleet Administrators (NAFA) in the *Fleet Maintenance Operations Guide*, gross vehicle weight and physical characteristics of the fleet and equipment are typically considered in the development of equipment classes. According to NAFA, the gross-vehicle-weight-based classification system provides common attributes to compare vehicles from widely different fleets and fleet applications. Also, operating and maintenance costs have a correlation to gross vehicle weight, vehicle type, and function. Table D.3.1 shows equipment classes and examples.

Table D.3.1. Equipment classes and examples.

Equipment Class	Examples
A. Small engine	Chainsaws, grass trimmers, lawnmowers
B. Seasonal attachments	Plows, salt and sand spreaders
C. Light duty	Sedans, light pickup trucks, light trucks
D. Medium duty	Heavy pickups, medium dump trucks
E. Heavy duty	Heavy trucks
F. Specialized	Tractors, loaders, graders, backhoes, oil spreaders

Due to different designs and functions as well as considerations of the typical availability of service providers, tractors and construction equipment are in separate categories, with the purpose of differentiating them from the heavy-duty class.

9.11 Appendix D.4—Bibliography

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10.0 APPENDIX E - TRANSPORTATION STRUCTURES WHITE PAPER VISION

10.1 Description of Transportation Area: Transportation Structures

The discussion of *transportation structures* in this white paper focuses on the design and construction of new structures to both renew and expand the highway system, as well as the ongoing maintenance and preservation of existing structures. Transportation structures include but are not necessarily limited to:

- Bridges, viaducts, and culverts.
- Tunnels and their ancillary equipment.
- Earth-retaining structures.
- Structural supports for highway signs, luminaires, and traffic signals.

The research team used the baseline scenario and selected three alternative scenarios that represented the most variability and had the greatest implication for the transportation structures area from the baseline scenario. These scenarios were further developed into specific applications for the transportation structures transportation area. These alternative scenarios include:

- "Back to the Future."
- "Escape to the Centers."
- "Meltdown."

The research team also identified the potential for new materials, tools, technologies, and approaches for the baseline scenario and for each of the alternative scenarios.

10.2 Description of the Baseline Scenario: Managed Decline

In the baseline scenario, a future is projected based on the known and observed state of affairs in the early 21st century. Potential implications of this scenario for transportation structures are as follows:

- Challenges remain because of the huge backlog of deferred maintenance that stems back to the 1950s era of construction boom with the inception of the Eisenhower Interstate Highway System.
- While the construction of transportation structures in the 20th century was largely provided by public-sector finance, the early 21st century saw the emergence and popularization of public-private partnerships (PPPs). But tension remains between the two competing systems, with the latter struggling to gain ascendency.
- The old construction materials of the 20th century—structural steel and structural concrete—remain in vogue but are used in new ways, largely due to the higher strengths and working stresses.
- Due to work site pressure to minimize on-site construction times and occupation, efforts continue to modularize and prefabricate structural components. Hence, the workforce and its management become increasingly sophisticated.

In this business-as-usual scenario, due to state and federal government indebtedness and entitlement obligations, finance for new capital projects is increasingly scarce. This is in spite of unprecedented private-sector technological advances. Thus, state transportation agencies (STAs) have been forced to primarily manage and maintain the deterioration of their portfolio of infrastructure assets.

Constructed facilities continue to be maintained, in spite their age, far exceeding their initial 50- to 75-year design life. Creative methods have been developed to markedly extend the life of these 1950s and 1960s assets. For example:

- Steel girder bridges routinely have their reinforced concrete decks renewed on a planned preventative maintenance cycle of 20 to 25 years. In the process of this maintenance, some minor capital improvements are made, such as providing span-to-span continuity to remove deck joints. Retrofitting and upgrading the bearing seats and piers to provide improved collision and seismic resistance are also undertaken where appropriate.
- Aged steel truss bridges that possess many fatigue-prone connections are upgraded. As part of this exercise, methods are developed that augment the live-load-carrying capacity, which in turn also reduces the fatigue proneness.
- Prestressed concrete girder bridges are also upgraded where appropriate. Where necessary or appropriate, continuity is provided by using external post-tensioned prestressing.
- Tunnels are also upgraded. Many older tunnels have suffered partial lining failure with the continued spalling of ceramic tile linings. In an attempt to mitigate or avoid such deterioration problems, many tunnels have their original linings removed, an enhanced dewatering and drainage system installed, and new linings installed. The linings are either a modern modular lightweight interlocking system that can be undertaken with minimal off-peak tunnel closures, or rock-bolts and reinforced shotcrete systems.
- Culverts that require continued maintenance are replaced with simple oversized pipe barrels using traditional rapid cut-and-cover methods, which provide ease of maintenance. In this way, clogging with stream-flow debris is minimized. Where old culvert cover depths are insufficient to achieve replacement with larger barrel systems, renewals consist of short (<50 feet) single-span precast slab bridges.
- Retaining walls are merely maintained by customary patch-and-repair processes.

Online renewals of existing structural assets become increasingly rare due to the sophisticated maintenance techniques described above. The only motivation for a complete renewal is when a given structure is deemed functionally obsolete. Such obsolescence generally concerns the lack of safety associated with narrow bridges where it is often less costly to renew than to maintain and widen the existing bridge deck.

Highways are seldom expanded, largely due to the lack of capital to finance major projects. A major impediment is the extraordinarily high cost and protracted difficulty of the acquisition of new land. Thus, most expansion, particularly for the provision of new lanes, uses existing right of way. This often necessitates the construction of long stretches of viaducts, and even tunnels when aboveground alternatives are exhausted.

When rare new green-field projects are undertaken, it is generally under a PPP scheme with finance provided by the international capital markets. The owning public has huge expectations in terms of quality, greenness, and in-built safety features and longevity, each also adding significantly to the delivery cost. One major feature is the expectation of an extended life—well in excess of 100 years. Thus, highly durable materials are commonly specified. For example, high-strength stainless steel is the preferred construction material for both the rarely used steel girder bridges and the more common cost-effective concrete structures.

Ultra-high-performance concretes are commonly used, in part because of their overall lightness but more importantly because of their improved durability. Longer bridge spans are commonplace for two reasons. First, highway overpasses endeavor to remove piers to minimize the risk of collision. Second, longer spans are also used in river crossings to minimize environmental disruption to riverbeds, reduce scour potential, and minimize deep-foundation construction cost.

10.3 First Alternative Scenario - Back to the Future

The economy returns to health with lengthy boom periods of stability in this scenario. Thus, the transportation system has the finance available for expansion and renewal as well as sufficient budget to maintain existing assets. Potential implications of this scenario for transportation structures are as follows:

- The robotics industry is thriving in every sector of the economy; many formerly laborious tasks in construction and maintenance are performed with various arrays of robotic equipment that minimize human operations.
- Ubiquitous sensor networks are deployed on existing and new structures. This permits just-in-time maintenance and/or renewal operations to be performed more cost-effectively.
- High-tech energy-harvesting opportunities abound and where appropriate are realized for bridges and tunnel systems.
- State and federal governments devise new creative finance portfolios to defray (avoid) taxation for high-income earners (top 5 percent).
- Near metropolitan areas, highway capacity is governed by commuter demands, whereas long-distance connectors between the large metro centers, as well as many rural roads, are governed by freight.

In the 2040–2060 time frame, the national economy repositions itself due to a second wave of significant technological advancements. Capital for new projects in both the private and public sectors is not scarce due to new wealth generated by robotics-led manufacturing and service industries. While the government has been tempted to tax and spend this new wealth, it refrains from doing so based on the failed experiments during the latter half of the 20th century and the early 21st century. Instead of heavily taxing upper income earners, state and federal governments devise a simple but clever form of public-private ownership of major public infrastructure, which had formerly been owned and operated on a taxation-only basis. Instead of paying punitive taxes, high-income earners are encouraged to invest in stock ownership of major public assets; the less attractive alternative is to pay a very high marginal tax rate. The practice of owning a major bridge, for example, and renting it back to the public users is considered appropriate and socially responsible. And part of that ownership agreement necessitates a high level of quality maintenance—everyone is a winner.

New (and not so new) technologies are incorporated into these high-quality investment structures. For bridge sites in colder northern climates, for example, energy is harvested through heat exchangers associated with deep-pile foundations. The energy exchange is used to avoid icing in wintertime, and during the summer the deck is partially cooled to minimize differential thermal stresses to improve bridge-deck longevity. Surplus energy in shoulder seasons is converted and fed back into a local electric power grid where it is used in high-efficiency lighting systems and other traffic control systems and signage.

These major transportation assets are traded as hot commodities on the capital markets, but to ensure their value remains high with a good return to the investor, an excellent service condition and record are essential.

Thus, bridges and other structures are also continuously monitored with a new generation of smart sensors that can detect overload and material deterioration from wear and tear. In this way, early warnings can be assessed, and structural members and elements selectively maintained to minimize operational costs and also maximize the overall asset longevity.

It is due to this monitoring that the road transport lobby has successfully cajoled regulators to increase the axle loads on trucks by 25 percent to permit 10-ton axles. On the face of it, this increase is modest, but the consequences are not. The increase in axle load increases the wear and tear on pavements and bridge decks by a factor of 3, and the gross-weight increase on bridges, particularly steel structures, reduces their fatigue life by a factor of 2. So, while on the one hand designers in the early 21st century improved the design life of modern structures through better materials, these gains are offset by the increase in axle loads. Moreover, the older 20th century structures age more rapidly, requiring an accelerated maintenance and renewal program.

Under this scenario, the attitude is quite different than in the late 20th century. Structures receive minimal maintenance, largely due to the relatively high labor rates, and so when maintenance becomes a burden, structures are scheduled for replacement and renewal. Moreover, when a structure approaches its design life, it is scheduled for renewal.

The approach is used to shift the unknown maintenance cost burden from the state owner to one of the new ownership mechanisms in which maintenance is built into the own–operate–maintain–lease-back arrangements. In this way, maintenance is not only minimized due to the newness of the structure, but its future maintenance cost is clear and transparent and already budgeted for within the contractual arrangements.

Certain mega-structures, however, cannot be replaced due to their location, such as tunnel systems and earth-retaining structures. These assets continue to be maintained as they have been historically.

Because older structures tend to be renewed and replaced in the same (online renewal) or close-by location instead of being maintained beyond their design life, many structures are renewed on an annual basis. Moreover, while the budgets to undertake such recapitalization work did not permit such wholesale renewal at the dawn of the 21st century, the current attractive financing arrangements mean that new capital does indeed abound.

While the STAs continue to own and maintain the roadway, it is the ownership of specific structures worth less than $50 million that makes the investment attractive for small to medium-size investors.

