The Role of Research in Improving Infrastructure:
An Analysis of U.S. Transportation Research & Development

by

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B.S. Civil Engineering
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Submitted to the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Technology and Policy

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Abstract

Infrastructure systems are central to quality of life and economic competitiveness in nations worldwide, but daunting challenges stand in the way of providing systems capable of delivering needed infrastructure services. In the United States, the transportation system, which is widely considered to be the nation’s largest infrastructure system, provides a case study of the complex investment, design, and operations-related problems of infrastructure service provision. An effective and efficient research and development (R&D) system is needed to support the search for solutions to these problems; the nation is served by a large and well-developed transportation R&D system, but given the magnitude of outstanding needs for new technologies, systems, and policies and the persistence of resource shortfalls, it is appropriate to re-examine all aspects of the transportation R&D enterprise in search of strategies for improving its performance.

This thesis identifies and analyzes factors that influence the performance of the transportation R&D system and how it can respond to emerging infrastructure challenges. It first discusses categories and characteristics of infrastructure and seeks to place analysis of infrastructure systems, like the transportation system, in a broader socio-economic and environmental context. The thesis then outlines the basic composition of the transportation research and development system and explores the policy environment and critical issues that influence both transportation R&D challenges and the behavior of the system in response to those challenges. Data on transportation R&D expenditures, including longitudinal data for the sector as well as limited cross-sectoral comparisons to place it in context, is presented. Finally, examination of issues (like coordination and integration) related to the structure of the R&D system, is included to frame the prior analysis of expenditures within a broader range of potential strategies for improving the efficiency and effectiveness of the transportation R&D system.

Thesis Supervisor: Fred Moavenzadeh
Title: James Mason Crafts Professor of Civil and Environmental Engineering and Engineering Systems
DEDICATION

This thesis is dedicated to my mother, Esther Frazier, whose support and steady faith in me have been invaluable sources of strength, and to my late father, Terry Frazier, a man whose reasoned advice, commitment to service and community, and high standards of professionalism and achievement have, even after his passing, been a source of inspiration and determination in this endeavor.
ACKNOWLEDGEMENTS

I would like to express my appreciation to a number of individuals at the Massachusetts Institute of Technology to whom I am indebted for support and assistance in completing this project. I owe many thanks to Professor Fred Moavenzadeh for his service as my thesis supervisor. He has given generously of his time to provide scholarly guidance, constructive criticism, and professional encouragement throughout my time at MIT, and I have benefited immeasurably from the deep knowledge of the engineering and construction industry and civil engineering systems that he has shared. I am also grateful to Patricia Vargas, Danielle Severino Atwell, Susan Cass, and Jennifer Peterson at the Technology and Development Program for their friendship and assistance navigating MIT and keeping this project moving in numerous ways—large and small, direct and indirect—over the past several years. At the Technology and Policy Program, I owe thanks to all the staff, especially Sydney Miller, who has been a wonderful resource and friend since I arrived at MIT. Many other individuals have assisted me along the way as well. Professors Joe Sussman and Karen Polenske and Dr. Kirk Bozdogan have each taken time to provide comments, advice, or encouragement on various pieces of the work reported in this thesis, and Dr. Ann Brach at the Transportation Research Board provided invaluable help obtaining data on federal transportation research budgets. Finally, I thank my friends and officemates for their steady friendship and the many good times we have had together, and I thank my family for their love, support, and understanding along this journey.
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CHAPTER 1: INTRODUCTION

The United States’ economic competitiveness and the quality of life of its citizens depend, in part, on the existence of a well-functioning set of infrastructure systems providing services in sectors like energy, water, communications, and transportation. Over the course of its expansion and development from a fledgling union of newly independent colonies to a global economic and political power over the past two centuries, the United States has built and operated a vast stock of these systems: canals, locks, and other inland navigation aids; railroads and rail yards; water supply and sewerage infrastructure; telegraph and telephone lines; electric transmission and distribution networks; airports and seaports; and the Interstate Highway System. The nation today is more reliant than ever on the services provided by infrastructure systems such as these, yet there is wide concern that years of underinvestment—or simply ineffective investment—may threaten the ability of these systems to meet the demand for their services.

The U.S. transportation system, its largest infrastructure system, is under strain—coping with aging physical infrastructure, chronic congestion and capacity constraints, and limited financial resources to address these problems; and decision-makers at all levels are facing pressure to institute changes that will improve the performance of this system. (See, for examples of proposed reforms, Ehrlich and Landy 2005; Transportation Research Board 2006; Transportation for Tomorrow 2007; Doshi, Schulman et al. 2007; ASCE 2009; and Schrank and Lomax 2009.) The transportation system, however, is vast, complex, and open; its boundaries are difficult to define, and the relationships among its many components are not fully understood. As a result, the system’s behavior is difficult to predict, compounding the problem
of devising and implementing solutions to the critical issues it faces. In helping to bridge the knowledge gap and overcome these challenges, transportation research and development (R&D) activities can play an indispensable role. Indeed, although the multi-stage nature of innovation processes dictates that building knowledge through research could never by itself be a sufficient condition for improving the performance of the system (ultimately someone must also put that new knowledge to use in practice), it is quite conceivable—indeed, quite likely—that increasing knowledge and searching for new solutions through R&D will be necessary activities if the transportation system is to meet, successfully and affordably, the demands imposed on it.

The transportation R&D system is well-established, consisting of both academic, public-sector, and private-sector entities that compete and collaborate in a market for research that is heterogeneous and decentralized (Transportation Research Board 2009a). In this market in the United States, sums in excess of one billion dollars are spent each year on transportation-related R&D activities (Brach 2005). These expenditures are, by definition, investments consciously directed toward increasing “our understanding and [discovering] new and better ways to achieve our goals” in the transportation sector, suggesting that they have a critical role to play in providing needed knowledge and solutions (Lemer, Chong et al. 1995). Considerable disagreement about the adequacy of this investment exists. The Transportation Research Board (TRB) has argued that, “Greater investment in innovation can provide the breakthroughs, the new ideas, and the creativity that are so urgently needed” (Transportation Research Board 2006), but reliable and complete information on current and past patterns of investment in transportation R&D is not systematically tracked or compiled (Brach 2005). (The latter point is especially applicable when the full, decentralized, and largely uncoordinated range of transportation R&D sponsors and performers is considered, but it applies as well even within the federal government,
which is the largest sponsor of such research.) On the other hand, critics like Representative David Wu, Chairman of the Subcommittee on Technology and Innovation of the U.S. House of Representatives’ Committee on Science and Technology, have challenged the need for and/or practicality of additional R&D investment, stressing instead the potential to improve results by better utilizing existing resources. Chairman Wu explained his position during a hearing on transportation reauthorization priorities and related R&D activities in February 2009, stating:

In reviewing some of the Transportation Research Board’s recent assessments of our surface transportation investments, I have been disappointed by their recommendations that focus on increased funding as the means to overcome the challenges they identify, including slow technology transfer and a lack of clear national priorities in DOT’s R&D spending. I don’t think more money is a practical or realistic recommendation in our current economic environment. What I hope to learn today, and in this series of hearings, is how to make our federal investments in surface transportation R&D as effective and efficient as possible…. (An Overview of Transportation R&D 2009)

There can be little doubt that meeting transportation challenges in the United States will require renewed investment in the system, including in research and development. However, the nature of this investment will be as crucial as its magnitude in determining its ultimate effect. As suggested above, recent national transportation policy debates often have focused on financial resources as the primary variable with which to influence the system, but spending more provides no guarantee of better results, especially in the realm of R&D. Research is an inherently risky and uncertain endeavor, compounded in this case by the complexity and openness of the research challenges necessary to address the systems-level issues driving the transportation and infrastructure agenda. In this thesis, we utilize investigation of the challenges of infrastructure provision as a broad point of departure and seek more narrowly to understand
the role of investment in infrastructure research and development (R&D) in contributing to solutions to these challenges within the context of the transportation system, the nation's largest critical infrastructure system.

1.1 Purpose and Motivation for Research

Because of the pervasiveness of infrastructure systems—including society’s widespread dependence on their services and the large magnitude of their direct and indirect environmental impacts, the stakes associated with these challenges are high. The National Research Council’s (NRC) Board on Infrastructure and the Constructed Environment has framed the issue well, stating that, “How we as a nation choose to renew our infrastructure systems in the coming years will help determine quality of life for future generations. It will also help determine our success in meeting other national challenges, including those of remaining economically competitive and reducing our dependence on imported oil, and of dealing with issues related to global climate change, national security, and disaster resilience” (National Research Council 2009). Another report frames the issue even more bluntly, stating, “The [United States] faces a stark choice – either avert its slide from prosperity through greater investment and innovation [in transportation and infrastructure] or hurtle into more gridlock, congestion, and potential systemic failure” (Infrastructure 2009: Pivot Point 2009).

The same NRC report notes, however, that “Renewing and restructuring some of the nation’s critical infrastructure systems to meet some of the important challenges of the 21st century constitutes a task radically different from that of building new systems across undeveloped territory” (2009). As this suggests, past approaches—including not only technologies but also the systems in which they are used and the policies that govern them—may be poorly suited for meeting current and future challenges in infrastructure sectors. The resulting
innovation imperative in turn suggests a significant opportunity for infrastructure systems-related R&D to provide the new knowledge and ideas with which solutions to these challenges can be devised.

Many shortcomings in the services delivered by the operational transportation system are well-documented and generally accepted – in aggregate if not in detail, but the efficacy of the transportation R&D enterprise is much less well-understood. Motivated by this gap in knowledge, the purpose of this thesis is to contribute to a better understanding the effectiveness of transportation research and, by extension, infrastructure R&D more generally by critically examining structural characteristics of the system as well as data on past research investments.

1.2 Problem Statement and Objectives

The nation’s transportation and infrastructure systems must adapt to meet dynamic, evolving needs placed on them, and they must do so in an environment characterized by serious limitations on available resources, especially financial capital. Research and development activities are relied upon to generate solutions to these challenges, but as with elsewhere in the system, deployment of R&D resources must prove both effective (successfully addressing salient challenges) and efficient (providing the greatest benefit possible for a given level of resource inputs). Within that context, this paper explores the following research questions:

1) How much is spent annually on U.S. transportation research and development and, to provide context, how does this compare to research and development expenditures in other sectors of the economy?

2) What structural factors in the transportation research and development system influence the performance of the system?
Using these questions as guides, the objective of this thesis is to identify and analyze factors that influence the performance of the transportation R&D system and how it can respond to emerging infrastructure challenges, which were briefly outlined above. Seeking to formulate definitive, complete answers to the research questions would be unrealistic, but it may be possible to provide a better foundation for future policy and investment decisions by improving the state of knowledge about the performance of the transportation research enterprise—even if the gains are incremental and incomplete. Accordingly, the paper is intended to provide a first step toward establishing an improved, data-based foundation for R&D investment decisions and to contribute to a better understanding of how factors like levels of R&D investment, R&D coordination, and R&D scope (or integration) contribute to the effectiveness of the U.S. transportation R&D system.

1.3 Research Approach and Methodology

The approach used to investigate these questions is best described as exploratory data collection and trend identification and includes logical integration of both quantitative and qualitative data. To answer the first question listed above, an ideal data set would contain comprehensive data on R&D expenditures in multiple economic sectors made by all sponsors—public and private—of these activities and would include present-year expenditures as well as historical data for the past thirty years or more (to enable examination of the effects of the landmark 1991 Congressional surface transportation legislation, the Intermodal Surface Transportation Efficiency Act, known as ISTEA, as well as subsequent reauthorizations). Because of significant gaps in transportation R&D investment data availability and accessibility, time and resource constraints dictate a more practical goal: to identify, compile, and analyze the data that is accessible within those constraints, with the objective of assembling enough data to
begin forming a basis for understanding historical trends in transportation R&D investments and how those levels of expenditure compare to other economic sectors.