And because there is a continuous program of major renewals continually underway, construction contractors develop a large variety of accelerated construction techniques for project delivery. For example, on a Friday afternoon, a commuter drives home from work on an old and decrepit bridge; he then returns to work on Monday morning, pleasantly surprised to see three new bridges in place, which occurred over a 60-hour closure. The first of the three new bridges was built alongside the existing structure on falsework piers, the old spans removed and the new bridges slid into place on new piers. The second bridge is a relatively short span and was moved into position on a giant transporter. The third bridge is an off-line renewal where a new bridge was built a short distance downstream; over the weekend, a curve easement was implemented that bypassed the old structure. The final result is three new bridges, from three different contractors, having three proud new owners—one a top 1 percent millionaire, the second an owner-operator corporation, and the third a STA pension fund. Figure E.1 and Figure E.2 illustrate how giant transporters may be used in accelerated construction techniques.

Figure E.1. Use of a giant transporter to move a bridge section into position on land.

Figure E.2. Use of a giant transporter to move a bridge section into position over water.

Under this scenario, highways are often expanded to provide increased capacity, while older less efficient systems are abandoned or repurposed. Thus, completely new highways are constructed, all under broadened PPP arrangements. Some highways are electronically tolled, while certain portions are deemed freeways with funding for use returned to the owner-operator by the state.

The private-sector ownership unleashes unprecedented creativity in both project delivery methods and structural type and form. Ownership, operations, and maintenance are for long sections of highway and include roads, bridges, and other control structures as part of a turn-key operation. Ownership consists of giant conglomerates such as “Buffy Bert,” a successor of Berkshire-Hathaway; “Google de-Road,” a high-tech company with long-established interests in modern transportation systems; the Teachers Insurance and Annuity Association - College Retirement Equities Fund (TIAA-CREF); and numerous other companies.

Assets use an expedient mix of older (early 21st century) and newer construction materials and methods, with some examples as follows:

- Bridges are mostly constructed with high-performance materials (concrete and stainless steel) using lightweight composite materials as stay-in-place forms where needed. However, most bridge structures are built from modular (precast/prefabricated) components. The new generation of concrete is more enduring through appropriate admixture dosages and a new generation of chopped fibers used to inhibit tensile cracking.
- Tunnels are cut-and-covered where possible, with the linings being completely prefabricated precast units. Where high soil overburden or nearby buildings necessitate tunnel boring, low-vibration boring methods are used, with the lining extruded directly into place, complete with drainage and ventilation systems. The methods include considerable robotics.

- Earth-retaining structures for cut slopes and embankment fills are chosen from a wealth of proprietary systems on a competitive basis.

In summary, premanufactured structural systems are the norm. Large firms develop such systems because they are incentivized by large payback through widespread uptake (market forces).

10.4 Second Alternative Scenario - Escape to the Centers

The Escape to the Centers scenario is characterized by continued suburbanization and urbanization of the population around several mega-centers in the nation.

In the new urbanization, the old suburbs of the 20th century densify due to choked highway connectors and thoroughfares. Consequently, the population coalesces around several mega-centers. The centers consist of a very high-density core plus several essentially self-contained dense satellite centers. While this arrangement means demand on lane miles is relatively modest for commuting purposes, what highways and connectors remain also have increased pressure placed on them from freight transportation. Thus, the deterioration of roads and bridges increases from the relative increase in heavy axle tonnage.

These centers include but are not limited to New York-New Jersey, Baltimore-Washington Metro, Atlanta Metro, Miami-Dade Metro, the Texas triangle (Houston, San Antonio, and Dallas-Fort Worth), Phoenix Metro, Greater Los Angeles (from San Diego to San Bernardino), the Bay Area (San Francisco, Sacramento, and San Jose), Seattle Metro, and Chicago Metro.

Long-distance travel between these population hubs remains a mix of traditional modes: highway, train, and airplane. Heavy freight is shared between road, rail, and sea. From this point of view, the Escape to the Centers and the Back to the Future scenarios are similar. Where the two are markedly different, however, is in the unprecedented demand for transportation services in these mega-metro centers. Congestion is rife on all major highways and arteries with the following effects:

- Maintenance of the existing highways and roadways is difficult, and on certain key connectors it is almost impossible to obtain daily maintenance windows.
- Renewals of existing facilities and capacity expansion remain difficult and costly.
- Land available for expansion is quite rare, especially in older coastal cities that were built out and landlocked by geography.
- Because the transportation system could not expand outward, the only alternative is to go either upward or underground.

The principal ramification for this scenario is a dire need for more elevated viaducts and tunnels. Naturally, the budget to deliver such capacity expansion is an order of magnitude greater that the normal at-grade highways. Thus, budgets of between \$0.25 and \$1 billion per mile of expansion become commonplace. Moreover, regulatory approval, including arduous environmental impact and planning approvals, delays most projects for about a decade or more.

On certain key highways within the mega-metro centers, the only way that maintenance operations can be achieved under this scenario is to schedule complete road closures on certain days of the week and often on weekends. During these closures, a convoy of maintenance vehicles progresses on a work face, undertaking the needed maintenance operations and inspections. Citizens become accustomed to this approach and re-order their lives accordingly. For example, the re-decking of bridges is often undertaken over a weekend closure.

It is often easier to apply partial renewals than to maintain decrepit aged structures. Old spans are removed, and new modern lightweight structures are wheeled in. Where possible, lane expansion is performed by widening bridge decks; the older structures that remain on the original portion of highway are then rapidly removed and replaced as well.

Constructing a new viaduct system is generally less expensive than an equivalent beneath-grade tunnel system. Accordingly, designers in concert with contractors develop a new generation of bridge structures that minimize the footprint of the piers.

Viaduct construction is conducted by self-guided traveling overhead gantry cranes that are sufficiently large to remain in place with normal traffic operating beneath. And to maximize progress and minimize disruption, the construction operations progress continually around the clock.

10.5 Third Alternative Scenario - Meltdown

In the Meltdown scenario, the fourth decade of the 21st century sees a series of recurring natural disasters throughout the United States. These disasters are both weather related and of a tectonic nature. In addition, the country is constantly exposed to random acts of terrorism, both cyber-terrorism and the explosion of improvised explosive devices (IEDs).

The weather-related disasters are spurred on by the ongoing effects of climate change. While on the one hand transportation agencies are able to cope with the gradual change that climate change brings, such as higher average temperatures and sea level rise, they are unable to anticipate where the next weather bomb might hit land. Constant weather-related disasters hit the eastern seaboard and Gulf Coast region in the form of hurricanes and winter storms. Often these combine into even larger events like Hurricane Sandy in 2012. Hurricanes also often combine with massive summer flooding in the Midwest, leading to combined floods and hurricanes in the coastal cities of the Gulf Coast. The central United States is also plagued with an increasing frequency of devastating tornados and severe winter blizzards.

Tectonic activity is heightened along the West Coast through to Alaska. Often these areas have to deal with the combined effects of earthquakes and near-shore tsunamis. Events are reminiscent of the 2011 Japan Tohuku M9.1 earthquake and tsunami disaster, but due to climate change, effects seem to be more frequent and violent.

The effects of these natural disasters, promoted by climate change and increased tectonic activity, on transportation structures lead to the following:

- Bridge structures are severely damaged in the directly affected regions. This requires a disproportionately high degree of resources from general maintenance budgets to be diverted to cleanup operations.

- Due to severely damaged structures, the capital budgets of the affected states are totally reallocated to the reconstruction program. Prices for materials and labor surge some 30 to 50 percent due to the need for rapid replacement of completely damaged assets.
- Due to these unprecedented disasters and the need for endless rebuilds, the federal government is unable to cope with the ongoing high demand for funds. Thus, the government has to severely ration out very small budgets to these states that were fortunate not to be directly hit by the ongoing swarm of disasters.
- In the regions affected by a specific disaster, severe damage also occurs to nontransportation structures, specifically severe damage and total loss of housing and commercial buildings. Consequently, the private sector that was mostly well insured can command the resources it needs, in terms of both labor and materials for major repairs and reconstruction. This leaves the public sector at a major disadvantage.

Furthermore, in the West Coast earthquakes, there are numerous incidents of serious and widespread liquefaction. Cities and counties thus have their sewerage systems destroyed, requiring complete rebuild of most city streets—again consuming labor-intensive construction resources.

The liquefaction also causes serious damage to the highway system; many road alignments are subjected to rock falls and landslides in cutting, slumped embankments, and major differential settlements requiring safe operating speeds are reduced below 50 mph. While these portions of damaged highways could be repaired and reconstructed more quickly than major bridges and other structural damage, the high cost of these damages strains already exhausted budgets.

In the Meltdown era, the failure of major structural assets causes several serious semi-permanent changes in travel behavior. For example, an M7.9 earthquake on the Hayward fault near Oakland causes a partial failure of both the Golden Gate Bridge and the main suspension span of the San Francisco Bay bridge crossing. Both bridges are permanently closed due to tilting of the towers, some fractured hangers, and excessive distortion of the stiffening girders. Furthermore, there is serious liquefaction in the seabed of the San Francisco Bay that causes a partial failure of the Bay Area Rapid Transit (BART) tunnels—the BART connection between San Francisco and Oakland is permanently closed pending a complete reconstruction of the affected region. Consequently, the Oakland and East Bay regions are completely severed from San Francisco; travel behavior between the two reverts to pre-1930s fashion—use of ferries. Furthermore, the reconstruction time for replacement also becomes a major problem. Exceedingly high standards are set by the community and various regulators, which leads to a 20-year replacement and reinstatement program.

In addition to these natural disasters, there are also numerous incidents of man-made disasters. Cyber-attacks are frequent, and although they do not directly harm the physical infrastructure in a significant way, cyber-bombs constantly disrupt traffic flow and in-vehicle automated guidance systems. This does not bother older drivers because they learned to drive cars and trucks in the old-fashioned way—manually. But the younger generation is accustomed to only minimal auto-driver override, and when the cyber-control systems goes down, the built-in safety features lead to a myriad of crashes and hence gridlock. Clearing crash sites on bridges and within tunnels is particularly slow.

Insofar as structures are concerned, the more worrying man-made disasters are of the IED type because bridges and tunnels are primary targets—maximum chaos can be inflicted with minimum effort. And although the human toll is not always drastic, the disruption that results is. Terrorists seem to gain an upper hand in slowing down the effectiveness of transportation system operations, and the re-establishment following an attack is always extremely cautious and slow. The direct and indirect costs on society become a significant drag on economic well-being in general.

Overall ramifications under this scenario lead to new and different ways to deal with the maintenance, renewal, and expansion of the highway infrastructure, and structures in particular. Under the Meltdown scenario, very little maintenance is performed on normal structures (those unaffected by disasters). All maintenance resources are redirected into the rebuilding and reinstatement of damaged facilities.

A few states, however, are fortunate in that they are essentially unaffected by these disasters of national consequences, but there are still significant indirect consequences. First, skilled labor and technical (engineering) expertise are all focused on the rebuilding elsewhere. This has a high inflationary effect on labor rates and salaries, basically doubling on a permanent basis. The price-surge effect means much less can be achieved locally with budgeted funds.

Bridge renewals lead to the majority of renewal expenditures for all structures. Numerous bridges suffer damage from earthquakes and storm surge effects, and while this damage is often irreparable, necessitating complete replacement, much of the damage can be repaired. Nevertheless, it is not expedient to repair badly damaged structures with tilted foundations from ground movement through liquefaction and lateral spreading effects, nor is it cost-effective to repair shaking damage. For example, whether piers have sustained significant plastic hinge rotation in the remaining fatigue life, while not consumed, is unknown—the ongoing reliability of these bridges is sufficiently uncertain to warrant replacement.

The difficulty arises with the overwhelming workloads, with essentially all structures demanding attention, but that attention cannot be given immediately. Thus, significant challenges arise with scheduling, inspection of damaged structures, and then the design and construction of replacements.

Some three years after a major earthquake, the rebuild is ready to get underway in earnest. STAs through their consultants demand aggressive construction schedules, with significant bonuses being paid for early completion, but likewise there are harsh liquidated damages for late completion. This puts a huge burden on the STAs for construction engineering and monitoring, as well as redirecting traffic onto alternate roadways.

To discourage travel, public transport becomes heavily subsidized, and heavy gas taxes are imposed as well—in part to pay for the rebuild. These necessary draconian measures fuel inflation, first and foremost in the local economy, but it also has an effect nationwide, consuming significant percentage points from the national economy.

The manufacturing industries adjust to the wartime-like basis—large bridge components are manufactured in steel plants and shipyards, and new large-scale precast concrete plants abound to satisfy the huge demand for premanufactured bridge components. There is generally insufficient time to develop task-specific robotic techniques for manufacturing; thus, contractors focus on tried and proven 20th century labor-intensive methods.

The new products that started to become fashionable prior to the rebuild—stainless steel and nano-engineered high-performance concretes—are in part abandoned in favor of regular steel and concrete.

The “Buy America” regulations are reluctantly abandoned by presidential order to enable international markets, especially China and a revitalized Europe, to fulfill many orders, but quality assurance of the imported products is problematic.

Under the Meltdown scenario, the expansion of highways nationwide comes to a virtual standstill. In fact, in unaffected regions, pre-disaster projects that had commenced are mothballed to permit diversion of funds into more needy disaster-affected regions.

There are a few exceptions. In some very badly affected regions that need complete rebuild, entire stretches of highway are abandoned, and completely new routes are implemented and fast-tracked for both roads and bridges.

10.6 Identifying Potential for New Materials, Tools, Technology, and Approaches

After understanding the conditions and impacts, the next step was to identify the potential for new materials, tools, technology, and approaches for each of the scenarios. Check marks in Table E.1 show how STAs may react to each scenario by adopting and/or developing new materials, tools, technologies, and approaches.

Visual assessment of Table E.1 shows a high concentration of tick marks under moderate mechanization, accelerated construction, and funding mechanisms such as PPPs. Accordingly, regardless of how the future turns out, these approaches have critical priority for STAs. Detailed examples for each column are provided as notes in the matrix of Table E.1.

Table E.1. Implications of the scenarios for STAs.

Multi-driver Scenarios	Materials	Tools			Technologies				Approaches							
	High-Performance Materials	Manual Labor	Moderate Mechanization	Automation	Extended-Life Design	Embedded Sensors	Energy Harvesting	Robotics	Cast-in-Place Construction	Fatigue-Prone Mitigation Measures	Precast Construction	Accelerated Construction	Tax-and-Spend Emphasis	PPP Emphasis	Privatization of Specific Assets	Creative Private Financing
Baseline (Managed Decline)		✓	✓						✓	✓	✓		✓			
Back to the Future	✓		✓	✓	✓	✓	✓	✓				✓		✓	✓	✓
Escape to the Centers	✓		✓	✓	✓	✓	✓	✓				✓		✓	✓	✓
Meltdown		✓	✓								✓	✓	✓	✓		

Notes:

- Approaches can be divided into two major categories: construction means/methods and innovative financing.

10.7 Implications for State Transportation Agencies

Based on the previous discussion, several implications arise that will affect the future planning and technological needs of the various transportation agencies in the United States, particularly the STAs. This section discusses those implications that are expected to affect most futures.

Moderate Mechanization

In the future, particularly during high-resource and low-demand scenarios, there will continue to be a rapid advance in technology. Historically, the transportation sector has been a low, or at best slow, adopter of new technologies. Remaining this way in the future will lead to lost opportunities for improving the cost-effectiveness and delivery of quality transportation structures. In turn, this affects the sustainability of the transportation system as a whole because the system also needs to compete with other sectors of the economy.

By adopting new technology, it should be possible to establish a more sustainable transportation system. High-performance materials with embedded sensors for health monitoring and energy-harvesting techniques are but two examples of technologies that can lead to more sustainable structures. Moreover, when using extended-life designs coupled with high-performance materials, the annualized costs of ownership can be minimized. Consequently, the owning public or private investor receives a higher rate of return.

Accelerated Construction

Using accelerated bridge construction (ABC) techniques should allow STAs to markedly reduce construction time frames. Concrete bridges are likely to remain the most commonly constructed transportation facility in the foreseeable future; it is this class of structure that stands to gain the most from ABC techniques.

ABC and rapid construction techniques for other classes of transportation structures will also require a higher degree of automation and mechanization than what currently exists. Much automation and mechanization maybe achieved through off-site robotic manufacturing of component parts that will lead to rapid on-site assembly.

A significant percentage of bridge structures are well known to be either structurally deficient or functionally obsolete. There remains a continued need to renew structures so classified. Although the renewal of existing structures presents additional challenges associated with keeping lanes open and traffic flowing, this only emphasizes the need for embracing additional automation, mechanization, and general ABC techniques.

As time proceeds, aging structures require additional maintenance. This is unlikely to change or even abate in the future. Maintenance activities are more labor intensive and often difficult to automate. It is therefore essential that STAs and their contractors maintain a well-trained and engaged skilled labor pool for such work. Moreover, given the likelihood of periodically tightened budgets (managed decline) or unforeseen disasters (meltdown), the maintenance (rather than renewal) of structures in either poor or damaged condition is essential.

PPP Emphasis

It is highly likely that the future will necessitate the development and broadening of new financial instruments and funding mechanisms (such as PPPs) for asset-specific major projects—particularly for bridges, viaducts, and tunnels. Since major projects will most likely use some form of private capital, it will be essential to minimize the time cost of money through the construction phase. Moreover, major structural assets often require the most lengthy construction time frames. For this reason, STAs would benefit from embracing accelerated forms of construction. Such programs are currently being advanced through the Strategic Highway Research Program 2.

10.8 Appendix E.1—Conditions and Impacts in the Baseline Scenario and Six Alternative Scenarios

Table E.1.1 summarizes the conditions in the six alternative scenarios. The reasoning was to understand the availability and level of funding to determine what activities or efforts STAs would focus on to provide the necessary level of service to the public. This condition determined the type of transportation structures technologies and techniques that would be developed to support the transportation structures activities in a safe and efficient way. The specific impacts that each condition would generate on individual scenarios are summarized in Table E.1.2. Finally, the development of new techniques and technology will be governed by other external conditions such as environmental concerns.

Table E.1.1. Summary of conditions in the baseline scenario and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Higher Resource Scenarios		Lower Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Economic Growth	Big government with large unsustainable deficits. Small economic growth.	Small government with large role for private sector in all walks of life. Expanding economy.	Big government with large deficits. Most growth of economy.	Economy governed by technology.	Large government with growing economy. Considerable government investment.	Moderate government but with considerable regulation.	Negative growth as ongoing catastrophes drag on the national economy.
Funding Amount	Tax and spend primarily for maintenance and some new construction with limited private finance.	Limited taxation revenue used for maintenance. User-pays doctrine prevails. PPP-led projects with private ownership of major assets.	Direct tax and spend for maintenance and renewal. Government bonds and user pays (tolling and mileage tax) for expansion.	Transportation demand curbed by technology. Funding focuses on maintenance with some limited renewals.	General funding shifts toward new and innovative transportation systems.	Funding for freight-heavy connectors maintained through distance taxes. Commuters shift to alternative mass transport.	Funding focused on rebuilds of damaged structures and facilities. Much diverted away from highways to other essentials.
Govern-ment Role	Big government with interventionist policies to control both capacity and demand.	Government divests ownership of major assets to private sector.	Government nationalizes many facets of transportation.	Broad adoption of technology in both public and private sectors.	Government nationalizes many facets of transport, including alternatives such as rail and shipping.	Government controls the planning and zoning processes with a heavy hand.	Government unequipped to cope with recurring catastrophic problems.
Road Freight	Current proportions maintained.	High road freight demand. Axle loads increased.	Modest. Modes somewhat controlled by government.	Modest, but farm-to-market remains important.	Diversification to other modes leads to modest freight demand.	Heavy freight due to focused demand.	High freight demand constantly impeded.

Table E.1.2. Summary of the impacts in the baseline and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Higher Resource Scenarios		Lower Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Economic Growth	Stimulus used to fuel economy via public works including roads and bridges.	Public works stimulated by private sector as a safe haven for mega-investments.	Deferred maintenance as part of growth control strategy.	Technology harvested for public good, including transportation.	Alternative modes bolstered, often at expense of highways.	Regulations require investments in public works—roads and bridges.	Declining economy, but much compulsorily directed into the ailing transportation system.
Funding Amount	Maintenance and renewal.	Capital projects. Private equity a principal source.	Expansion and maintenance. Capital projects, with government funds main source.	Maintenance and small demand for renewal.	Re-purposing right of way to construct multimodal systems.	New construction, maintenance, and renewal in urban areas.	Maintenance, renewal, and adaptation.
Government Role	Bridges/tunnels maintained by STAs.	Private sector controls construction and maintenance of structures.	Bridges/tunnels maintained by STAs. Unions prevail.	Robotics and off-site manufacturing predominant.	Maintenance predominant with some renewals.	Viaduct and tunnels construction essential in urban centers.	Rebuild of damaged bridges principal priority.
Road Freight	Wear and tear takes toll on aging bridge inventory. Other structures also deteriorate beyond their design life.	Bridges and other structures renewed rather than maintained.	Wear and tear takes toll on aging bridge inventory. Renewals tightly controlled.	Rural and secondary routes prone to deteriorate.	Rural and secondary routes prone to deteriorate. Between main centers, alternative modes used, relieving wear and tear.	Rural and secondary routes prone to deteriorate. Main thoroughfares between centers well kept.	Many routes weight restricted due to damage.

11.0 APPENDIX F - ROADSIDE AND DRAINAGE WHITE PAPER VISION

11.1 Description of Transportation Area: Roadside and Drainage

The term *roadside and drainage* describes the transportation facility area between the edge of the pavement and the right-of-way boundary that has the general functions of:

- Stormwater conveyance, treatment, and storage.
- Pedestrian, bicycle, streetscape, and other activities.
- Vegetation management for safety, traffic operations, and invasive weed control.
- Creation/maintenance of self-sustaining and complex biological/ecological systems.
- Erosion control for infrastructure stability.
- Roadside development for aesthetic enhancement.