The R&D expenditures data referenced in this report come primarily from four sources and are heavily concentrated on the federal component of transportation R&D investment. The National Science Foundation, through its Science and Engineering Statistics program, annually collects and publishes data on federal funding for research and development. The American Association for the Advancement of Science (AAAS) supports an R&D Budget and Policy Program that also compiles information on federal support for research and development. These sources are useful for gathering data on transportation-related R&D support across the federal government, while budget data from the U.S. Department of Transportation (USDOT) provides another source of data on USDOT spending on R&D. For data that places transportation R&D spending in a broader context, this paper draws on comparisons published by the Transportation Research Board in the context of its reviews of federal highway research.

1.4 Organization and Scope of this Document

The remainder of this paper analyzes the effectiveness of the transportation research and development system in the United States and, drawing on this analysis, discusses the role that R&D can play in providing solutions to current infrastructure challenges. Chapter 2 provides background information on infrastructure systems with a particular focus on the transportation system. It discusses categories and characteristics of infrastructure and seeks to place analysis of infrastructure systems, like the transportation system, in a broader socio-economic and environmental context. Chapter 3 outlines the basic composition of the transportation R&D system and explores the policy environment and critical issues that influence both transportation R&D challenges and the behavior of the system in response to those challenges. Chapter 4
presents data on transportation R&D expenditures, including longitudinal data for the sector as well as limited cross-sectoral comparisons to place it in context. In Chapter 5, the focus shifts from analysis of the R&D expenditures data to examination of issues, like coordination and integration, related to the structure of the R&D system. Chapter 6 offers tentative conclusions about the efficacy of the transportation R&D system and possible ways to improve it.
CHAPTER 2: TRANSPORTATION & INFRASTRUCTURE BACKGROUND

To lay the groundwork for later analysis of research and development in the transportation system, this chapter provides a basic, conceptual overview of infrastructure systems and frames discussion of the transportation system as an example of such an infrastructure system. It seeks to answer, or at least to address, two basic questions: 1) what is infrastructure (in the context of civil engineering systems), and 2) what is a transportation system and (how do transportation systems relate to infrastructure systems)?

2.1 An Overview of Infrastructure

The term “infrastructure” is used to describe a wide range of facilities and systems, and no single definition of the concept—or demarcation of its boundaries—is widely accepted. Frischmann (2005) captures the most common meaning, writing that the term “generally conjures up the notion of physical resource systems made by humans for public consumption,” yet he and others have argued for an even broader definition of infrastructure which would include certain natural resource systems that provide “infrastructure services” in a way similar to traditional, human-made infrastructure systems. For example, Allenby (2004) notes that, “Systems that are considered ‘natural,’ ranging from the elemental cycles of carbon and nitrogen to the hydrologic cycle, are increasingly integrated with [traditional] infrastructure systems;” and he argues that, because of this integration, it is growing more difficult for engineers to answer the question, “What is infrastructure?” This question surely will remain challenging to answer as awareness of the interdependencies among built environment systems and natural environmental systems continues to grow among infrastructure scholars and practitioners alike. Setting aside such (primarily academic) debates for now, however, the venerable dictionary can provide
guidance on the most essential meaning of the word: infrastructure is simply, “the underlying framework or basic foundation (as of a system or organization)” ("Merriam-Webster" 2009). Many such frameworks – both abstract and physical - form the foundation of modern societies; these frameworks include economic and financial infrastructure, social infrastructure, and physical infrastructure systems. As already noted in this document, the concept of physical infrastructure systems commonly includes transportation networks, electricity transmission and distribution systems, water supply and sewage utilities, and telecommunications networks.

In recent years, infrastructure--distinguished by its economic characteristics, which will be discussed in the next section of this document--has emerged as a distinct asset class for private investors, a development providing one lens for classifying different types of infrastructure. As Figure 1 shows, the “traditional” categories of transport, energy and utilities, and communications infrastructure are typically accompanied in investment-based classifications by a category of “social infrastructure,” which includes facilities such as universities and schools (educational infrastructure), hospitals (health care infrastructure), public housing, and others. Investors seek out these types of assets because of perceived desirable likenesses in their investment characteristics, notably the ability to generate stable, long-term cash flows and returns from mature infrastructure assets, an attribute that has drawn many pension funds into this market sector (Investing in Global Infrastructure 2007). Not all of these asset types, however, share the core economic characteristics of traditional, network-centric infrastructure systems, as will be discussed in Section 2.1.2. In the context of this thesis, the term infrastructure will refer primarily to those network-centric systems: transportation, energy and water utilities, and communications.
### Figure 1: Infrastructure Categories (from a Private Investment Perspective)

Source: (Investing in Global Infrastructure 2007)

#### 2.1.1 Infrastructure Types

Just as no single definition of infrastructure exists, so no widely-accepted typology of infrastructure systems exists; but one basic classification based on function and form (or architecture) is presented here to establish a basis for discussion of infrastructure systems within this paper. As Figure 1 suggests, infrastructure systems can be broadly grouped by function into:

<table>
<thead>
<tr>
<th>Economic Infrastructure</th>
<th>Social Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>Universities</td>
</tr>
<tr>
<td>Roads</td>
<td>Schools</td>
</tr>
<tr>
<td>Bridges</td>
<td>Hospitals</td>
</tr>
<tr>
<td>Tunnels</td>
<td>Prisons</td>
</tr>
<tr>
<td>Airports</td>
<td>Sports stadiums and facilities</td>
</tr>
<tr>
<td>Rail systems</td>
<td>Convention centers</td>
</tr>
<tr>
<td>Seaports and shipping</td>
<td>Public housing</td>
</tr>
<tr>
<td>Cargo &amp; logistics centers</td>
<td>Community facilities</td>
</tr>
<tr>
<td>Urban mass transit</td>
<td></td>
</tr>
</tbody>
</table>
two categories: economic and social infrastructure. Within the category of economic infrastructure, systems can be grouped into those for transportation, for energy and utilities, and for communications. It is important to note that the distinction between economic and social infrastructure systems presented here does not imply that there is no cross-over functionality in these systems, as nearly every infrastructure system makes some contribution to both economic and social goals. For instance, water supply systems facilitate commercial activity, but the primary service they provide—clean water—is arguably as much a social service (contributing to sanitation and public health) as it is an economic one. To the categories of economic and social infrastructure systems might be added one more: national security infrastructure (e.g., defense facilities and installations as well as border security systems). National security infrastructure, too, may serve more than one high-level function.\(^1\) For instance, the U.S. interstate highway system is a vital facilitator of commerce, but its official name, the Dwight D. Eisenhower System of Interstate and Defense Highways, belies its intended role as not only an economic asset but also a portion of the national security infrastructure. Adding a second dimension—based on a binary specification of the architecture of these systems as either network-based or stand-alone facilities—completes the classification framework by generating a simple, two-fold typology of form and function, as shown below. (National security is included in the figure as a grayed-out functional class to highlight the fact that, although economic and social classifications are most

\(^1\) Including national security infrastructure in the typology as a functional category is not without analytical problems; for instance, communications systems used exclusively by the national security sector are clearly part of the national security infrastructure, yet they could, looking at the sub-categories of economic infrastructure, quite understandably be classified as communications infrastructure. Thus, in classifying a system, it is necessary to rely first on the broad categories—economic, social, or national security infrastructure—and only then consider subclasses.
common in the literature, it is possible to identify other functional roles into which infrastructure systems may be grouped.)

<table>
<thead>
<tr>
<th>Function</th>
<th>Economic</th>
<th>Social</th>
<th>National Security, etc.?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network-based system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stand-alone asset</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: A Simple Infrastructure Systems Typology

Network-based infrastructure systems include transportation, telecommunications, electricity and gas transmission, sewerage, and water supply and distribution systems. The characteristics of any given component of a network infrastructure system typically are relatively well understood, and performance of an individual component can be predicted with reasonable accuracy. Generally speaking, complexity of a network system and uncertainty about its performance increase with the number of interconnecting links, the density of development, and the degree of capacity utilization (Moavenzadeh 2002). The difficulty of planning, designing, and managing network-based infrastructure systems also tends to increase in line with these factors.

The second basic infrastructure form is the stand-alone facility or system. Examples include power plants, waste-water treatment plants, and facilities like schools and hospitals. As the label “stand-alone” suggests, these types of infrastructure assets can be analyzed independently more easily than network-based systems. Large-scale, stand-alone infrastructure assets often exhibit considerable internal integration and complexity, and design and construction of all their components must be fully completed before any element can begin generating value.
Network-based infrastructure systems, by contrast, often can be expanded incrementally, rather than requiring large, discrete investments (Moavenzadeh 2002.).

2.1.2 Economic Characteristics of Infrastructure

The two axes of the typology presented above clearly suggest that infrastructure may be defined by both physical and functional characteristics. Engineers often tend to specialize in one infrastructure sector (e.g., transportation) and think of that infrastructure first in terms of its physical form and technical function, but a considerable body of economic literature has been devoted to the study of infrastructure defined by its functional role in the production, distribution, and consumption of goods and services— that is, it is possible (and helpful) to use economic characteristics of infrastructure systems to distinguish physical infrastructure systems from other physical assets.

Prud’homme (2005) identifies six economic attributes that can be used collectively to define infrastructure systems, although he cautions that they should be viewed as a loose definition rather than a precise and complete one. He further notes that using these attributes to characterize infrastructure excludes most “social infrastructure,” arguing that the services provided by social infrastructure are typically due more to the labor input to those systems than to the physical infrastructure assets themselves; the result, placing the emphasis of the definition on ‘economic’ physical infrastructure systems, is consistent with the focus of this thesis. (For “economic infrastructure,” in contrast to social infrastructure, labor inputs may be required but are not a primary determinant of service quality, which is instead determined mostly by the “infrastructure” input (Prud’homme 2005).) The six attributes are:
1. Infrastructure systems are *capital goods*, which are goods used to produce other goods and services rather than for immediate, direct consumption. For instance, the transportation system is composed of capital assets, like roads and bridges, which are combined with rolling stock, labor, and other inputs to provide economic services (e.g., mobility). A corollary to this attribute is that the value associated with infrastructure systems is created primarily by the services they enable or provide rather than being embodied in the infrastructure assets themselves. Consequently, Prud’homme argues that, “[infrastructure] policies should focus on the end, service provision, not on the means, infrastructure endowment” (2005). Because infrastructure services are capital intensive, the correlation between means and ends may often be close, but the distinction between the two is vital to understanding how to design and manage infrastructure systems for optimal service provision.

2. Infrastructure systems typically require *lumpy*, rather than incremental, investment profiles. It was earlier noted that stand-alone infrastructure facilities must usually be fully completed (at a large, up-front construction cost) before they begin delivering services or generating any return on investment. Network-based systems, which may often be relatively easier to expand incrementally, still require large, lumpy investment at the time of initial build-out, and subsequent required outlays for maintenance and repair or replacement generally are lumpy as well.

3. Infrastructure systems are *long-lasting*, with expected service life often on the order of decades (and sometimes longer). For instance, the USDOT reported in 2006 that, “Bridges in the national inventory are, on average, 40 years old, with an average year of construction of 1964. Urban structures are slightly younger than rural structures, with an
average year of construction of 1968” (USDOT 2006a). More dramatically, Prud’homme notes that, in Europe, there are still isolated instances in which roads built centuries ago by the Roman empire are in use (2005). Infrastructure systems not only respond to demand for their services at the time of construction but also shape the future demand for similar services. Given continuing demand, when a particular asset or facility becomes obsolete or otherwise unable to deliver desired services, it will likely be replaced by another asset designed to support similar services. Thus, planners and designers of infrastructure systems must be cognizant of the consequences of design decisions at multiple time scales; the design of a particular facility may have direct consequences for several decades or longer (during the design/service life of that facility), but the broader systems-level impact of the decision to provide infrastructure in a certain location (see attribute #4 below) will almost certainly be even longer lasting.