The research team used the baseline scenario and selected three alternative scenarios that represented the most variability and had the greatest implication for the roadside and drainage area from the baseline scenario. These scenarios were further developed into specific applications for the roadside and drainage transportation area. These alternative scenarios include:

- “Back to the Future.”
- “Many Ways to Go.”
- “Meltdown.”

The research team also identified the potential for new tools, materials, technologies, and approaches for the baseline scenario and for each of the alternative scenarios.

11.2 Description of the Baseline Scenario: Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for transportation facilities’ roadside and drainage issues are as follows:

- Challenges remain in roadside management/maintenance and renewal of the existing infrastructure, and there is less emphasis on new capital projects.
- Progress in information technology (IT) allowed for the development of autonomous vehicles and semi-autonomous roadside maintenance equipment, yet human interaction is still an integral part of roadside management/maintenance.
- The roadside management/maintenance workforce is more sophisticated to accommodate the increased technology present in the rights-of-way.
- Concern for sustainability leads to more efficient and effective roadside development and drainage designs that focus on stormwater conveyance, storage, treatment, and re-use.

The focus for state transportation agencies (STAs) shifts from new projects to the rehabilitation, preservation, and maintenance of their existing infrastructure. Much of the available funding is delegated for safety-related issues. Urban and suburban roadside vegetation management/maintenance activities are mostly privatized, or contracted by local/municipal agencies and volunteer groups. Public-private partnership drives innovation and modest technological advancements including semi-automated roadside maintenance equipment and technologies.

Roadside management/maintenance equipment manufacturers develop machines that require software-driven platforms to support complex operations, such as global positioning systems (GPS), geographical information systems, and radio-frequency identification (RFID). For example, beginning in 1998, the Construction Industry Institute started researching the possible uses of RFID and GPS in construction for materials tracking and inventory management, and successfully used these technologies for improving the efficiency of activities. Such technologies are applied to roadside drainage and water quality structures, environmentally sensitive areas, and other components typically found within the rights-of-way that require routine management and maintenance. New emission regulations also change the design and specification of equipment used. The widespread push by regulators prompts innovations in green technology that spread from vehicle manufacturers to construction and maintenance equipment powered with technology that uses energy sources other than fossil fuels, i.e., electric with solar batteries, fuel cells, etc.

Roadside management/maintenance activities are still somewhat labor intensive, even with the use of semi-autonomous equipment. Some tasks still require a manual labor workforce, and so this workforce sustains injury and chronic medical conditions from job activities such as lifting, making repetitive motions, working in confined spaces, carrying heavy loads, and using tools and equipment that vibrate. While these injuries have always been common in these dangerous occupations, the public, and therefore the government, are less tolerant of work-related injuries that can be prevented by ergonomic measures. The increasing cost of health care also makes prevention a better long-term investment. Ergonomics typically involves changing tools, equipment, materials, and work methods. Most roadside management/maintenance equipment is designed with flexibility to accommodate individual operators' physical dimensions and strength. Sophisticated auditory and visual systems increase the safety of the workforce operating within the confined spaces of the roadsides, in medians, and adjacent to traffic lanes.

Since the late 2000s, significant advances have been made in both technology and legislation relevant to autonomous cars. Numerous major companies have developed working autonomous prototypes, including Google, Nissan, Toyota, and Audi. As of 2012, three U.S. states—Nevada, Florida and California—had already passed laws that allowed driverless cars. The advent of the autonomous car and other advanced driverless technologies increases the placement of a network of sensors and other technology/devices within the medians and roadside areas. While many IT-to-vehicle commands are sent via wireless communications, backup systems are put in place within the roadsides to meet emergency demands. This technology, located within the rights-of-way, requires a more sophisticated roadside management/maintenance workforce to conduct routine maintenance, replacement, and repairs and other roadside and drainage activities without disruption of service.

Personnel tasked with the planning, design, construction, and maintenance of a transportation facility are keenly aware of how much technology changes their approaches. Universities or colleges that offer design/construction programs become more integrated with manufacturers and vendors to prepare the industry for the next generation of workers. STAs implement training to meet their need for a more sophisticated workforce.

The extreme nationwide drought and rampant wildfires in 2011 lead to a vigorous campaign to implement more sustainable roadsides and improve stormwater management technologies. Low-impact development techniques that use natural systems for stormwater runoff control and stormwater capture for re-use become commonplace out of the necessity to conserve water.

In summary, in the 2040–2060 time frame, most of what was predicted occurs and continues to develop to meet the future demand and market.

11.3 First Alternative Scenario - Back to the Future

In the Back to the Future scenario, the economy returns to health, and transportation has the technology and resources to grow again. Potential implications of this scenario for transportation roadsides and drainage are as follows:

- Advancements in IT provide opportunities for totally autonomous vehicles as well as construction and maintenance equipment. These could be programmed to perform tasks or navigate to a destination requiring no real-time human interaction.
- IT advancements also eliminate the need for designing and maintaining a safety clear zone in most locations. Vehicles have the ability to sense danger, avoid it, and redirect.
- Development of sustainable materials allows for new and innovative roadway systems such as designer road surfaces and roadsides using biotechnologies in systems for stormwater capture, storage, treatment, and re-use.
- There is a need for a more sophisticated roadside management/maintenance workforce.
- The increase in freight movement has environmental impacts.

In the 2040–2060 time frame, rapid development in computing, sensing, and control makes highway maintenance activities faster and safer. Industrial robots perform well-defined repetitive tasks in carefully controlled environments.

The scale and precision of robotic technology enable a much safer roadside management/maintenance environment. Robotic mowers had been used on a small scale, i.e., residential and golf greens, since Husqvarna produced the first robot mower in 1995. This technology becomes more advanced due to the enhanced accuracy and precision of GPS combined with the network of IT sensors within the roadsides for autonomous vehicles and solar-powered batteries that extend the duration of use. With autonomous and semi-autonomous robots, part of roadside management/maintenance operations such as landscape, water quality treatment facilities, and drainage infrastructure maintenance can be safely conducted in hazardous roadside conditions such as adverse topography, near water sources, in medians, and adjacent to traffic lanes.

Remote-controlled drones become commonplace for STAs. Drone use escalated in the early 2000s through increased military research and activity. This led to adapted applications for STAs such as the ability to inventory roadside drainage structures, water quality areas, and other features, and to detect and track drainage flow problems back to the source. Habitat and wildlife monitoring become safer and more efficient. Construction site regulatory compliance is made easier through the use these airborne tools. Site inspections are conducted with greater safety through the use of drones. By the late 2010s, the Environmental Protection Agency had resolved the problems encountered with implementing a numeric effluent limitation (NEL) for stormwater discharge from construction sites. The erosion and sediment control industry develops more effective and efficient materials to facilitate meeting NEL requirements. Discharge locations and strategic best management practices (BMPs) use embedded sensors to remotely monitor for discharge turbidity and other BMP management/maintenance indicators. Drones routinely monitor discharge locations, inspect for maintenance needs, and identify other ongoing construction site issues. On the other hand, regulatory agencies also use drones to identify, track, and record illicit stormwater discharges from construction sites, regulatory infractions, and other noncompliance issues.

The safety clear zone concept is virtually eliminated in many areas due to applications of IT sensor networks within transportation corridors, both wireless and physical. Vehicles have the ability to sense danger, avoid it, and redirect. In many urban and suburban locations, the rights-of-way once used for clear zone are designated for other uses such as alternative travel modes and streetscapes. In rural areas, surplus rights-of-way are used for energy capture and re-use such as solar, wind, and biofuels.

As other uses creep into the roadside, the right-of-way available as a vegetated roadside also diminishes, so the effectiveness of the vegetated roadside had to increase. Roadside vegetation and soils are designed to maximize their effectiveness for stormwater treatment and carbon sequestration. Genetically engineered agricultural crops have been commonplace for decades. The first genetically modified plant was produced in 1982, using an antibiotic-resistant tobacco plant. The plant DNA was manipulated to provide better disease and pest resistance, and to improve growth potential. The need to reduce mowing, chemical use for weed and pest control, and other maintenance activities led research to produce grasses that do not exceed the maximum desired height and are tolerant of the harsh roadside environment.

Research also develops plant species to maximize the removal of pollutants from stormwater and carbon from the atmosphere. Soils and soil amendments are biotechnically enhanced to work in concert with the plants and stormwater to retain available moisture, consume pollutants, and enable greater carbon capture. The soils are enhanced using genetically engineered microorganisms and adapted recycled materials. These designer plants and soils nearly eliminate the need for using chemical treatments on the roadsides for weed and pest control. Right-of-way carbon sequestration becomes not only more environmentally effective but also a source of revenue for STAs. The carbon market had a slow and very uncertain start in the 1990s with the Kyoto Protocol. By 2003, U.S. corporations were able to trade carbon dioxide (CO_2) emission allowances on the Chicago Climate Exchange under a voluntary scheme. Attempts at cap and trade systems in the United States, such as the Western Climate Initiative and Regional Greenhouse Gas Initiative, did not see much success. Most initiatives targeted industrial source pollutants.

Transportation facilities are no longer viewed as the great polluters of the past due to emissions reduction through alternative energies/fuels and more efficient vehicles. However, STAs recognize the opportunity for a revenue source and finally agree to participate in a carbon trade system by allowing the millions of acres of right-of-way (over 1 million acres in Texas alone) to be used as carbon offsets/credits. A carbon offset is a compensatory measure made by an individual or company for carbon emissions, usually through sponsoring activities or projects that increase CO_2 absorption, such as tree planting. Carbon credits are tradable certificates or permits representing the right to emit 1 tonne of CO_2 or the mass of another greenhouse gas

(GHG), such as methane, perfluorocarbons, and nitrous oxides, with a carbon dioxide equivalent (tCO_2e) equivalent to 1 tonne of CO_2.

The first decade of 2000 progressed in environmental sustainability. The use of sustainable materials changed how the United States built roads. Stormwater treatment and re-use (rainwater harvesting) grew out of the need for water conservation in many areas of the country. In 2006, research on the use of porous friction course (PFC) overlays discovered its water quality treatment benefits (Figure F.1). From this, research proceeded to designer pavements that use specialized aggregates that work at the molecular level to chemically bond with and remove the specifically targeted pollutants from runoff. This technology eventually leads to totally permeable roadways able to remove the targeted pollutant, capture it, store it, and treat surface runoff under the roadway. The treated stormwater is then discharged to municipal nonpotable or grey water storage facilities for re-use.

Figure F.1. Differences in spray from conventional (left) and PFC (right) pavements (Barrett, 2006).

Grey water use escalates. California connects grey water use and water conservation to the state's GHG reduction goals due to the energy consumption for pumping, treating, and transporting potable water. In 2009, the California Building Standards Commission approved the California Dual Plumbing Code that established statewide standards for installing both potable and recycled water plumbing systems in commercial, retail, and office buildings; theaters and auditoriums; schools; condominiums and apartments; hotels; barracks and dormitories; and jails, prisons, and reformatories. Montana passed grey water use legislation in 2009, and Wyoming followed in 2010 by allowing surface and subsurface irrigation and other nonspecific use of grey water. The California Department of Transportation led the way in the use of grey water for roadside irrigation. Stormwater capture and re-use and/or grey water use for construction, maintenance, and operations activities are now standard procedure, thereby greatly reducing the demands on potable water treatment and supply systems.

With the advanced technologies used within the rights-of-way, the roadside operation, management, and maintenance workforce requires more sophisticated training. Equipment is now semi-autonomous or autonomous and requires a greater level of training for safe operation. The roadside also has numerous technologies that require specific skill sets. Networks of IT sensors direct everything from vehicles to mowers to traffic. Roadside maintenance personnel are not only required to maintain stormwater conveyance systems and vegetation, but they must also be able to perform tasks related to IT such as sensor replacement and repair.

Freight transport throughout the world faces major changes in the first two decades of 2000. Technology changes the mindset and purchase methods of the consumer, i.e., purchase online and ship directly to the consumer. The Panama Canal expansion in 2015 nearly doubles the canal’s capacity by allowing more and larger ships to move through. Inland and coastal ports face both air and water quality issues associated with accommodating vast quantities of transport vehicles and their associated pollutants. The increased ground, rail, and waterway shipping leads to environmental impacts for roadsides and drainage areas, including the increased incidence of hazardous and nonhazardous material/load spills. Truck loads are larger and heavier, as are rail and ship cargo.

The introduction of nonindigenous species, both plant and animal, increases due to expanded global shipping. Although the inspection process is in place, contamination occurs. One of the most well-known examples of nonindigenous specie stowaway is *Solenopsis invicta*, the imported red fire ant (RIFA), introduced into the United States in the 1930s from freight shipped from their native South America. RIFAs rapidly spread throughout the United States, infecting 320 million acres by 2011. The spread becomes global as other regions of the world with suitable climate are invaded through the movement of freight and people. The economic impacts of RIFA infestations are enormous due, in part, to their incompatibility with technology placed in the rights-of-way (Figure F.2).

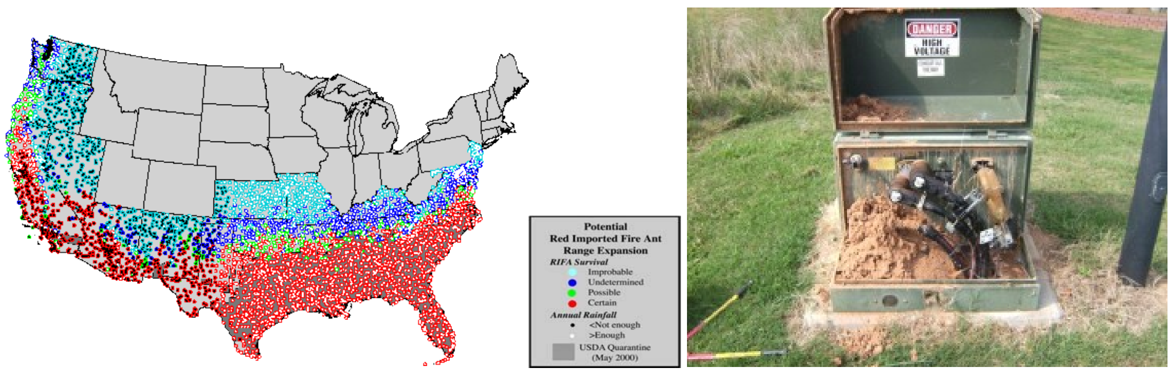

Figure F.2. Fire ant potential spread (left) (U.S. Department of Agriculture, 2006) and electrical component impacts (right) (Rocha, 2011).

Freight traffic also contributes to an increase in habitat gradation. The scale of transportation facilities in primary routes increases, thereby further reducing available roadsides with additional lanes designated for freight, rail, etc. This leads to even greater plant and wildlife habitat fragmentation. The noise, vibration, and pollution from small and medium-sized vehicles are greatly reduced through alternative fuels, technology, and quieter pavements. However, large transport vehicles remain a pollutant source. The soil and plant technologies prove very useful in sequestering atmospheric carbon and treating runoff, but airborne particulates stress roadside vegetation by interfering with photosynthetic processes in many ultra-urban areas and in transportation hubs. Large-vehicle noise, vibration, and pollutants, although lessened over the past decades, still create quality of life issues for both people and the rest of nature.

In summary, in the 2040–2060 time frame, advancements in technology and materials allow complete automation of management/maintenance activities and provide innovative roadways and sustainable roadside systems capable of stormwater management and treatment.

11.4 Second Alternative Scenario - Many Ways to Go

In the Many Ways to Go scenario, the government invests in new transport and IT that include significant shares of many different transportation modes. Potential implications of this scenario for roadsides and drainage are as follows:

- Accommodating a functional roadside with addition of IT systems and active transportation modes has many challenges.
- Sustainable development prompts innovative roadside management techniques.
- Management/maintenance activities increase for repurposed rights-of-way for natural habitat restoration and preservation.

In the 2040–2060 time frame, the roadside management/maintenance workforce becomes more sophisticated to support development of new and innovative transportation systems. Moreover, development of new and advanced transportation systems and IT leads to a great deal of convenience in traveling.

The notion of U.S. transportation facilities providing for all travel modes took off in the 1970s when Oregon passed its "bike bill," the first statewide complete streets policy. It required that new or rebuilt roads accommodate bicycles and pedestrians, and that state and local governments fund pedestrian and bicycle facilities in the public right-of-way. The Oregon Department of Transportation's acknowledgment of and support for sustainable and active transportation led to the development of its Active Transportation Program as the STA looked out to 2030 and changing user needs. Many other states have followed with support from municipalities. The Nashville Area Metropolitan Planning Organization's Active Transportation Funding Policy, adopted in 2010, dedicated $115 million in funding for active transportation infrastructure and education about active transportation through 2035.

Implementation of complete streets and active transportation policies impacts the roadsides in limiting the available space to perform necessary roadside functions. There are many modes and their respective useful areas to consider. Not only do separate access lanes/paths need to be provided, but there are other considerations in urban and suburban areas. Many travel lanes are designated for other uses such as streetscape development with additional landscape plantings and other appurtenances that require management and maintenance. Retrofitting a built-out environment means competition for space within the constraints of limited rights-of-way. Stormwater management is a concern as more areas are designated as active travel ways. Innovations in porous or pervious pavements help to maintain site hydrology by facilitating movement of stormwater while providing a usable surface (Figure F.3). Another issue faced by STAs is the conflict of active transportation areas and the space required for snow removal and storage. Many strategic routes and bridges use solar energy to power heating elements within the pavements. This does not eliminate the problem; however, keeping strategic roadways at a temperature that does not allow for snow accumulation does reduce the quantity of snow that needs to be removed and stored at these locations.

Figure F.3. Pervious pavement (Source: http://en.wikipedia.org/wiki/File:Permeable_paver_demonstration.jpg).

The IT applications in transportation reach most travel modes. With this come placement and use of various roadside applications. In urban areas, this may consist of dedicated areas as transportation hubs. Although many of these are privatized, some STA responsibilities exist. Management and maintenance of such facilities require advanced training to meet ever-changing technologies. As with any cluster of human activity, trash, debris, and other pollutants remain a maintenance concern.

Because many other transportation options are available for the general public and for movement of goods, STAs close some of the obsolete road corridors and repurpose them for other uses. In essence, the surplus vacant lands provide new opportunities. These lands are sometimes sold off for a profit, co-developed with the private sector, repurposed as green belts, or repurposed for growing foods and even for generating alternative energy. Since sustainability is an issue, STAs and the government can use the surplus real estate to develop green infrastructures such as areas to manage (hold and filter) stormwater runoff and recover the damaged ecosystem. Roadside and drainage activities related to repurposing include the development of sustainable landscape areas; restoration and preservation of diverse habitats/ecologies; incorporation of stormwater collection, treatment, and re-use systems into the landscape; and surfacing of bike paths and walkways that maintain site hydrology. More landscape maintenance activities grow out of these transformations.

In summary, in the 2040–2060 time frame, the country develops a new, innovative, and sustainable transportation system that provides many alternative ways that people can travel. In the process, obsolete and cost-prohibitive transportation infrastructure is repurposed with sustainability in mind.

11.5 Third Alternative Scenario - Meltdown

In the Meltdown scenario, abrupt climate change shifts priorities from growing the economy to struggling with nature. Potential implications of the Meltdown scenario for roadsides and drainage are as follows:

- Rapid climate change requires a strict policy on reducing GHG emissions and increasing roadside carbon sequestration capabilities.

- Catastrophic power failures prompt projects to bury all overhead/surface energy, power, and IT distribution structures within the roadsides to minimize the impacts caused by extreme weather events.
- Preservation of the roadsides and drainage capacities is challenging as maintenance activities increase due to rapid climate change.
- Highway maintenance equipment is robotic for the most part to increase workforce safety. All other equipment uses alternative energy sources such as electric with solar batteries.
- Climate change impacts current design standards and approaches to emergency preparedness that use the roadsides for evacuation.

In the 2040–2060 time frame, abrupt climate change, prolonged drought followed by severe storms, and rising sea level bring increasing challenges to roadside management/maintenance as well as to methods to move great quantities of stormwater within established systems. The government sets out a strict GHG limit in an effort to reduce GHG emissions. However, GHG production and impact are a global effort. In 2013, many other countries were still lagging behind in regulatory controls of GHG production from vehicles, equipment, industries, and other uses. Fossil fuel consumption was declining in the United States with the widespread use of alternative fuels and energy sources. As older, more polluting vehicles and equipment were phased out of production and use, the United States saw a decline in GHG production related to transportation facilities. The use of alternative fuels and/or fuel-efficient equipment used for roadside activities becomes part of STAs' compliance with environmental regulations. The ever-diminishing roadside area becomes a focus for its ability to sequester carbon in the soil and vegetation. Roadsides use genetically engineered vegetation and designer soils to maximize their effectiveness for water quality and quantity treatment, and carbon sequestration.

Mitigating climate change makes environmental preservation the most important priority rather than growing the economy. To maintain the required physical infrastructure and preserve jobs, the federal government uses labor-intensive methods as an economic policy, where labor is already the dominant resource for carrying out work. Severe and repetitive weather events generate widespread and enduring power outages that are safety hazards for the general public and the maintenance workforce tasked with clean-up, repair, and restoration (Figure F.4). The solution is to bury all of these technologies within the rights-of-way, thereby minimizing the effects of severe weather on power, communication, and IT distribution. Overhead pole/wire-based technologies routinely affected by weather events—such as high winds, extreme heat, wildfires, and severe storms—are targeted. Transportation agencies, municipalities, private-sector communications, and utilities work together to determine the best approaches to accommodate numerous services such as telephones, electricity distribution, natural gas, cable television, fiber optics, traffic lights, street lights, storm drains, water mains, and wastewater pipes. In some locations, major oil and gas pipelines, national defense communication lines, mass transit, rail, and road tunnels also compete for space underground. These local labor-intensive projects serve both as a fiscal measure to expand public spending as well as a short-term measure to alleviate unemployment. While much of the new construction starting in the 1970s buried utility and communication systems, many older, well-established areas of the country still use existing overhead structures. Unfortunately, many of these areas are located along coastal regions that are subject to multiple and severe storm events.