4. Physical infrastructure facilities are generally immobile or location-specific. Once a facility is constructed in a given location, it may be impossible or, at the very least, impractical to relocate it at some future time, with the result that the value of the services delivered by that infrastructure (and thus of the infrastructure itself) depends in large part on a facility-siting decision made at the beginning of the asset’s lifecycle. (Recall from above that the time scale for this lifecycle is often measured in decades.)

5. Many infrastructure systems are closely associated with market failures, so they are typically delivered and administered with heavy involvement by the public sector. Prud’homme identifies the general market failure problems of public goods, (network and other) externalities, and natural monopoly as the primary justifications for public intervention in infrastructure provision and operation (2005). Referencing, implicitly, the
public goods and network issues associated with infrastructure systems, Steinmuller, quoted in Frischmann (2005), offers the following comments on the economics of infrastructure:

Both traditional and modern uses of the term infrastructure are related to ‘synergies’, what economists call positive externalities, that are incompletely appropriated by the suppliers of goods and services within an economic system. The traditional idea of infrastructure was derived from the observation that the private gains from the construction and extension of transportation and communication networks, while very large, were also accompanied by additional large social gains....Over the past century, publicly regulated and promoted investments in these types of infrastructure have been so large, and the resulting spread of competing transportation and communications modalities have become so pervasive, that they have come to be taken as a defining characteristic of industrial nations. (Steinmuller 1996)

Models for financing, delivery, and management of infrastructure systems have a direct effect on the socio-economic efficiency of those systems (Prud’homme 2005), and the refining of relevant institutions and the re-allocation of roles and responsibilities for infrastructure provision among various public- and private-sector actors has been an ongoing activity worldwide for several decades. (Prud’homme notes that, “Because infrastructure always has a government dimension and can also have a private dimension, the menu of institutional options available is quite large: from direct government provision...to unsubsidized concessions” (2005).) Generally, it may be said that traditionally-heavy reliance on the public-sector-led provision--and often public delivery--as the solution to market failures is being slowly replaced by emerging public-private partnership models and other mechanisms that seek to increase the level of private participation in infrastructure in response to shortcomings (e.g., financial, managerial, etc.) in the public-delivery paradigm, but, despite these trends, the public sector’s role in infrastructure provision, redefined though it may be, is likely to remain quite strong.
6. Finally, the services provided by infrastructure systems are *consumed by both households and enterprises*. In economic terms, then, infrastructure is both a final consumption item and an intermediate consumption good. Prud’homme states that the intermediate consumption role of infrastructure (increasing productivity) generally tends to be greater than its final consumption role (directly increasing welfare), noting that research on French infrastructure services in 2001 showed that household or final consumption of infrastructure services accounted for one third of the total value of services provided (2005).

2.1.3 **Infrastructure in a Broader Context**

Infrastructure systems do not exist in isolation as technological artifacts; rather, they are an enabler of a wide range of human activities. As part of the built environment, infrastructure systems exist at the intersection of the social (or socioeconomic) system, the natural system, and the technological system. (This intersection of systems is illustrated in Figure 3.) Demand for infrastructure services (and, thus, infrastructure systems) arises from within the socio-economic system, which is also responsible for providing the regulatory framework for provision of the infrastructure systems needed to meet this demand. This system includes as well the economic activities which mobilize resources for building, operating, and maintaining infrastructure. The natural system serves two functions, as both a source and a sink. As a source, the natural system provides the physical inputs to infrastructure systems: land and raw materials, such as iron ore for the production of steel; petroleum for asphalt binders; and sand, stone, and gravel for concrete aggregate. As a sink, the natural system must absorb the waste and other environmental effects of infrastructure construction, operation, and eventual decommissioning or abandonment. Finally, the technological system provides the knowledge and tools with which the demand for
infrastructure, arising from the socio-economic system, is satisfied within the constraints imposed by the natural and socio-economic systems (Moavenzadeh 2002).

Within the socioeconomic system, demand for infrastructure derives from its value for two broad objectives: economic competitiveness and socio-economic development. Infrastructure systems contribute to development through impacts on both households and enterprises. Prud'homme (2005) identifies three main mechanisms behind these impacts: improving welfare, enlarging markets, and lowering costs. Water supply and sewerage create positive public health and welfare effects through their contribution to sanitation; power supply and access to transportation services similarly raise welfare for households. Infrastructure can facilitate trade by enlarging and connecting markets, and it can reduce barriers to the flows of goods, labor, and ideas. Finally, economists view infrastructure as a subset of the capital stock and as a factor in the cost of production for firms; efficient infrastructure systems reduce production costs for the enterprises that utilize their services. This last point not only affects socioeconomic development but also serves as the basis for infrastructure’s role in theories of
economic competitiveness. The quality of a city, state, region, or nation’s infrastructure systems affects the attractiveness of that jurisdiction for potential investors, businesses, and residents—a fact reflected in the economic development policies of governments worldwide.

Figure 4: Dimensions of Sustainability  
Source: (World Bank 1996)

Infrastructure’s location at the intersection of the socioeconomic, natural, and technological systems also highlights the importance of considering both socioeconomic and environmental impacts when responding to demand for infrastructure services. It has been proposed that using sustainability as an overarching design goal for infrastructure systems can provide a mechanism for balancing infrastructure’s effects on these two systems, minimizing environmental impact without unduly constraining economic growth. In this context, sustainability is a broad concept encompassing not only environmental sustainability but also dimensions relating to economics, politics, and social equity (Roos, de Neufville et al. 2004) as shown in Figure 4 and articulated by the National Research Council’s Board on Infrastructure and the Constructed Environment: “Sustainability is broadly defined to mean systems that are able to meet the needs of current and future generations by being physically resilient, cost-effective, environmentally viable, and socially equitable” (2009).
2.2 Key Characteristics of the U.S. Transportation System

The U.S. transportation system is generally considered the nation's largest infrastructure system, and vast networks of physical infrastructure underpin the broader system, which includes rolling stock and control systems as well as guideways and associated physical infrastructure. The nation's 300 million residents have access to approximately four million miles of public roads, including over 45,000 miles of Interstate highway. (The scale and scope of the nation's highway systems are graphically illustrated in Figure 5 below.) More than 5,000 public-use airports; nearly 100,000 miles of mainline railroads; 26,000 miles of navigable waterways (served by thousands of shallow-draft and deep-draft terminals or ports and an extensive system of locks, dams, levees, and other navigational aids); hundreds of thousands of miles of oil and natural gas pipelines, and several thousand miles of urban transit or commuter rail lines complete the physical transportation infrastructure network—a network that is clearly consistent with the economic characteristics of infrastructure outlined above (Bureau of Transportation Statistics 2009).

The transportation system, however, is more than a stock of expensive physical networks; it is a multi-dimensional and complex socio-technical system, with those physical networks at its core. Sussman (2000) identifies three dimensions that are useful for understanding transportation systems: technology, systems, and institutions. Technology refers to elements such as vehicles, fuels, guideways (e.g., highways and railroads), methods of propulsion, and guidance and control systems. In the systems dimension, technologies are combined to deliver transportation services, and supply and demand for these services interact with each other to produce flows over transportation networks. According to Sussman, the institutional dimension of the transportation system (which is similar to the 'policies' dimension referenced later in this
document) includes both the organizations that deploy and operate transportation networks and
the rules and procedures that govern the provision of transportation facilities and services (2000).
At the federal level, the U.S. transportation system is overseen by the U.S. Department of
Transportation (USDOT), although other federal agencies engage in some transportation-related
activities, including transportation-related R&D. There are eleven operating administrations
under the Office of the Secretary in the USDOT. These are largely organized according to
transportation modes and include the Federal Aviation Administration (FAA), the Federal
Highway Administration (FHWA), the Federal Motor Carrier Safety Administration (FMCSA),
the Federal Railroad Administration (FRA), the National Highway Traffic Safety Administration
(NHSTA), the Federal Transit Administration (FTA), the Maritime Administration (MARAD),
the Saint Lawrence Seaway Development Corporation (SLSDC), the Research and Innovative
Technologies Administration (RITA), the Pipeline and Hazardous Materials Safety
Administration (PHMSA), and the Surface Transportation Board. State transportation agencies
own and manage many of the facilities and infrastructure assets in the national transportation
system (particularly the nation’s highways), and local government transportation agencies play
an important role in the system as well. Increasingly, agencies are being formed for
transportation planning and management at the regional level—combining multiple localities in a
metropolitan area and/or spanning multiple states, a trend that reflects the importance of

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2 The United States Coast Guard and the Transportation Security Administration were under USDOT
authority until March 1, 2003, when the Homeland Security Act of 2002 transferred them to the new
Department of Homeland Security.
matching transportation institutions with the geographic scales and areas at which demand arises rather than relying solely on the jurisdictional boundaries formed by existing political divisions.

Understanding the relationships among the various system dimensions and components is necessary for transportation analysis, management, and policy-making. The network-centric nature of transportation has long drawn attention to the interconnections among different transportation assets, and systems-focused analysis is well entrenched in the transportation sector. Generally speaking, five levels of analysis (listed in order of increasing scope) are possible: component, modal subsystem, modal system, multi-modal system, and enterprise-level analysis (Skinner Jr. 2009). Most emphasis to date has been placed on components, modal subsystems, and modal systems; and the dominance of modal systems (e.g., highways, railroads,
and passenger airlines) has been widely institutionalized. For instance, although the USDOT originally was intended to provide cross-cutting institutional leadership for integrated oversight and management of transportation issues in the United States, the political power of modal agencies—which pre-existed the cabinet-level transportation department—was preserved when the USDOT was created in 1967 (Hazard 1988). The individual modal agencies (e.g., Federal Highway Administration, Federal Aviation Administration, and Federal Railroad Administration) today remain important centers of power at USDOT. Within the transportation research community, increasing emphasis is being placed on multi-modal and, to a lesser extent, enterprise-wide analysis, but the tools and knowledge needed for analysis and management at these levels are not yet fully developed (Skinner Jr. 2009).

The relatively low level of analytical emphasis on fully-integrated multi-modal and enterprise-wide aspects of transportation helps to perpetuate an existing system state characterized by segmentation and decentralization along multiple dimensions. On one such dimension, both in research and in practice, the system’s organization along modal divisions not

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Figure 6: Possible Scopes of Analysis for Transportation Systems
Source: (Skinner Jr. 2009)
only creates useful concentrations of expertise within modal organizations but also raises potential barriers to holistically addressing inter-modal, multi-modal, and system-wide challenges, which are rising in importance. On another dimension, the federal nature of the U.S. political system segments the system into multiple layers of public authority: the U.S. federal government, state governments, local and city governments, and some mixed jurisdictions, like agencies with regional or metropolitan-scale authority. The federal government ultimately oversees national transportation networks, but most infrastructure networks themselves are owned and operated by state or local agencies (or by the private sector).

Furthermore, the system often is additionally divided into organizations with expertise in or authority over guide ways and infrastructure, vehicles and rolling stock, system operations, and other functions. Some degree of decomposition of system complexity and division of responsibility or expertise is logically necessary to reap the benefits of specialization – or simply to make certain tasks or problems tractable – but too much segmentation can be detrimental to the system as a whole, tipping the balance from useful segmentation to harmful fragmentation. (An additional dimension of segmentation is professional divisions between planners, designers, builders, operators, and other functional groups.)

Consistent with the “Infrastructure in a Broader Context” discussion above, the transportation system—itself a complex, sociotechnical system as noted above—exists within similarly complex socio-economic, political, and natural environmental contexts. Transportation is one of the largest sectors of the U.S. economy; according to data from the Bureau of Transportation Statistics, approximately $1.45 trillion of 2007 U.S. gross domestic product (GDP) can be attributed to the production of transportation-related goods and services (which equates to 10.5% of the total GDP, $13.81 trillion) (Bureau of Transportation Statistics 2009).
The demand for transportation services is derived from activity in other sectors of the economy, and the availability and efficiency of transportation infrastructure services affects factors like the costs of conducting commerce and associated patterns of social and economic activity.