Figure F.4. Downed power lines (Source: http://www.datafoundry.com/the-importance-of-a-concrete-encased-underground-power-feed/).

Rising sea levels and groundwater make stormwater conveyance most challenging. Standing water creates health and safety hazards not only for the traveling public, but for the workforce managing and maintaining the roadside environment and the transportation infrastructure compromised by severe erosion. While coastal regions deal with too much water, the Midwest struggles to have enough water to grow crops for food production. Many coastal areas have very flat terrain and at-capacity soils, which leave negligible methods for moving excess water away from transportation facilities to restore service after a storm event. The solution is costly but necessary. Systems are put in place to move the excess water inland. The system follows the interstate highway rights-of-way to facilities for desalination and/or grey water storage/treatment and distribution for nonpotable uses.

Policy makers adopt approaches for improving emergency planning and preparedness in an attempt to minimize the possible effects of disruptions caused by major incidents. The burden of restoring utilities, water, and communication services is lessened through their relocation to the subsurface. Reliable communication equipment, emergency response procedures, and workforce training become a standard safety practice in storm aftermath cleanup and repairs. Roadside areas become very valuable in evacuation corridors and are now designed as alternative traffic lanes. Structural pervious surfaces are designed to accommodate vehicle flow demands while maintaining stormwater drainage capacities to the maximum extent possible.

In 2040–2060, green construction in transportation becomes the norm. The use of the roadside area is greatly expanded to accommodate many different uses, from evacuation routes to water transport. The management/maintenance workforce knowledge base is increased to meet the ever-growing challenges created by climate change.

11.6 Identifying Potential for New Tools, Materials, Technology, and Approaches

After understanding the conditions and impacts, the next step was to identify the potential for new tools, materials, technology, and approaches for each of the scenarios. Check marks in Table

F.1 show how STAs may react to each scenario by adopting and/or developing new tools, technologies, and approaches.

Visual assessment of Table F.1 shows a high concentration of tick marks under sustainable practices and workforce training. Accordingly, regardless of how the future turns out, these approaches have critical priority for STAs. Detailed examples for each column are provided as notes in the matrix of Table F.1.

Table F.1. Implications of the scenarios for STAs.

Multi-driver Scenarios	Materials	Tools	Technologies	Approaches	
	Innovative Materials	Light Equipment	IT Applications	Sustainable Practices	Workforce Training
Baseline (Managed Decline)				✓	✓
Back to the Future	✓	✓	✓	✓	✓
Many Ways to Go	✓	✓	✓	✓	✓
Meltdown	✓	✓		✓	✓

Notes:

- *Innovative materials* include designer pavements, genetically engineered vegetation, and enhanced soils.
- *Light equipment* includes small robots, mowers, integrated quality control capabilities, and automated equipment.
- *IT applications* include using sensors, RFID, and GPS tools.
- *Sustainable practices* cover topics such as using biotechnologies, stormwater re-use, solar and silent equipment, and low-impact construction and maintenance methods.
- *Workforce training* refers to the next generation of the workforce trained for performing sophisticated tasks involving new systems, equipment, methods, and materials.

11.7 Implications for State Transportation Agencies

Several important themes arise following a review of the future scenarios and impacts for roadside and drainage.

Sustainable Practices

In general, one of the main concerns for the U.S. transportation industry is that the highway system is aging, and state agencies need to maintain, preserve, and rehabilitate existing highway infrastructure. The public is increasingly more aware and empowered by the quantity of information available regarding transportation agency policies and practices. Concerns for adverse societal and environmental impacts of transportation facilities range from endangered species to chemical controls used on the roadsides. Integrating innovation is one of the most critical priorities for STAs. This influence covers a wide range of topics including tools (e.g., sensor and wireless technology), equipment (e.g., silent and low-emitting equipment), materials (e.g., bioengineered soils and vegetation), and stormwater management (e.g., capture, storage, treatment, and re-use).

Competition for roadside space and conflicting uses will be at the forefront. As effective rights-of-way shrink through facility expansion, new technology placement, repurposing, or other scenarios, coordination and cooperation between transportation agencies, utilities, communications, municipalities, etc. will be imperative for successful planning and design. Such planning will include roadsides and drainage activities. There is an emerging trend among STAs to use municipalities, local agencies, and volunteer groups for a part of the roadside maintenance in an effort to sustain an expected level of service with ever-diminishing funds.

Extreme weather events impact STAs' management of the aftermath. Changing and unpredictable weather patterns affect roadside management/maintenance activities. The super storms in the Northeast and drought throughout the Midwest and South affect the sustainability of vegetation and its ability to provide structural stability to the roadsides. This is a concern for STAs because eroded roadsides compromise infrastructure. Designer soils and vegetation will become part of roadside design and management because these components work together to provide better adapted vegetation and soils capable of withstanding harsh roadside environments. STAs should be proactive and diligent with research efforts that support the development of more effective roadside management and drainage tools, materials, approaches, and technologies.

Workforce Training

As with the evolution of new tools, equipment, materials, and methods, so evolves the need for a more educated workforce in the near future. A higher level of knowledge, skill, and capabilities will be required to operate high-tech tools and equipment, and perform sophisticated tasks involving new materials and methods for maintaining environmental compliance and sustainable roadside management/maintenance operations. This includes reducing the environmental impacts of equipment use through new technology such as alternative energy sources. Current practices for many STAs typically consist of vegetation management, invasive species control, slope management for erosion, and drainage infrastructure management, maintenance, and replacement. Innovative materials for stormwater management such as biotechnology, genetically engineered plants, and designer pavements and soils will impact not only the management/maintenance workforce, but how engineers, landscape architects, and planners view the design of the roadside as these new uses are incorporated into the already constrained urban roadside environment. Training is an emerging trend for the future of the planning, design, and management of roadsides and drainage operations across all six alternative scenarios. Securing sustainable funding for long-term training programs needs to become a higher priority. STAs should be disciplined about workforce planning and continuously research and develop training programs to recruit, retain, and strengthen the current talents within the organization. In addition, as new technologies and methods are implemented within the rights-of-way, public education will become necessary to disseminate the principles and practices to ensure user safety and efficient operation.

Overall, the design, management, and maintenance of roadsides and drainage will see innovative and resourceful use of sustainable tools, equipment, materials, and methods that address stormwater quantity and quality concerns while providing the opportunity to incorporate technologies that make transportation facilitates more environmentally sound and user friendly.

11.8 Appendix F.1—Roadside Management/Maintenance Activities

The following are some examples of roadside management/maintenance activities:

- Earthwork including clearing and grubbing, removal of structures and obstructions, excavation and embankment, subgrade preparation, erosion and sediment control, salvaging, and placing of topsoil/soil amendments.
- Miscellaneous construction including concrete barriers, culverts and storm drains, underdrains, guardrails, fences, sidewalks, curbs and gutters, paved ditches and paved flumes, turf establishment, and provision of trees, shrubs, vines, and ground covers.
- Systems operations including traffic incident management, safety service patrols, surveillance and detection, traveler information and dynamic message signs, road weather information systems, work zone management systems, ramp metering systems, traffic signal optimization/retiming, traffic adaptive signal control, electronic toll systems, electronic border crossing systems, commercial vehicle information systems, bus rapid transit, transit signal priority, parking management systems, transit automated vehicle locator/computer-aided dispatch, and high-occupancy toll facilities.

11.9 Appendix F.2—Conditions and Impacts in the Baseline Scenario and Six Alternative Scenarios

Table F.2.1 summarizes the conditions in the six alternative scenarios. The reasoning was to understand how climate change, new technologies, and environmental concerns would impact what activities or efforts STAs would focus on to facilitate compliance with environmental regulations and provide the necessary level of service to the public. This condition determined the type of roadside design/management/maintenance and stormwater management technologies and techniques that would be developed to support the roadside and drainage activities in a safe, effective, and efficient manner. The specific impacts that each condition would generate on individual scenarios is summarized in Table F.2.2. The High-Resources scenario combines the Back to the Future and Government Redux scenarios. The Lower-Demand scenario combines the Bits over Buses, Many Ways to Go, and Escape to the Centers scenarios. The Disruptive scenario encompasses the Meltdown scenario, which includes man-made and natural events that create havoc for transportation systems.

Table F.2.1. Summary of conditions in the baseline scenario and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	High Resource Scenarios		Lower Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Climate Change	Emphasis on rehabilitation, preservation, and maintenance.	Emphasis on new materials/ techniques for stormwater management, vegetation, and soils.	Expansion of existing network reduces available right of way for stormwater management and evacuation routes.	Roadsides maintained at minimal level by state transportation agencies.	Construction of new transportation system brings various challenges.	Construction in urban areas brings challenges.	Roadside maintenance activities increase due to rapid climate change and urbanization.
Technology and Techniques	Moderate adoption of IT in stormwater and roadside management.	Solar, electric, alternative energy equipment, and more IT placement in right of way.	Rigorous application of technology to improve worker safety on roadsides.	Low to moderate application of new technology in construction and maintenance.	Rigorous application of information technology in all aspects of construction and maintenance.	Innovative subsurface stormwater management in highly urban areas.	Challenges of limited right of way for functional roadside with vast subsurface utilities, IT systems, etc.
Environmental Concerns	Overall concern for sustainable practices.	Robust concern for environmentally friendly and sustainable practices.	Overall concern for sustainable practices.	Concern for sustainable practices increases due to reduced overall funding.	Roadside challenges with active transportation modes, conversion of abandoned roads, and IT networks.	Concern for increased stormwater runoff from built-out areas with limited right of way.	Sustainability is the top priority. Concern for methods with low impact on environment and public well-being

Table F.2.2. Summary of the impacts in the baseline and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	High Resource Scenarios		Lower Demand Scenarios			Disruptive Scenario (Meltdown)
		Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	
Climate Change	Maintenance and preservation.	Innovative materials and techniques.	Innovative materials and techniques.	Maintenance and preservation of existing right of way.	Cooperative effort to use right of way.	New construction, maintenance, and renewal in urban areas.	Multiple uses within existing right of way.
Technology and Techniques	Semi-autonomous maintenance equipment. More sophisticated maintenance workforce.	Sophisticated but safer work environment. Totally autonomous maintenance equipment.	Sophisticated but safer work environment. Totally autonomous maintenance equipment.	Semi-autonomous maintenance equipment.	Sophisticated but safer work environment. Semi- to totally autonomous maintenance equipment. Competition for right of way space.	Techniques and technologies to compensate for reduced areas for stormwater management.	To create employment and prevent economic downturn, government starts supporting labor-intensive public work programs as an economic policy tool.
Environmental Concerns	Equipment uses alternative fuels and/or is fuel efficient and designed for human ergonomics.	Innovative road systems, such as designer permeable roads, allow stormwater storage, treatment, and re-use.	Roadside maintenance equipment is fuel efficient. Alternative fuels and designed for human ergonomics (similar to baseline).	Maintenance equipment is fuel efficient and designed for human ergonomics.	Repurposed roadways seen as opportunities to restore habitats lost by urbanization.	Construction/ maintenance equipment is fuel efficient, emits less GHG, and is quiet and designed for human ergonomics.	Climate change impacts current design standards and reduces worker productivity, efficient equipment, and green construction.

11.10 Appendix F.3—Equipment Classification

State transportation agencies operate a wide variety of vehicles and equipment, ranging from light-, medium-, and heavy-duty vehicles to specialized equipment, small-engine equipment, and seasonal vehicle attachments. As proposed by the National Association of Fleet Administrators (NAFA) in the *Fleet Maintenance Operations Guide*, gross vehicle weight and physical characteristics of the fleet and equipment are typically considered in the development of equipment classes. According to NAFA, the gross-vehicle-weight-based classification system provides common attributes to compare vehicles from widely different fleets and fleet applications. Also, operating and maintenance costs have a correlation to gross vehicle weight, vehicle type, and function. Table F.3.1 shows equipment classes and examples.

Table F.3.1. Equipment classes and examples.

Equipment Class	Examples
G. Small engine	Chainsaws, grass trimmers, lawnmowers
H. Seasonal attachments	Plows, salt and sand spreaders
I. Light duty	Sedans, light pickup trucks, light trucks
J. Medium duty	Heavy pickups, medium dump trucks
K. Heavy duty	Heavy trucks
L. Specialized	Tractors, loaders, graders, backhoes, oil spreaders

Due to different designs and functions as well as considerations of the typical availability of service providers, tractors and construction equipment are in separate categories, with the purpose of differentiating them from the heavy-duty class.

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12.0 APPENDIX G - CONNECTIVITY WHITE PAPER VISION

12.1 Description of Transportation Area: Connectivity

The term *connectivity* in this study focuses on how highway infrastructure interfaces with all other modes: transit, aviation, ports, trains, subways, pedestrians, and cycling. The highway infrastructure can interact with these modes in essentially two ways:

- Direct integration—these modes can be incorporated into the highway system either longitudinally or laterally: transit, passenger rail, pedestrians, bicycles, and trucks/commercial.
- Indirect integration—these modes will not likely have direct integration with highways, but highway planning could incorporate techniques for enhancing accessibility to them: aviation, ports, subways, and freight rail.

This paper focuses on those modes with the potential for direct integration because they have the greatest impact on the topics of construction, maintenance, and preservation. And because connectivity is so broad, it requires a level of generalization and simplification for analytical purposes. This generalization reduces the complexity of the technical area—increasing analytical ability—but decreasing the robustness of the analysis.

The research team used the baseline scenario and selected three alternative scenarios that represented the most variability and had the greatest implication for the connectivity area from the baseline scenario. These scenarios were further developed into specific applications for the connectivity transportation area. These alternative scenarios include:

- "Bits over Buses."
- "Government Redux."
- "Meltdown."

The research team also identified the potential for new tools, technologies, and approaches for the baseline scenario and for each of the alternative scenarios.

12.2 Description of the Baseline Scenario: Managed Decline

In the baseline scenario, much of the future turned out as expected. Potential implications of this scenario for transportation connectivity are as follows:

- This scenario paints a picture of a society that could benefit greatly from an increase in public transit and multimodal transportation services but is largely unable to pay for them.
- Limited roadway capacity and limited funding, coupled with a high demand for mobility, creates a population that desperately wants to move but is physically unable to due to limited capacity and funding.
- High technological advances can facilitate private-sector alternatives, but these measures can only go so far to ameliorate the pressure created from mobility demand that far outstrips supply.
- High density also creates a society that could feasibly take advantage of public transit but lacks the necessary funding. It is likely that either private entities begin to supply "public

transit," or the public at large vociferously demands local governments supply higher levels of public transit, which results in an increased state transportation agency (STA) role in transit construction and maintenance.

In the business-as-usual scenario, society constrains itself by an inability to move effectively. People wish to commute from suburbs to central locations at the same time of day, with the majority of commuters using highways and local roads. This situation creates a huge demand for mobility at peak periods. Density increases in cities as individuals realize the true opportunity costs of living in suburban and exurban communities: gridlock during the morning and evening commutes creates an unsustainable life for commuters living outside of the core city areas.

At the same time, much of society consistently refuses to increase funding for transportation projects. This only worsens the already unbearable congestion problem. What is left is a society in an intractable dilemma: the costs to travel are extraordinarily high, but there is high resistance to raising the funds for projects that would ameliorate the congestion. Additionally, the costs to develop transportation infrastructure are now exceedingly high because land in the most congested areas commands much higher prices than before.

Cities and states that decided early in the 21st century to invest heavily in multimodal transportation solutions gain a competitive edge, and businesses choose to relocate to these areas. Transit, walkable cities, bus services, and other multimodal transportation become among the highest priorities for STAs and local governments.

Cities and states that were late to develop multimodal solutions are not able to implement as many services, especially those that require constructing additional infrastructure. Nonetheless, some improvements can be made to improve mobility. States and cities attempt to implement robust bus and transit services. State and local governments coordinate efforts to modify existing infrastructure to improve cycling and walking facilities.

In the most heavily congested and densely populated areas, private companies begin to operate transit services. Travelers are willing to pay for increased mobility, and in very specific circumstances, transit becomes a profitable venture.

In summary, in the 2040–2060 time frame, most anticipated trends occur. Society continues to struggle to find the correct balance between limited government and meeting mobility needs.

12.3 First Alternative Scenario - Bits over Buses

In the Bits over Buses scenario, higher than expected increases in crude oil prices reduce the ability of ordinary people to travel as much as they used to. They turn instead to an expanded Internet, not only for communication but also for most work and leisure activities that previously required physical movement. Potential implications of this scenario for transportation connectivity are as follows:

- The decreased demand for mobility from expanded information technology (IT) (i.e., accessibility to goods and services via the Internet) reduces the congestion strain on the transportation network.

- As a result, the work of STAs is reduced, as is its funding. In comparison to the baseline, STAs and local governments do not need to develop and manage as many multimodal solutions.
- Companies must still ship goods, however, because teleportation is still in the realm of science fiction. STAs focus more on solutions for improving throughput at ports, on trains, and through freight on the roadways.

In the 2040–2060 period, Americans become increasingly dependent on the use of the Internet and Internet-enabled technologies to live. They can seemingly fulfill all aspects of their lives through the Internet and related technologies. Commuting is no longer needed for most knowledge-based industries because work is accomplished on computers. Meetings usually take place via teleconferences. Physically traveling to work is the exception, not the rule.

As a result, the burden on the transportation network is greatly diminished in comparison to the baseline scenario. Rush-hour gridlock is a bygone frustration, a memory from a time before the online revolution. STAs and local governments have no need to focus on increasing multimodal transportation options.

The exception to this general trend is the movement of goods. Moving physical goods from the producer to the consumer still requires physically transporting it. As a result, a growing population continues to consume physical goods, which results in demand for physical products increasing. STAs begin focusing on improving the infrastructure to move goods as traditional traffic diminishes. State and local governments convert previously used park-and-ride and transit centers to distribution centers and freight hubs. Some high-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes are converted to dedicated freight lanes, or new managed lanes are operated as truck-only lanes as illustrated in Figure G.1.

Figure G.1. Rendering of dedicated truck lanes on I-70 (Source: http://www.i70dtl.org/images/TA_1_-_Literature_Review.pdf).

In summary, in the 2040–2060 time frame, the Internet replaces the need for mobility for many consumers. The overwhelming driver of transportation demand becomes freight movement, and roads are redesigned to facilitate this need.

12.4 Second Alternative Scenario - Government Redux

In the Government Redux scenario, the government reasserts itself as the primary driver of transportation in the United States and develops the funding resources to do so. Potential implications of this scenario for transportation connectivity are as follows:

- The government increases its revenues for transportation projects through taxes and user fees.
- Under this scenario, high investment in additional capacity reduces the demand for multimodal transportation. The additional capacity also reduces density so that society is less able to take advantage of public transit.
- As a result, STAs do not invest heavily in multimodal transportation because demand is low and providing it is highly inefficient.

The government takes on an increased role in society following the limited government trend of the early 21st century. The government reasserts itself as the primary mover in the transportation sector—increasing taxes and developing more user-fee-based revenue sources. STAs continue to expand capacity, further facilitating sprawl and the growth of "mega-regions." Suburbs become passé as a gradual exodus occurs, moving families further from city centers where exurban life quickly becomes the norm.

STAs continue their traditional role of building highway capacity that facilitates the continued use of the single-occupant vehicle (SOV) as the primary mode of transportation. As a result, multimodal transportation is not a serious option; it requires higher density than the sprawling cities allow. The use of HOV, HOT, and other managed lanes increases as commuters demand a highway option that provides reliable travel times. Some commuters use transit park-and-ride facilities, placed strategically along the largest highway routes.

In summary, in the 2040–2060 time frame, the government reasserts itself as a prime mover in the transportation world. STAs build more highways that facilitate additional geographic expansion. As a result, the demand for multimodal transportation is essentially nonexistent. The few cases that remain are facilities like park-and-ride lots or the use of managed lanes for transit priority.

12.5 Third Alternative Scenario - Meltdown

In the Meltdown scenario, the most pessimistic climate change projections end up being more accurate than the optimistic ones. As a result, the most important priority for the next few decades is struggling with nature rather than growing the economy. Potential implications of the Meltdown scenario for transportation connectivity are as follows:

- Strict policies on limiting greenhouse gas emissions increase the costs for operating an SOV, creating incentives for commuters to travel via public transit.
- City density increases as a result of policies discouraging carbon consumption.
- Social and political changes result in individuals wishing to consume goods produced locally, driving down the amount of freight moved across the country.

Following years of severe droughts, wildfires, intense storms, sea-level rise, and other ill effects of climate change, the United States decides to focus efforts on decreasing carbon emissions. Among the policies implemented, pricing carbon has among the most dramatic effects on all of society. The transportation area is no exception.

Pricing carbon increases the costs of driving for all motorists, even those driving electric vehicles since most electricity generation requires carbon-based fuels. As a result, motorists finally bear the external costs of driving that had not been charged under previous pricing systems. The increased costs reduce vehicle miles traveled and create strong incentives for motorists to use alternative transportation options.

Multimodal “green” transportation becomes a priority for many cities and STAs. These government agencies begin working in closer collaboration to provide feasible alternatives to the SOV that dominated the roads in the past. STAs and local governments dedicate more lanes to HOV and HOT lanes as carpooling becomes a normal practice. High-speed rail becomes a topic of great interest; many states begin investing heavily in its development and implementation. These states use high-speed rail as a means to connect cities to each other.

Denser cities create additional opportunities for multimodal transportation solutions. Greater density enables cities and STAs to operate successful transit systems in areas without previously established successful transit programs. Some cities and states begin replacing vehicle lanes and parking facilities with bicycle and pedestrian lanes.