The nation’s legacy transportation system is the result of two centuries of transportation infrastructure development, and the capital stock embodied in the system is massive. The Congressional Budget Office (CBO) reports that public expenditures on water and transportation infrastructure annually have accounted for over two percent of U.S. gross domestic product since the 1950s, and the transportation sector receives the largest share of this investment. In 2006, the federal government’s transportation infrastructure capital expenditures totaled nearly $50 billion dollars\(^3\) out of a total federal infrastructure capital investment of slightly more than $56 billion in that year. State and local governments, in 2004, spent nearly $59 billion on transportation infrastructure capital projects. Public spending to operate and maintain these existing assets was even higher, as state and local governments alone spent an additional $100 billion that year to operate and maintain highways, roads, mass transit, aviation, and water transportation systems (Congressional Budget Office 2007). Furthermore, public investments in physical infrastructure are hardly the only investments or expenditures associated with the transportation system. Public financing dominates sectors like road building and public transit systems, but capital investments in railroads, on the other hand, come primarily from the private sector. Investments in vehicles and in rolling stock are also large and are dominated by private sector funding.

\(^3\) Values reported by the CBO in this report are expressed in 2006 dollars.
2.3 Transportation and Infrastructure Systems: Defining the Perspective

The term “infrastructure” can be somewhat ambiguous, as it is used to describe a variety of similar and sometimes-overlapping systems, and infrastructure by one definition may not be completely distinct from infrastructure as denoted by the term in another context. For example, transportation services and public works infrastructure are interrelated, indeed interdependent, concepts. As discussed previously, at one level a transportation system is composed of many components and subsystems, including infrastructure, rolling stock, management and control systems and organizations, and users. In this context, transportation infrastructure is a component part of the national transportation system. Viewed from a different perspective -- one employing a broader definition of “infrastructure system” -- the nation is served by a number of infrastructure systems that support a variety of services (e.g., electric power, clean water, mobility, communications); and the transportation system is just one such infrastructure system. Thus, the term “infrastructure” may be used in reference to the entire transportation system or in reference to a particular component subsystem within it (i.e., guideways and other fixed components like control systems).

Furthermore, while the nation’s various infrastructure systems are often planned, built, and operated separately, the delivery of services to the public frequently is dependent on the effective functioning of more than one type of infrastructure system. For example, the United States’ transportation and energy systems are related in a number of ways, including key interdependencies. Perhaps most obviously, transportation is a source of demand for energy supplies; the transportation sector accounts for approximately 28 percent of the total energy used in the United States each year (EIA 2009). Without adequate and secure supplies of vehicle fuels (and electric power), the transportation system cannot function. Energy efficiency varies...
for different modes of transportation, so mode choice and vehicle characteristics influence the energy demand and environmental effects of transportation systems. Congestion on transportation networks also can reduce efficiency and waste energy, and the condition and serviceability of transportation infrastructure affects the energy efficiency of transportation services (e.g., poor infrastructure may make it difficult for vehicles to operate at fuel efficient speeds). The energy system, in turn, is characterized by dependencies on the transportation system, the services of which are necessary to move raw energy sources to power plants for generation of electricity and refineries for production of fuels—and then to distribute those fuels to retail markets (NETL 2001).

Transportation research, development, and deployment activities thus have the potential to make vital contributions to the nexus of two broad challenges: the direct provision of accessibility and mobility (i.e., transportation services) through an efficient transportation system, and, more broadly, the provision of cost-effective physical infrastructure systems to support the national economy and quality of life. The next chapter outlines the research and development system that supports the U.S. transportation system.
CHAPTER 3: RESEARCH & DEVELOPMENT IN THE U.S. TRANSPORTATION SYSTEM

The transportation system is one of the nation's largest and most visible infrastructure systems. Networks of roads, railways, air corridors, shipping lanes, and pipelines connect cities with towns, production facilities with markets and consumers, and — via international airports, ports, and transnational border crossings — the fifty states with the rest of the world. This chapter provides an introduction to the current challenges in the sector and the research and development (R&D) activities that support that system.

3.1 A Note on Research, Development, and Innovation

For the purposes of this thesis, these research and development activities are analyzed from a systems perspective and may be conceptualized as themselves comprising a system—that is, transportation R&D activities are a subsystem of the overall transportation system. Because a system is fundamentally "a regularly interacting or interdependent group of items forming a unified whole" ("Merriam-Webster" 2009), this chosen perspective reflects the author’s intent to focus on the ways in which various R&D activities interact to meet, collectively, the needs of the transportation system. It should be stressed, however, that these R&D activities are diverse and are organized in a variety of ways; some take place within well-defined, bureaucratic systems while others are guided more by market-based mechanisms.

Although it may seem pedantic, careful attention to terminology is important in discussing the activities aimed at expanding knowledge of transportation issues and generating solutions to transportation problems—or simply advances in transportation practice. Research, development, deployment, diffusion, technology, and innovation are all terms denoting concepts
of relevance to this subject. In this paper, “research and development” or “R&D” is typically used to refer to this set of knowledge-generating activities generally, but it is nonetheless important to realize that there are differences among the terms listed above (and the ways in which they are often combined, as in “research and development” or “research, development, and deployment”) and that one must be careful to note how they are used in particular contexts (e.g., in reviewing the published academic literature, in interpreting data, etc.). The basic distinctions between the terms are perhaps illustrated most clearly in the linear model of innovation, which provides a simple, systems-based description of innovation as a process. According to this model, new ideas are generated by scientific research and invention, then refined and adapted for practical use through a development process, and finally put into production or deployed in practice, gaining more widespread use after first deployment through a process of diffusion (Jamison and Hard 2003). Research, the most upstream activity in the model, is “studious inquiry or examination, especially: investigation or experimentation aimed at the discovery and interpretation of facts, revision of accepted theories or laws in the light of new facts, or practical application of such new revised theories or laws” ("Merriam-Webster" 2009). More concisely, it is “a conscious and directed effort to increase our understanding and discover new and better ways to achieve our goals” (Lemer, Chong et al. 1995). This final step, the novel, nontrivial implementation of a change to a product, process, or system, is the event usually identified by the term “innovation” (Slaughter 1998), although the entire sequence, including research and development, is considered part of the innovation process. (The linear model itself is widely recognized as oversimplified and incomplete (e.g., it ignores the possibility that innovation may originate in the absence of focused research, and it discounts the role of feedback loops that allow information to flow upstream as well as downstream through the process chain).
but—as with many simple models—it can provide a useful tool for understanding the basic elements of a system, in this case transportation research, development, and related activities.)

3.2 Transportation and Infrastructure Policy and Challenges

Research and development activities are driven in large part by current and emerging challenges in the transportation system, and both these challenges and the R&D activities addressing them are influenced by the prevailing public policy environment (which may, in turn, be influenced by new knowledge generated through transportation-focused R&D). This section provides a brief description of the most salient features of the American infrastructure and transportation policy landscape and identifies several critical issues that are likely to affect R&D (or, more broadly, innovation) needs in the near future.

3.2.1 The Infrastructure Challenge: A Multidimensional Problem

As suggested previously, the problems of the U.S. transportation system—and infrastructure systems more generally⁴—are multi-dimensional, including technological, financial, organizational and managerial, political, and socio-cultural aspects. Generally speaking, insufficient public funds are available to meet infrastructure needs, yet attracting private investment capital to some of these systems, the full social benefits of which may be hard to appropriate, can be a difficult task. Procurement and delivery models frequently

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⁴ The Organization for Economic Cooperation and Development (OECD) has estimated global infrastructure needs, excluding energy infrastructure—a huge market, at $53 trillion through the year 2030. In some countries (or in some regions), the focus for the foreseeable future will be primarily on the expansion of capacity in infrastructure systems. In other countries, like the United States, greater emphasis will likely be placed on renewing and modernizing legacy infrastructure systems (and expanding the capacity of those systems) For more information, see: OECD (2007). Infrastructure to 2030, Volume 2: Mapping Policy for Electricity, Water, and Transport. Paris, Organization for Economic Cooperation and Development.
institutionalize conflict between public and private sector stakeholders, compounding the difficulty of forging mechanisms, like public-private partnerships, which seek to utilize contributions from both sectors. Similarly, planning, design, construction, and operation processes often are poorly integrated, resulting in inefficiencies like designs that lead to higher-than-necessary construction and operation costs--further compounding the difficulty of assembling adequate funding for the systems. Reconciling, or balancing, increasing concerns about protection of the natural environment with economic and social needs for better or more man-made infrastructure likewise is not straightforward, requiring difficult tradeoffs among competing objectives in the face of considerable uncertainty about cause-effect relationships and future costs and benefits. Meanwhile, fragmented authority and conflicting incentive structures may hinder the development and diffusion of technological innovations that could make possible greater reductions in cost than process model/procurement model improvements can yield (Transportation Research Board 2009a). Technologists and policymakers, planners and operators, engineers and managers all have a role to play in solving the challenges of critical infrastructure.

In the midst of this complexity, three forces in particular are driving change in the infrastructure landscape. First, as infrastructure systems are increasing in size, scope, and complexity, understanding the nature of interrelationships among various components and systems is becoming more important, not only to infrastructure designers and managers but also, less directly, to the end-user public, which depends on the services that these systems provide; however, increases in complexity lead to higher probabilities that systems will exhibit emergent
properties\(^5\) and have unanticipated consequences, compounding the difficulty of ensuring that infrastructure systems deliver the intended types and levels of service (Roos, de Neufville et al. 2004). Second, as noted above, traditional mechanisms for financing and funding infrastructure systems are proving inadequate to the task, and the search for satisfactory alternatives is a major driver of the reshaping of roles for the public and private sectors in infrastructure markets. Significant portions of the existing infrastructure stock are nearing or are already beyond their design service lives, and years of deferred maintenance have contributed to declines in the physical condition of assets and increases in the investments needed to renew them, further complicating the task of ensuring that infrastructure can provide desired services (National Research Council 2009). Finally, increasing global concern about the threats posed by a changing climate—controversial though the science and politics of the issue may be—and, more broadly, the often-adverse environmental impacts of human activity are placing greater focus on the relationship between the built environment and the natural environment, and demand for infrastructure development processes that incorporate principles of sustainable development is growing (National Research Council 2009; Transportation Research Board 2009c).

3.2.2 **Shaping Infrastructure Systems through Policy Choices**

Major civil infrastructure systems in the United States are built and maintained by a combination of public and private stakeholders, and the institutional arrangements differ from system to system. Policymakers influence these arrangements not only through direct regulation

\(^{5}\) Emergent properties are related to behavioral complexity in a system and result when the rules governing behavior of individual components are simple, but the patterns of behavior observed in the broader system are complex and would not be predicted by straightforward extension of component-wise behavioral expectations to the system as a whole. Holland, J. H. (1998). *Emergence: From Chaos to Order*. Reading, MA, Addison-Wesley.
and related legislative action but also through the power of the purse. Infrastructure systems are capital-intensive and require lumpy investments—often making them difficult for state and local governments to finance, and the presence of externalities and other market failures impedes the ability of the private sector to invest profitably in many infrastructure systems; together, these factors mean that federal-level policies guiding disbursements of funds for infrastructure provision are critical system drivers, especially in the highway sector. The influence of federal infrastructure financing policies is evident in the historical infrastructure development record. For example, the nation’s transportation system today has been extensively shaped by federal decisions to support railroad construction in the nineteenth century and to finance a vast program of interstate highway construction beginning in the mid-1950s. More recently, commitments of federal funding for planning and design of high-speed rail systems in selected corridors nationally have generated new debate about national infrastructure policy priorities.

Mobilizing financing for infrastructure is made vital by the dual imperatives of expanding the capacity of infrastructure systems (to keep up with population increases and to facilitate
economic growth) and renewing or modernizing the aging stock of infrastructure on which the nation’s twentieth-century economic might was built. Federal funding often is made available for new construction (capital investment) in infrastructure systems but not for maintenance, operations, or rehabilitation—a policy bias that de-emphasizes the lifecycle costs of infrastructure systems and may, by subsidizing system expansion, encourage state and local governments to invest in new facilities without sufficient resources for long-term operation and maintenance. (The political attractiveness of ribbon-cutting ceremonies and a temporal mismatch between relatively short political/electoral cycles and much longer infrastructure lifecycles provide further explanation of this behavior.) Federal financing of infrastructure often draws on a general tax base and obscures the economic linkage between enjoyment of benefits and bearing the burden of costs. (For example, the Highway Trust Fund is financed by fuel taxes paid by all motor vehicle users, but these users do not all place demands on the highway system in proportion to the taxes each has paid.) Many economists agree that wider implementation of a user-pays principle—a more efficient allocation of costs among classes of users—would improve long-term productivity of infrastructure systems (Ehrlich and Landy 2005).

Public-sector contracting policies that dictate competitive bidding and lowest-cost procurement models may help to control costs and minimize corruption, but they also discourage innovation. High concern for public safety and associated liability issues also create barriers to innovation in infrastructure systems. Low levels of innovation, in turn, slow the widespread adoption of technology changes that may bring about increased efficiency or improved services. For instance, Ehrlich and Landy note that redesigning policy to facilitate the adoption of changes in infrastructure management technology could transform roads into “platform[s] for new technologies that monitor traffic flow, interact with users, and orchestrate movement to reduce
congestion” and “create new opportunities for project design, capacity expansion, user cost recoupment, and peak-load management” (Ehrlich and Landy 2005). Absent a conducive policy environment, however, the pace of change is likely to remain slow.

These issues have been a cause of increasing concern as existing infrastructure systems age. For instance, in 1981 the Council of State Planning Agencies published a landmark, provocatively-titled report on the nation’s infrastructure: America in Ruins. The report argued strongly that the nation faced an “infrastructure crisis” as the result of underinvestment in maintenance of existing public works facilities and inadequate spending on the construction of new infrastructural assets. This was not the first document to raise questions about the condition of the nation’s infrastructure, but it proved relatively more effective than similarly-themed reports at gaining the public’s notice and focusing attention on the issue. Discussing the impact of America in Ruins in a study published in 1995, Sanford, Tarr, and McNeil note that, “For the American people, who usually took infrastructure facilities and services for granted, the idea that they were in need of extensive repair and expansion was a shock” (Sanford, Tarr et al. 1995).

Despite the report’s modest success in raising awareness of the challenges of maintaining adequate infrastructure, the public policy response was less than overwhelming, reflecting perhaps a perception that the ‘crisis’ was not as severe as the report warned (Sanford, Tarr et al. 1995). Almost thirty years after the publication of America in Ruins, the civil infrastructure policy landscape seems little changed overall. Federal policies still favor new construction, and policy changes occur as reactions to extraordinary events (e.g., a renewed attention to investing in bridges driven by safety concerns following the catastrophic collapse of the I-35W bridge in Minneapolis in August 2007) rather than as proactive strategies to meet projected challenges. As
a general rule, infrastructure policy issues usually are given much lower priority on the national agenda than a host of other chronic public issues. As one observer has written,

“[In the past there have been] vigorous debates about investing in transportation, water, energy, communications, the built environment, and waste management systems. These debates have not ended, but they have moved off the front page as the nation faces many other financial challenges, including military commitments, Social Security, and a current account deficit. Infrastructure issues return to the front page when there is a failure such as a bridge collapse, but then they lie down as larger issues overtake them.” (Grigg 2010)

Perhaps the most notable change in infrastructure policy has been establishment of a trend towards increased private participation in infrastructure delivery, a shift that may relieve some pressure on public budgets and bring new approaches to managing operations, technology, and reinvestment but one that is far from displacing public finance and provision as the dominant paradigm.

Meanwhile, infrastructure advocates and experts have continued to warn the public and policy-makers of the dangers of under-investing in the infrastructure system. For example, the American Society of Civil Engineers (ASCE) periodically publishes a ‘report card’ on the nation’s infrastructure system; the latest version assigned infrastructure overall a ‘D’ rating and pronounced a need for $2.2 trillion in spending on infrastructure over the next five years to “bring the condition of the nation’s infrastructure up to a good condition” (ASCE 2009). As shown in Table 1, ASCE has increased its estimate of needs with each successive report card, and it has never awarded a composite rating of higher than ‘D+’ to the nation’s infrastructure systems. Although the ASCE “report card” studies are open to legitimate methodological
Table 1: Summary of ASCE Infrastructure Report Cards  
Source: (ASCE 2005; ASCE 2009)

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| Overall/Composite         | D    | D+   | D    | D    |
| Estimated Need ($ trillions) | --   | $1.3 | $1.6 | $2.2 |

1 For 2009, ASCE states that it evaluates each category on the “basis of capacity, condition, funding, future need, operation and maintenance, public safety, and resilience” (ASCE 2009). By comparison, ASCE reports that the 2005 report was prepared using evaluations of condition and performance, capacity vs. need, and funding vs. need (ASCE 2005).
2 The grading scheme is: A = exceptional, B = good, C = mediocre, D = poor, F = failing.
3 The “Security” infrastructure category was included in the 2005 report card due to the environment of heightened security awareness after the events of Sept. 11, 2001. By 2009, the organization had decided that security was not a stand-alone quality but was instead an attribute of each category and it was incorporated into the criteria for resilience.
4 Assumes 3% annual inflation.
criticism, their message about underinvestment is clear, their cross-sectoral scope exposes the breadth of the problem, and their record of success as a tool for stimulating public debate is strong.

As the next section makes clear, however, underinvestment is far from the only challenge that must be addressed through research and innovation in transportation and infrastructure.

3.2.3 Issues and Challenges

Transportation and other infrastructure systems exist in a dynamic environment and must respond to ever-changing social and economic needs in the communities and geographies they serve. Numerous reports have been published by a variety of organizations describing the factors thought to be driving these needs at present and the trends thought likely to exert the most influence on needs in the near future. Drawing on one of these, Figure 8 below lists eight challenges identified in a report entitled, *Investing in Global Infrastructure 2007: An Emerging Asset Class*, the first installment in a series of annual reports on infrastructure policy and trends published by the Urban Land Institute and Ernst & Young. Factors like population and economic growth contribute to a need to expand infrastructure capacity, while increased global competition can create pressure for improved efficiency as well as greater capacity. At the same time, the gap between needed and existing infrastructure capacity is exacerbated by the deteriorating condition of aging systems, and the tasks of renewing and expanding these systems are made more difficult by rising development costs and the inadequacy of existing investment models.

A similar picture emerges if one focuses specifically on the transportation system rather than on the infrastructure sector more generally. For the past three decades, the Transportation Research Board of the National Academies has periodically published a list of 'critical issues
in transportation.’ The most recent such list, which was published in January 2006 and emphasizes nine issues, is shown in Table 2 below. The TRB describes the purpose of this list as being “to focus attention on the most significant policy decisions facing the country and on the areas most in need of innovation” (Transportation Research Board 2006). Many of the items on the list correspond to challenges identified in Figure 8: aging capital stock coupled with difficult financing issues, growing congestion as demand for use of this infrastructure increases, and, importantly, the need to reconcile institutions developed in the last century with the evolving needs of the system in the new century. The TRB report breaks this last item down into five institutional sub-issues: “Adopting a systems perspective instead of a modal perspective, Integrating priorities across levels of government more effectively, Emphasizing operations instead of expansion, Improving the balance between national and local interests, and Expediting a decision-making process that has become slow and cumbersome” (Transportation Research Board 2006).
Table 2: 2006 TRB Critical Issues in Transportation  
Source: (Transportation Research Board 2006)

<table>
<thead>
<tr>
<th></th>
<th>TRB 2006 Critical Issues in Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Congestion</td>
</tr>
<tr>
<td>2</td>
<td>Emergencies</td>
</tr>
<tr>
<td>3</td>
<td>Energy and Environment</td>
</tr>
<tr>
<td>4</td>
<td>Equity</td>
</tr>
<tr>
<td>5</td>
<td>Finance</td>
</tr>
<tr>
<td>6</td>
<td>Human and Intellectual Capital</td>
</tr>
<tr>
<td>7</td>
<td>Infrastructure</td>
</tr>
<tr>
<td>8</td>
<td>Institutions</td>
</tr>
<tr>
<td>9</td>
<td>Safety</td>
</tr>
</tbody>
</table>

Also included in the list is a perhaps misleadingly brief reference to “extraordinary challenges” in energy and the environment. As discussed in the previous chapter, sustainability is an important general issue in infrastructure design and management, and global concerns about mitigation of—and, increasingly, adaptation to—climate change are raising its priority on policy and research agendas alike. In transportation, the challenge of improving sustainability is crucial; as TRB notes, “A growing consensus associates global warming with fossil fuel consumption; the transportation sector accounts for roughly 30 percent of all fossil fuel consumption, and the share is rising. Any measure to reduce carbon-based fuel consumption significantly will have to involve the transportation sector” (Transportation Research Board 2006). Solutions may be devised from a range of possible actions: changing the fuels that power vehicles and rolling stock, improving the efficiency of engines, shifting the distribution of modal shares for passenger travel and freight transportation, identifying and seizing opportunities to increase the efficiency of system operations, or introducing demand-side measures to mitigate projected growth in travel demand. Continued utilization of existing knowledge and
technologies can help to address these and similar challenges, but the search for solutions must inevitably include research, development, and related activities as well.

3.3 Research and Development in Transportation

In response to these needs (and, no doubt, because of a prevailing societal belief that technological progress is a vital driver of economic growth and development), research and development activities are sponsored and performed by a variety of transportation stakeholders, including federal, state, local, academic, and private-sector organizations. In a recent report, TRB has identified key structural characteristics of the system for transportation R&D (or, more broadly, innovation) in the United States. These include: a highly decentralized and fragmented marketplace and a heterogeneous research and technology development system (Transportation Research Board 2009a).

3.3.1 A Decentralized and Fragmented R&D Marketplace

The transportation R&D marketplace is heavily influenced by the fragmented nature of the system overall. The previously-discussed division of the transportation system into modal systems, in both research and practice, is one of three prevailing dimensions of fragmentation within the sector. The second is related to the federal nature of the U.S. political system, which fragments the transportation system along multiple layers of public authority: the U.S. federal government, state governments, local and city governments, and some mixed jurisdictions, like agencies with regional or metropolitan-scale authority. The federal government oversees national transportation networks, but most transportation infrastructure networks themselves are owned and operated by state or local agencies. For the national highway system, Table 3 illustrates this allocation of responsibility to various government entities.
Table 3: Highway Mileage & Expenditures Classified by Administrative Responsibility
Source: (Transportation Research Board 2001)

<table>
<thead>
<tr>
<th>Administration</th>
<th>Number of Agencies</th>
<th>Highway Miles (% of total) for Which Responsible</th>
<th>1999 Revenues (% of total) Used for Highways by Collecting Agency ($ millions)</th>
<th>1999 Expenditures for Highways (% of total) by Expenditing Agency ($ millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal agency</td>
<td>5</td>
<td>118,391 (3)</td>
<td>26,016 (22)</td>
<td>1,424 (1)</td>
</tr>
<tr>
<td>State agency</td>
<td>52</td>
<td>773,903 (20)</td>
<td>62,097 (53)</td>
<td>71,414 (61)</td>
</tr>
<tr>
<td>County agency</td>
<td>2,815&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1,766,394 (45)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Town and township</td>
<td>14,051&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1,206,917 (31)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Municipality</td>
<td>18,100&lt;sup&gt;a&lt;/sup&gt;</td>
<td>NA</td>
<td>29,765 (25)</td>
<td>44,595 (38)</td>
</tr>
<tr>
<td>Other jurisdictions&lt;sup&gt;c&lt;/sup&gt;</td>
<td>-</td>
<td>66,399 (2)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Total</td>
<td>35,023</td>
<td>3,932,004</td>
<td>117,878&lt;sup&gt;d&lt;/sup&gt;</td>
<td>117,433&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Estimates based on census data.
<sup>b</sup> Municipal mileage is combined with town and township mileage.
<sup>c</sup> “Other jurisdictions” include state park, state toll, and other state agencies; other local agencies; and roadways not identified by ownership.
<sup>d</sup> Differences due to funds placed in reserve.