Carbon pricing and social changes lead to a “local” revolution, with consumers placing a high priority on purchasing goods that are made locally. As a result, the amount of international freight decreases, and the world becomes a little less flat. Interstate and cross-country freight movement also decreases.

12.6 Identifying Potential for New Tools, Technology, and Approaches

After understanding the conditions and impacts, the next step is to identify the potential for new tools, technology, and approaches for each of the scenarios. Check marks in Table G.1 show how STAs may react to each scenario by adopting and/or developing new tools, technologies, and approaches.

Visual assessment of Table G.1 shows a high concentration of tick marks under alternative funding, future organizational structures, and workforce training. Accordingly, regardless of how the future turns out, these approaches have critical priority for STAs. Detailed examples for each column are provided as notes in the matrix of Table G.1.

Table G.1. Implications of the scenarios for STAs.

Multi-driver Scenarios	Tools			Technologies	Approaches		
	Managed Lanes	Dedicated Structures	Dedicated Truck Lanes	IT Integration and Standardization across Modes	Alternative Funding	Future Organizational Structures	Workforce Training
Baseline (Managed Decline)					✓	✓	✓
Bits over Buses		✓	✓		✓		✓
Government Redux				✓	✓	✓	✓
Meltdown	✓	✓	✓	✓	✓	✓	✓

Notes:

- *Managed lanes* refer to special-use lanes, such as HOV lanes, HOT lanes, or express toll lanes. Implementing managed lanes could also entail repurposing existing highway lanes for dedicated special use.
- *Dedicated structures* refer to supporting highway infrastructure for alternate mode use, including in-line rail or direct-access ramps for exclusive use by bus transit, carpools, trucks, or other user group.
- *Dedicated truck lanes* refer to new lanes built to serve large commercial vehicles or repurposed existing lanes for heavy vehicles.
- *IT integration and standardization across modes* refer to digital connectivity of operational functions such as traveler information, flow optimization, and fare/toll payment.
- *Alternative funding* covers topics related to nontraditional funding approaches, especially cross-modal subsidization
- *Future organizational structures* refer to consolidating highway administration, construction, and operations functions with those of alternative mode agencies to integrate modes more cohesively and achieve greater economies of scale. It also involves engaging the private sector in various business models to manage the development, deployment, operations, and/or maintenance of integrated modes.
- *Workforce training* refers to the next generation of the workforce trained for performing sophisticated tasks involving integrated modes and alternative organizational models for delivery and management of those systems.

12.7 Implications for State Transportation Agencies

Several important themes arise following a review of the future scenarios and impacts for connectivity.

Alternative Funding

The worlds of the future require strategic decisions for STAs when trying to fund our nation's transportation infrastructure and services. STAs should consider alternative funding and financing tactics as they attempt to provide acceptable levels of mobility and accessibility.

One of the first places STAs may consider for funding is the private sector. Reforming the traditional transportation revenue sources may take time and be politically difficult. Consequently, STAs need to find alternative options to maintain minimum levels of service. State and local governments could develop partnerships with financial organizations and private-sector transportation service providers to improve access to private capital. STAs could consider a greater use of toll roads and managed lanes to finance new construction or expansion projects. States should use caution when pursuing these options because the public has expectations about the proper balance between mobility expectations and financial impacts. The use of these tactics may require educational outreach about the state of the country's transportation funding.

STAs could also consider other nontraditional funding approaches. It is possible that the federal government will continue to use programs like the Transportation Infrastructure Finance and Innovation Act (TIFIA), and states could continue to use these as a source for project capital.

Some states may wish to pursue nontraditional funding from the public sector through increased user fees and general revenue sources, like sales taxes. User fees have an equity and economic advantage (depending on the form), but general revenues are better known and may be more politically acceptable.

States also may consider breaking down transportation mode funding silos. Traditionally, transportation funding is allocated through discrete channels, divided based on transportation mode. This can result in some transportation areas struggling, while others flourish. The elimination of these policies could make it easier for struggling modes to gain a foothold in localities.

If future transportation funding is entirely dependent on user fees, some modes will inevitably end up underfunded. States are unlikely to ever successfully monetize many transportation modes and services. To address this, states should consider diverting revenues from modes that generate sufficient revenues to those that do not. This subsidization would ensure programs that provide a social good, but not necessarily a monetary one, do not end up neglected.

Future Organizational Structures

When technologies and times change, organizations often must either adapt with the times or face obsolescence. Changing technologies and context will require STAs and local governments to rethink their operations and retool their workforce to meet the demands of the new world. Government agencies at large will need to become more flexible and nimble to address the evolving needs of modern society. Interagency collaboration is a skill STAs could focus on developing because future increases in collaboration with state and local government will require it.

Local governments will continue to take on greater roles in operating and managing the transportation infrastructure and services. Thus, STAs could develop their skills at sharing information and working with metropolitan planning organizations and local governments to improve service delivery. States could consider the efforts of leaders in the area, like those of California, at improving collaboration and integration. Areas that may require additional focus include digitally integrating operational functions like flow optimization, traveler information, and payment systems. Interoperability of computer systems is an area governments could consider focusing on because it is often a large barrier to intergovernmental collaboration.

STAs could also benefit from investments in the development of technical guidance, such as design and construction standards, for repurposing infrastructure to incorporate multiple modes.

The way Americans move is likely to evolve over the next 40–50 years. STAs will need to manage the transition from infrastructure that only services one type of traffic, to better-serving multiple modes.

Workforce Training

State and local government collaboration and integration will have ramifications for STAs' workforce composition and skill base. STAs could consider hiring or training employees to be well versed in a wide variety of transportation areas. STAs will likely end up overseeing many different transportation areas, and managing these areas will require managers with a diverse skill set and understanding of transportation modes. The managers need strong skills in interagency project management, clear and effective communication, and negotiation in difficult situations. The new business models STAs undertake will require hiring individuals with strong skills in legal, procurement, and project management.

12.8 Appendix G.1—Conditions and Impacts in the Baseline Scenario and Six Alternative Scenarios

Table G.1.1 summarizes the conditions in the six alternative scenarios. The reasoning was to understand what activities or efforts STAs would focus on to provide the necessary level of service to the public in connecting with other modes. This condition determined the type of technologies and techniques that STAs would develop to support intermodalism in an effective way. The specific impacts that each condition would generate on individual scenarios is summarized in Table G.1.2. Finally, other external conditions like environmental concerns will govern the development of new techniques and technology.

Table G.1.1. Summary of conditions in the baseline scenario and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	Meltdown
Funding and Focus	Limited funding. Limited modal integration opportunities.	More emphasis on new construction. No incentive to integrate other modes.	More emphasis on new construction. No incentive to integrate other modes.	Limited funding. Limited modal integration opportunities but high demand.	Construction of new transportation system as a result of economic growth and funding.	Less highway expansion. More focus on urban areas and integration with multiple modes.	Construction maintenance activities increase due to rapid climate change and urbanization.
Technology and Techniques	Inability to respond to demand may prompt private provision of alternate modes where economically feasible.	Integration would be motivated by technological and economic stimuli.	Integration would be motivated by technological and economic stimuli.	Integration would be motivated by technological and economic stimuli that would engage private sector.	Widespread application of technologies through vehicles and personal devices to support connected travel needs across modes.	Demand for urban services would prompt intermodal interests.	Use of highway infrastructure for alternate modes to address environmental concerns.
Mobility Demand	Aggregate demand for mobility increases, despite decreases in per capita demand.	Aggregate demand for mobility increases.	Aggregate demand for mobility increases.	Decreased aggregate demand for mobility.	Increased aggregate demand for mobility.	Decreased aggregate demand for mobility.	Decreased aggregate demand for mobility.
Mobility Capacity	Capacity slowly increases.	Capacity slowly increases.	Capacity slowly increases.	Capacity remains essentially static.	Capacity slowly increases.	Capacity remains essentially static.	Capacity decreases.
Population Density	Density slowly increases.	Density decreases.	Density decreases.	Density decreases.	Density decreases.	Density increases.	Density increases.

Table G.1.2. Summary of the impacts in the baseline and six alternative scenarios.

Driver	Baseline Scenario (Managed Decline)	Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	Meltdown
Funding and Focus	Maintenance, operations, and renewal.	Capital projects oriented to operations.	Expansion, operations, and maintenance.	Maintenance, operations, and small demand for renewal.	Capital projects oriented to operations.	Capital projects oriented to operations in urban core. Ongoing maintenance.	Maintenance, operations, and renewal.
Technology and Techniques	Potential private opportunities in limited market-driven situations.	No difference from baseline. Outside forces (political, economic, and technological) could influence greater alternative mode applications.	No difference from baseline. Outside forces (political, economic, and technological) could influence greater alternative mode applications.	Potential private opportunities in limited market-driven situations.	Opportunities sought for in-lane/special use lanes, separate structures for alternate modes, and conversion of highway lanes to maximize person throughput.	Opportunities sought for in-lane/special use lanes, separate structures for alternate modes, and conversion of highway lanes to maximize person throughput.	Environmental concerns necessitate in-lane/ special use lanes, separate structures for alternate modes, and conversion of highway lanes to maximize person throughput.
Mobility Demand	Increase in demand coupled with limited funding supports growth in alternative modes and private options.	Increase in demand coupled with limited new capacity supports growth in alternative modes and private options.	Growing demand able to be accommodated through traditional means. Less pressure for modal integration.	Declining demand leads to less pressure for modal integration.	Strong emphasis on integration with other modes to meet growing demand.	Cooperation with modal agencies to address demand through multimodal solutions, especially in urban core areas.	Less demand. Actions driven by environmental concerns rather than levels of demand.
Mobility Capacity	Shortage of capacity results in increased demand for connectivity. Private sector provides limited multimodal transport.	Government and private sector better positioned to provide multimodal services due to high connectivity demand.	STAs have additional funding and choose to focus on increasing traditional capacity, limiting demand for connectivity solutions.	STAs focus on providing connectivity for transporting physical goods. Demand for personal transportation diminishes.	STAs and private entities focus on providing connectivity capacity in areas with high density.	Limited capacity in highly dense areas supports multimodal renaissance. STAs and private providers take a leading role in providing multimodal transportation.	Decreased demand for mobility and decreased capacity supply create society with higher demand than supply, resulting in shortage and congestion.

Driver	Baseline Scenario (Managed Decline)	Back to the Future	Government Redux	Bits over Buses	Many Ways to Go	Escape to the Centers	Meltdown
Population Density	Increase in density supports transit and nonmotorized modes and need for integration.	Decreased density reduces ability of STAs and private entities to provide multimodal services. They focus on connectivity for goods transport instead.	Decreased density reduces ability of STAs and private entities to provide multimodal services. They focus on connectivity for goods transport instead.	Decreased density and interest in transportation reduce need for multimodal transportation. STAs focus on providing connectivity for goods transport instead.	Decreased density reduces need for multimodal transportation. STAs focus on providing connectivity for goods transport instead.	Increases in density support transit and nonmotorized modes and need for integration.	Increase in density supports transit and nonmotorized modes and need for integration.