Note: NA = not available.

(The table displays data from 1999, and the current, total system mileage would be slightly higher. The relative roles apparent in the table are still applicable.) Federal agencies are directly responsible for only three percent of the highway system mileage, while state agencies control another 20 percent of the mileage, collect more than half of the revenues, and incur over 60 percent of the total expenditures.

The third dimension of fragmentation is division of the system into organizations with expertise in or authority over guide ways and infrastructure, vehicles and rolling stock, system operations, and other functions. Highways, for example, are typically owned and managed by public agencies, but the vehicles that traverse those routes are developed and brought to market
by a separate, private industrial enterprise. A relatively low level of technological coupling between highways and motor vehicles historically has contributed to flexibility for guideways and rolling stock development to be carried out more or less independently, with necessary integration guided primarily by standards for lane widths, acceptable pavement loadings, safety considerations, and the like. These characteristics (e.g., the optimal degree of coupling) can change, however. Technological developments, especially in information and communication technologies, have opened new possibilities for use in highway system design and operations, and researchers have begun to address ways in which vehicles and infrastructure—including control systems—must be more closely integrated to realize the full potential of these new technologies. Innovative models for research, bridging traditional boundaries of organizations and institutions, may alter the lines of organizational fragmentation more widely as the new technological paradigm matures.

In his contribution to the edited volume *Barriers to Sustainable Transport: Institutions, Regulation, and Sustainability*, Jonathan Gifford argues that improving system-level planning is a central research challenge for the transportation community, although he is careful to note that, “The appropriate degree of system level planning is difficult to specify” (Gifford 2005). Some degree of decomposition of system complexity and division of responsibility or expertise is logically necessary to reap the benefits of specialization – or simply to make certain problems tractable – but too much fragmentation can be detrimental to the system as a whole (e.g., fragmentation can result in localized solutions that sub-optimize the broader system, can increase costs of coordination and of achieving performance standards to encourage innovation, etc.) (Transportation Research Board 2009a).
### Table 4: Transportation R&D Programs

*Source: (Transportation Research Board 2009b)*

<table>
<thead>
<tr>
<th><strong>Federal Programs¹</strong></th>
<th><strong>Transportation Research Board Programs</strong></th>
<th><strong>State Department of Transportation Programs</strong></th>
<th><strong>University Transportation Center Programs</strong></th>
<th><strong>Private Corporations and Private Foundations</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal Highway Administration; Federal Transit Administration; Federal Aviation Administration; Research and Innovative Technology Administration; National Highway Traffic Safety Administration; Federal Rail Administration; Maritime Administration; Federal Motor Carrier Safety Administration; Pipeline and Hazardous Materials Safety Administration; National Science Foundation; National Institutes of Health; Department of Energy; Department of Homeland Security; Department of Education; Environmental Protection Agency; Department of Agriculture</td>
<td>National Cooperative Highway Research Program; Innovations Deserving Exploratory Analysis; Airport Cooperative Research Program; Transit Cooperative Research Program; Hazardous Material Cooperative Research Program; National Cooperative Freight Research Program</td>
<td>State Departments of Transportation Research Programs (intramural); Transportation Pooled Funds Program</td>
<td>First 10 University Transportation Centers (UTCs) authorized by federal legislation in 1987; now sixty (60) university transportation centers (UTCs) authorized by the Safe, Accountable, Flexible, Efficient Transportation Equity Act of 2005.</td>
<td>Assorted programs</td>
</tr>
</tbody>
</table>

¹Due to the impracticality of listing all relevant federal programs, this list instead identifies federal agencies that administer research programs which fund or perform transportation-related research projects.

#### 3.3.2 A Heterogeneous R&D System

In general, transportation research activities are organized into themed research programs, which in turn support individual research projects. As shown in Table 4, many of these programs are administered by the federal government and the independent Transportation Research Board (part of the government-chartered but independent National Academies, which provide advice to government on issues of science and technology), but state governments, universities, and private companies also operate programs. Much state-initiated transportation
research and development activity is supported by both state and federal funds through the mechanism of the State Planning and Research Program, which mandates that each state must dedicate a percentage of its annual allocation from certain federal transportation programs to planning and research activities. Several mission-focused cooperative research programs, administered by TRB, provide a mechanism for the states and local agencies to pool their funds and support R&D projects of interest to multiple state and local agencies (Transportation Research Board 2009b).

The nature of the R&D projects supported differs considerably across the programs listed above. Programs reliant on funds from the state departments of transportation tend to be heavily focused on short-term, applied research and development projects. Federally-administered programs support both short-term R&D and higher-risk, more basic research. University transportation centers engage in some basic research, but the extent to which they can do so is limited by a requirement that the federal funds appropriated for the program be matched dollar for dollar (on a project-by-project basis) by funds from other sources; in practice, these other sources typically are state and local agencies or industry associations, groups which tend to be relatively risk-averse in the construction of their research portfolios (Transportation Research Board 2009b).

The R&D projects funded through these programs are performed by an equally diverse group of organizations. Figure 9 shows the percentage of fiscal year (FY) 2006 USDOT-funded research and development obligated to nine categories of performing organizations. Just over one third of the total $535 million was spent internally by USDOT on R&D projects in its own facilities, while over forty percent was spent on industry-led R&D projects. The remaining funds
were directed to academic institutions; independent, federally-funded R&D centers (FFRDCs); state and local governments; and even (a very small amount) to foreign entities.

Figure 9 USDOT Research Obligations by Performer, FY 2006  
Source: (National Science Foundation 2008)

3.3.3 A Simple Matrix of Policy Options

In summary, the environment in which transportation policy choices must be made is characterized by the existence of a number of difficult challenges, some of which can be addressed utilizing existing knowledge and technologies while others may require input from a complex and diverse research and development system. Emphasizing certain challenges can appear to point the way to particular strategies for addressing them, but uncertainty and ambiguity cloud the issues, making it difficult to discern a clearly superior set of approaches or priorities. There can be no doubt that much can be gained from considering the full richness and complexity of this environment, but a simple model of the essential transportation policy options may be equally useful in bringing some conceptual clarity to the web of competing problems and solutions. As shown in Figure 10, resources may be devoted to improving the performance of the
existing system by implementing known solutions in practice or by supporting research and development activities to advance knowledge and search for newer, better solutions. In each of these cases, policy-makers may decide to emphasize increasing the financial resources available within the existing paradigm, or they may choose to re-think investment strategies and the structure of the system in which those investments are made. (These options are not mutually exclusive, although implementation of known solutions to current problems and support for R&D activities should be viewed as competing for limited financial resources; likewise, increasing investment and restructuring systems can be undertaken together, but the temporal sequencing of these options would affect the efficiency and effectiveness of using them in combination.)

Figure 10: Four-Quadrant Model of Transportation Policy Options
The model organizes the options into a simple matrix of four broad possible approaches to improving the transportation system. The two left-hand quadrants show strategies emphasizing improvements to the operational system, while the two right-hand quadrants show strategies emphasizing the role of research and development activities. On the other dimension, the top row quadrants share a common emphasis on increasing financial investment, while the two options in the bottom row are alike in emphasizing critical re-evaluation of the systems in which money is invested – in both the operational and R&D sides of the transportation system. Ultimately, the choice facing policy-makers thus is not one of selecting a single option from the matrix above, but rather one of choosing how much emphasis to place on each of the options and when to do so. As noted, while increasing investment and restructuring the systems in which that investment is made are not in theory mutually exclusive, in practice the choices made must be constrained by available resources, most notably money and political will. At a time when soaring budget deficits and difficult reforms are being confronted across the politico-economic spectrum, these resource constraints are likely to play a major role in shaping the national transportation strategy. The next two chapters of this thesis are intended to shed further light on these issues, first by assembling analyzing data on transportation R&D expenditures and then by framing several issues relating to research and development system structure and composition.
CHAPTER 4:
INVESTMENTS IN TRANSPORTATION RESEARCH & DEVELOPMENT

Vast amounts of capital are embodied in the U.S. transportation systems, and the nation spends millions more each year on operations, maintenance and repairs, design, construction, and research, development, and deployment activities related to transportation. The funds—public and private—that are dedicated to transportation purposes are one of the most important resources available to the transportation system. For both the operational and the research and development domains of the system, understanding the nature of funding is a necessary part of understanding the performance of the system.

Transportation R&D investments are intended to advance the state of knowledge about transportation-related issues and to aid in the development of technologies, programs, policies, systems, and other tools for improving the delivery of transportation services. The USDOT’s Research and Innovative Technology Administration’s (RITA) mission, for example, reflects this orientation, stating that RITA’s goal is to, “Identify and facilitate solutions to the challenges and opportunities facing America’s transportation system” (RITA 2005). Yet research and development expenditures are risky investments, as considerable uncertainty characterizes individual research projects, proposals for which must be evaluated ex ante for funding support. Ex post evaluation of research results is difficult as well; benefits may be inherently hard to quantify, and the perceived value of a project may depend heavily on the timing of evaluation since it is often difficult to predict not only if but also when the results of research will yield measurable benefits in practice. (Additional information about the issues involved in assessing the results of research can be found in Evaluating Federal Research Programs: Research and the
Fundamentally, assessing the value of transportation research and development efforts requires knowledge of both the costs and benefits of R&D investments. Benefits of transportation research are difficult to measure, but costs should—at least in theory—be easier (although not necessarily easy) to monitor and analyze. The remainder of this chapter is dedicated to investigation of the (direct financial) cost side of the transportation cost-benefit equation. The first section addresses issues related to identifying the sources and size of transportation R&D expenditures, while the second section presents analysis of historical trends in the available data. The chapter’s final section attempts to give some context to the numbers by comparing transportation R&D expenditures to R&D levels in other industrial sectors and, for federal expenditures, in other federal agencies.

4.1 Magnitude and Source of Annual Transportation R&D Expenditures

Determining the total amount of money invested in transportation R&D activities is not a straight-forward task. Two distinct approaches to measuring the investment can be identified. First, the total sums actually spent on transportation R&D could be measured at the point of spending, that is, at the level of individual research programs (or non-programmatic research sponsors that directly invest in relevant R&D). Collecting data on expenditures at the point of disbursement to research projects would make it possible to use a simple summation of these data to arrive at a total figure for annual transportation R&D expenditures; however, because many transportation R&D programs (e.g., the TRB-administered cooperative research programs and the University Transportation Centers) combine funds from multiple sources, this approach would not provide full information on the original sources of R&D funds. The second possible
approach is to collect data on the levels of R&D support from original sponsors prior to those funds being delivered to individual research programs. This method would have the advantage of making it possible to analyze the budgetary contributions of various agencies and organizations to transportation R&D, regardless of the particular mechanisms through which those funds are spent, but would furnish less information on the end-use of those funds. To be comprehensive, both approaches would require gathering data from literally thousands of public agencies and private-sector sources. In practice, the data that are accessible at reasonable cost in time and effort are a mixture of original-sponsor and research program budget data.

Federal government budget data is the most accessible and complete, and the expenditure totals and trends reported in the remainder of this report are based primarily on federal spending data. Three distinct attempts at estimating federal expenditures are included: expenditures by transportation budget function, expenditures at the USDOT, and an estimate prepared from multiple sources by TRB staff. In 2002, TRB conducted an internal review of federal transportation R&D spending; this was not published by TRB, but the results were later reported by Brach (2005). This estimate includes expenditures at multiple federal agencies and was gathered from a variety of sources, including agency web pages, budget reports, and TRB contacts at the agencies. Because of the method used, the resulting figures include transportation-related R&D expenditures that are not explicitly reported as such in agency budgets. As Table 5 shows, federal support for transportation R&D, as identified by the TRB review, totaled more than $2.5 billion (FY 2002 dollars), and only thirty percent of this (approximately $800 million) came from U.S. Department of Transportation budget items (Brach 2005).
Table 5: Approximate Federal Transportation Research Funding, By Agency (FY 2002)
Source: (Brach 2005)

<table>
<thead>
<tr>
<th>U.S. Department of Transportation (USDOT)</th>
<th>$ thousands (2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal Aviation Administration</td>
<td>$188,200</td>
</tr>
<tr>
<td>Federal Highway Administration</td>
<td>$308,611</td>
</tr>
<tr>
<td>Federal Motor Carrier Safety Administration</td>
<td>$9,828</td>
</tr>
<tr>
<td>Federal Railroad Administration</td>
<td>$55,908</td>
</tr>
<tr>
<td>Federal Transit Administration</td>
<td>$60,050</td>
</tr>
<tr>
<td>Maritime Administration</td>
<td>$11,593</td>
</tr>
<tr>
<td>National Highway Traffic Safety Administration</td>
<td>$121,000</td>
</tr>
<tr>
<td>Office of the Secretary</td>
<td>$10,976</td>
</tr>
<tr>
<td>Research and Special Programs Administration</td>
<td>$9,860</td>
</tr>
<tr>
<td>U.S. Coast Guard</td>
<td>$21,273</td>
</tr>
<tr>
<td>USDOT Total:</td>
<td>$797,299</td>
</tr>
<tr>
<td>Other Federal Agencies</td>
<td></td>
</tr>
<tr>
<td>Department of Commerce¹</td>
<td>$250,000</td>
</tr>
<tr>
<td>Department of Energy</td>
<td>$305,000</td>
</tr>
<tr>
<td>Environmental Protection Agency</td>
<td>$29,000</td>
</tr>
<tr>
<td>National Aeronautics and Space Administration</td>
<td>$522,000</td>
</tr>
<tr>
<td>National Science Foundation¹</td>
<td>$300,000</td>
</tr>
<tr>
<td>U.S. Army Corps of Engineers</td>
<td>$430,000</td>
</tr>
<tr>
<td>Other Federal Agencies Total</td>
<td>$1,836,000</td>
</tr>
<tr>
<td>Total Federal Expenditures (All Agencies)</td>
<td>$2,633,299</td>
</tr>
</tbody>
</table>

¹Data is from FY 1998; all data in 2002 dollars

Data on state, local, and private-sector expenditures on transportation R&D is less accessible and less complete than data on federal expenditures. In Table 6, an estimate of highway-sector industrial R&D spending that was prepared by the Transportation Research Board is displayed (2001). TRB cautions that the estimate is not comprehensive, but the almost-negligibly low total shown (approximately $10 million) suggests that the industrial contribution is dwarfed by public spending--at least in the highway sector. Further, it is important to note also that the estimate is only for highway infrastructure R&D, a subsector in which facilities are owned and operated almost exclusively by public authorities and one which is subject to multiple
Table 6: Estimates of Highway-Related Expenditures by Selected Industry Associations
Source: (Transportation Research Board 2001)

<table>
<thead>
<tr>
<th>Category</th>
<th>Selected Associations</th>
<th>Estimated Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete and Concrete Structures</td>
<td>Portland Cement Association</td>
<td>~ $4 million</td>
</tr>
<tr>
<td></td>
<td>American Concrete Pavement Association</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reinforced Concrete Research Council</td>
<td></td>
</tr>
<tr>
<td></td>
<td>American Concrete Institute</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Precast/Pre-stressed Concrete Institute</td>
<td></td>
</tr>
<tr>
<td></td>
<td>American Concrete Pipe Institute</td>
<td></td>
</tr>
<tr>
<td></td>
<td>National Ready-Mixed Concrete Association</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete Reinforcing Steel Institute</td>
<td></td>
</tr>
<tr>
<td></td>
<td>American Precast Concrete Pipe Association</td>
<td></td>
</tr>
<tr>
<td></td>
<td>National Precast Concrete Association</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Innovative Pavement Research Foundation</td>
<td></td>
</tr>
<tr>
<td>Asphalt, asphalt paving, and asphalt modifiers</td>
<td>Asphalt Institute</td>
<td>~ $3.5 million</td>
</tr>
<tr>
<td></td>
<td>National Asphalt Pavement Association</td>
<td></td>
</tr>
<tr>
<td></td>
<td>National Center for Asphalt Technology</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Asphalt Rubber Producers Group</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Asphalt Recycling and Reclaiming Association</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rubber Pavements Association</td>
<td></td>
</tr>
<tr>
<td>Aggregates</td>
<td>National Sand, Stone, and Gravel Association</td>
<td>~ $1 million</td>
</tr>
<tr>
<td></td>
<td>International Center for Aggregates Research</td>
<td></td>
</tr>
<tr>
<td>Steel and steel structures</td>
<td>American Iron and Steel Institute</td>
<td>~ $1.5 million</td>
</tr>
<tr>
<td></td>
<td>American Institute of Steel Construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>American Welding Society</td>
<td></td>
</tr>
<tr>
<td>Construction equipment</td>
<td>Construction Industry Manufacturers Association</td>
<td>Less than $10,000</td>
</tr>
</tbody>
</table>

NOTE: This is a partial list of associations involved in highway R&D for which data were readily available to the TRB study committee.

* Additional categories, such as composite materials, sealants, and contractors, could be included; AASHTO also funds some research.

* This is a list of the primary associations funding highway-related R&D; many professional societies, such as the American Society of Civil Engineers, the American Society of Municipal Engineers, and the Institute of Transportation Engineers are actively involved in technology transfer and professional training activities; some are also involved with the development of standards and specifications.

* Estimates are based on discussions with association representatives and are for highway-related research only.

* Does not include individual steel companies.

* Does not include individual equipment manufacturers.
barriers to innovation that result in weak incentives for private investors to engage in highway infrastructure R&D (Transportation Research Board 2009a). (If motor vehicles were included as part of the highway system definition used by TRB in that estimate, the contribution of private-sector R&D to the overall highway transportation R&D expenditure would almost certainly appear considerably more significant.) In any case, the estimates included in Table 6 must be interpreted as an individual data point rather than as evidence that private sector contributions to transportation R&D are generally insignificant.

4.2 Historical Trends in Transportation R&D Expenditures

The National Science Foundation (NSF) and American Association for the Advancement of Science (AAAS) both track R&D funding by the federal government and publish annual reports and data tables on the topic. Official agency budgets are the primary sources of this data, which is reported as either budget authority (the amount authorized, or made legally available by Congress, as part of the federal budgetary process) or budget obligations (the amount of the total budget authority which an agency commits to spending in a given fiscal year). For consistency, the data presented in this section all refer to budget authority.

Figure 11 illustrates trends in the USDOT R&D budget for fiscal years 1978 through 2008 using data from AAAS (2007). The solid line and the left-hand axis display the USDOT transportation R&D budget authority in constant 2000 dollars. After fluctuating wildly in the 1980s (including a precipitous drop in the latter part of the decade), the USDOT R&D budget climbed to near $700 million in real terms in the early 1990s (coinciding roughly with the passage of the Intermodal Surface Transportation Efficiency Act); the trend has continued to fluctuate but has displayed less volatility since the early 1990s, remaining relatively flat at near $700 million per year. The right-hand axis and lower, hashed line show how this R&D budget
has compared to USDOT’s total budget during that same period. In contrast to the USDOT’s R&D budget itself, the percentage of R&D in the USDOT budget has exhibited a sustained downward trend since the mid-1990s, falling from a level of approximately two percent of the budget to barely more than one percent in 2008. Both measures have exhibited a downward trend over the period shown, falling in the late 1970s and never regaining their 1978 levels (AAAS 2007).

![Figure 11: Trends in R&D in the USDOT Budget](source: (AAAS 2007))

While USDOT does play a lead role in funding transportation R&D, as the TRB estimate cited above demonstrated, USDOT is not the only federal agency that gives financial support to transportation R&D activities. The next two figures illustrate the historical trend in federal
transportation R&D spending based on data reported under the transportation R&D budget function in all agency budgets for fiscal years 1993 through 2008.

In Figure 12, changes in the total transportation R&D budget authority by budget function clearly result primarily from budget changes in the air transportation sector, which comprises the largest and most volatile component of the federal transportation R&D total throughout the period. The air transportation component is dominated by aeronautics research at the National Aeronautics and Space Administration (NASA), a non-USDOT agency; this budget item has experienced deep cuts since FY 2005 (National Science Foundation 2007). Ground transportation R&D (which includes research at the Federal Highway Administration, the National Highway Traffic Safety Administration, the Federal Railroad Administration, the Federal Transit Administration, and the Federal Motor Carrier Safety Administration) is the second-largest component of total transportation R&D spending by federal agencies. Although the level of expenditure on ground transportation research appears in Figure 12 to have remained relatively flat since FY 1993, closer examination of the ground transportation R&D authority trend reveals an appreciable increase—from $341 million to $421 million—as shown in Figure 13 (National Science Foundation 2007). Highway-sector R&D spending dominates the ground transportation R&D budgets in much the same way as air transportation R&D expenditures dominate the observed trends in the total federal budget authority for all types of transportation R&D activities.

In summary, the data presented above clearly show that several federal agencies provide financial support for transportation R&D programs and projects. Although the USDOT is the lead mission agency for the nation's transportation system, its R&D expenditures represent perhaps one third of the federal investment (Brach 2005). USDOT's research budget, though
Figure 12: Total Transportation R&D Budget Authority, FY 1993-1999
Source: (National Science Foundation 2007)

Figure 13: Ground Transportation R&D Budget Authority, FY 1993-2008
Source: (National Science Foundation 2007)
somewhat volatile, has neither increased nor declined significantly since the early 1990s, but the R&D share of the USDOT budget has been slowly decreasing (AAAS 2007). Data on federal budget authority by budget function reveal a steep decrease in air transportation research funding since FY 2005, but ground transportation R&D support from the federal government has increased modestly during that same period (National Science Foundation 2007).

4.3 Transportation Research Expenditures in a Comparative Context

Examination of transportation R&D expenditures has provided information on historical trends and on the contributions of different federal agencies to the total federal expenditure in this sector; however, this data provides no basis for evaluating effects of the magnitude of transportation R&D expenditures on the performance of the transportation R&D system—or even a basis for understanding how high or low the level of investment in transportation R&D is compared to other economic sectors. The latter task is the subject of the next two sub-sections of this chapter. Both primary comparisons presented and reviewed herein were published by TRB in a study of the federal role in highway research and are specific to the highway sector (Transportation Research Board 2001).

4.3.1 Highway System R&D Expenditures Compared to Other Industry Sectors

One way to provide context for transportation R&D expenditures is to compare the research intensity of the transportation sector to other industries or economic sectors, where research intensity is defined as R&D spending as a percentage of net sales (or system
expenditures) for a given industry. In 2001, a TRB committee used this method to compare highway system R&D intensity to the R&D intensity of eight industries, as shown in Table 7. (In the TRB comparison, the industrial R&D expenditures statistics were constructed using the total R&D expenditures of the top 50 corporations in R&D spending in 1997 for each of the eight industries, and the authors used highway system expenditures as a proxy for “net sales” in the highway sector.) The result of this comparison clearly suggests that the R&D intensity of the highway sector is low compared to all eight other industries included, but the authors of the TRB report warn that, “comparisons between industries should be made cautiously because the research and development (R&D) sales ratios may be as circumstantial as they are strategic. For example, in the pharmaceutical industry, R&D is performed not only for the sake of discovering new products, but also for the sake of product testing to meet regulatory requirements once a new product has been developed” (Transportation Research Board 2001); its magnitude is thus highly sensitive to regulatory requirements and may be, for the purposes of the cross-sectoral comparison, a misleading indicator of the effort devoted to generation of new knowledge and new technologies. (Table 8, which reports global R&D intensity for several industries as calculated by the consulting firm Booz & Company, provides two years of R&D intensity figures for a period falling one decade after the TRB data. Several industry entries are similar across the

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6 According to the National Science Foundation, R&D intensity is a key science and technology indicator and is most frequently defined as “the ratio of company-funded R&D to net sales,” although alternative constructions of the variable exist. R&D intensity is a measure of R&D relative to production, and “provides a way to gauge the relative importance of R&D across industries and among firms in the same industry.” For reference, the average R&D intensity of firms performing R&D in the U.S. peaked at 4.2% in 2001 but has since fluctuated at a somewhat lower level, varying between 3.5 and 3.9% through 2008. Source: National Science Board (2008). Science and Engineering Indicators 2008. Arlington, VA, National Science Foundation.

7 Note that the R&D intensity of the highway sector is but one component of R&D intensity in the full transportation system.
two comparisons, and the reported R&D intensities do not appear to differ substantially across the time period for similar industry/sector entries.) Ultimately, however, it is clear that while highway system R&D expenditures might very well be low compared to those of other sectors, the limited comparison made by TRB would need to be expanded and methodologically strengthened to attach full confidence to the result.

Table 7: R&D Expenditures of Major Industrial Sectors as Percentage of Net Sales
Source: (Transportation Research Board 2001)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Net Sales(^a) ($ billions)</th>
<th>R&amp;D Spending ($ billions)</th>
<th>R&amp;D as Percentage of Net Sales (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic industries and materials</td>
<td>727</td>
<td>8.4</td>
<td>1%</td>
</tr>
<tr>
<td>Motor vehicles and other surface transportation equipment</td>
<td>455</td>
<td>18.4</td>
<td>4%</td>
</tr>
<tr>
<td>Aircraft and guided missiles</td>
<td>130</td>
<td>4.7</td>
<td>4%</td>
</tr>
<tr>
<td>Medical substances and devices</td>
<td>168</td>
<td>19.8</td>
<td>12%</td>
</tr>
<tr>
<td>Chemicals</td>
<td>210</td>
<td>6.8</td>
<td>3%</td>
</tr>
<tr>
<td>Services</td>
<td>67</td>
<td>0.4</td>
<td>1%</td>
</tr>
<tr>
<td>Information and electronics</td>
<td>567</td>
<td>45.8</td>
<td>7%</td>
</tr>
<tr>
<td>Machinery</td>
<td>248</td>
<td>7.0</td>
<td>3%</td>
</tr>
<tr>
<td>Highway system</td>
<td>117(^b)</td>
<td>0.621 to 0.696</td>
<td>0.53 to 0.59%</td>
</tr>
</tbody>
</table>

\(^a\) for the top 50 corporations in R&D spending in 19977; \(^b\)Highway system expenditures.

Data source: For all but highway sector, Standard & Poor’s Compustat, Englewood, CO.

Table 8: Innovation Intensity by Industry (Global Industry Spending)
Source: (Jaruzelski and Dehoff 2008; Jaruzelski and Dehoff 2009)

<table>
<thead>
<tr>
<th>Industry</th>
<th>2008 Intensity</th>
<th>2007 Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health Care</td>
<td>12.0%</td>
<td>13.4%</td>
</tr>
<tr>
<td>Software and Internet</td>
<td>11.4%</td>
<td>13.6%</td>
</tr>
<tr>
<td>Computing and Electronics</td>
<td>7.1%</td>
<td>7.0%</td>
</tr>
<tr>
<td>Aerospace and Defense</td>
<td>4.5%</td>
<td>4.9%</td>
</tr>
<tr>
<td>Automotive</td>
<td>4.1%</td>
<td>3.9%</td>
</tr>
<tr>
<td>Industrials</td>
<td>2.0%</td>
<td>2.1%</td>
</tr>
<tr>
<td>Consumer</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>1.4%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Chemicals and Energy</td>
<td>0.9%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Other</td>
<td>0.8%</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

\(^1\)As in Table 7, R&D intensity is defined as R&D expenditures as a percentage of net sales.
4.3.2 USDOT R&D Expenditures Compared to Federal Agencies

A second comparative assessment of transportation R&D intensity was reported by TRB in the same document. In this second analysis, the authors compared the research intensities of various federal agencies to that of the USDOT, using R&D as a percentage of each agency’s total budget as the basis for assessment. The analysis shows that the R&D intensity of USDOT is low compared to that of other agencies, suggesting—as did the industrial sectors comparison—that R&D spending may be relatively low in the transportation sector. However, it is important to note that, as demonstrated in an earlier section, not all federal transportation R&D expenditures are channeled through the USDOT; therefore, low research intensity at USDOT does not strictly imply that overall transportation R&D investment is lower than in other sectors.

Table 9: Selected Federal Agency Total and R&T Budgets for Fiscal Year 2001
Source: (Transportation Research Board 2001)

<table>
<thead>
<tr>
<th>Department or Agency</th>
<th>Total Annual Budget ($ millions)</th>
<th>Annual R&amp;T* Budget ($ millions)</th>
<th>R&amp;T Budget as Percentage of Total Budget (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Department of Defense</td>
<td>283,915</td>
<td>42,258</td>
<td>14.9</td>
</tr>
<tr>
<td>Department of Agriculture</td>
<td>69,599</td>
<td>1,961</td>
<td>2.8</td>
</tr>
<tr>
<td>Department of Health and Human Services (National Institutes of Health)</td>
<td>430,466</td>
<td>20,859</td>
<td>4.8</td>
</tr>
<tr>
<td>National Aeronautics and Space Administration</td>
<td>13,777</td>
<td>9,925</td>
<td>72</td>
</tr>
<tr>
<td>Department of Energy</td>
<td>16,739</td>
<td>7,744</td>
<td>46.3</td>
</tr>
<tr>
<td>National Science Foundation*</td>
<td>3,967</td>
<td>3,279</td>
<td>82.7</td>
</tr>
<tr>
<td>Environmental Protection Agency</td>
<td>7,495</td>
<td>609</td>
<td>8.1</td>
</tr>
<tr>
<td>Department of Commerce</td>
<td>5,549</td>
<td>1,201</td>
<td>21.8</td>
</tr>
<tr>
<td>Department of Transportation</td>
<td>50,611</td>
<td>747</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*R&T stands for “research and technology” and may be interpreted as roughly equivalent in meaning to the term “R&D.”

*bUnlike other agencies listed, the National Science Foundation is a research agency, not a mission agency.
Because of USDOT’s central role in transportation system oversight, management, and operations (and its leading role in provision of certain elements, like highway infrastructure), it seems likely that low R&D intensity at USDOT is a credible sign that investments in these particular aspects of transportation R&D are comparatively low, but the data are insufficient to prove or disprove this hypothesis definitively.

4.4 Summary and Analysis

The federal government plays a leading role in funding transportation-related R&D in the United States, but the complexity of the system through which it delivers this support creates barriers to generating a comprehensive overview of this role. Available data indicate that through the mission-oriented USDOT, the federal government has authorized between $600 million and $800 million\(^8\) per year for transportation R&D since at least 1990—a funding level that has fluctuated but remained relatively flat for two decades. (In the total USDOT budget, however, the share for R&D support has declined.) R&D intensity is low, relative to that of other agencies, in the USDOT budget; but the significance of this result is limited by USDOT’s own limited role in funding transportation R&D. When a broad definition of transportation R&D is employed, USDOT R&D funding does not account for even a majority of federal transportation R&D funding, the balance of which is funneled through at least six other federal agencies.

Data on highway system R&D intensity appears to indicate that the highway system receives less R&D support than is common in a range of industries and economic sectors. (Indeed, the highway system R&D intensity of less than 0.6% of system expenditures is

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\(^8\) Expressed in constant 2001 dollars.
noticeably lower than every other industrial value reported by TRB or Booz & Company, and it is a fraction of the U.S. industrial R&D average reported by the National Science Board.) As TRB notes, however, cross-sectoral R&D intensity comparisons are subject to many potential flaws and limitations, so it is unclear how significant the result is. Private-sector expenditures on highway system R&D appear negligible compared to public expenditures—an unsurprising conclusion given the public-goods nature of highways and predominant, institutionalized public-led delivery models; accordingly, one might expect more significant R&D contributions from non-government entities in other transportation sectors.

Although the federal government is one of the primary actors in the transportation R&D market, it is not the only one to provide funding. The private benefit of vehicle or rolling stock R&D typically can be more easily captured and returned to the investor, and government’s role is diminished relative private industry in these transportation subsectors. For example, according to the National Science Board, automotive manufacturing is the nation’s sixth-largest business sector in terms of R&D and accounted for a reported $16 billion of R&D spending in 2007 alone—a figure far larger than any of the annual federal R&D expenditures discussed earlier (National Science Board 2008). Including numbers like the automotive R&D outlays in transportation R&D accounting suggests a much larger enterprise than is betrayed by the data on centralized, public funding support from the federal government.

Regardless of the true magnitude and intensity of total transportation-related R&D expenditures (statistics which are likely to remain shrouded in uncertainty and ambiguity), one cannot evaluate transportation R&D efficiency or effectiveness based on expenditures alone. The next chapter explores other, non-financial factors that may be of importance.
CHAPTER 5: COORDINATION AND INTEGRATION IN TRANSPORTATION R&D

In analyzing how research and development may be better able to contribute to improvements in the transportation system, it is vital to consider not only the overall level of resources committed to the R&D activities (e.g., the magnitude of R&D expenditures) but also the architecture of the system, the nature of the research undertaken, and the results of that research. As noted in a previous chapter, transportation R&D activities are an integral part of the overall transportation system; because systems by definition consist of elements that interact regularly as part of a larger whole, this implies that an “R&D system” must include mechanisms for organizing its components and enabling control of or communication among those elements. That is to say, a system must have both a structure and a means of organizing or coordinating activities within that structure (although both the system structure and the communication and coordination protocols may evolve over time). Furthermore, it is necessary also to consider the nature of the R&D projects themselves. In the context of overall transportation system needs, how appropriate are the content and scope of research projects and programs? Are the goals of transportation R&D activities properly aligned with those of the operational transportation system? Finally, of course, the effectiveness of the linkages between transportation R&D and transportation practice influences the impact of R&D activities. New technologies and knowledge generated within the transportation R&D system may have little practical utility without robust testing, demonstration, marketing, and other forms of deployment and implementation support.

This chapter discusses a number of issues related to these aspects of the transportation R&D system. The next section briefly discusses the potential to improve performance metrics,
and the remainder of the chapter focuses on issues of coordination and integration in transportation R&D. The arguments developed herein are not intended to offer a comprehensive treatment of any of these topics (a task beyond the scope of the thesis because each issue could easily be the subject of an in-depth, stand-alone study); rather, the objective is to demonstrate how improvements along these dimensions may be possible and how they relate to the performance of transportation R&D.

5.1 R&D Evaluation Methods and Metrics

Assessing the effectiveness or efficiency of R&D requires having knowledge of not only the costs of undertaking those activities but also the benefits that are attributable to them. As shown in the previous chapter, data for the cost side of transportation R&D cost-benefit assessment is available but incomplete. On the benefits side, reliable, quantifiable, and objective data is even scarcer; the benefits of research are notoriously difficult to measure, especially in a sector like transportation in which the role of private markets in signaling the value of innovations may be quite weak. Another fundamental limitation to assessing the results of research is the obstacle of selecting an appropriate time frame for assessment; some applied research programs and projects may be expected to have short-term payoffs, but the temporal separation between riskier or more basic research and its eventual benefits may be very long (e.g., decades or more). The National Academies have analyzed the difficulties of evaluating research (specifically, of research undertaken by the federal government) and found that benefits

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9 As one study concludes, “economists are not able to estimate the benefit-to-cost ratio ‘at the margin’ for fundamental science (that is, the marginal rate of return—or how much economic benefit is received for an additional dollar invested in research), and it is this information that is needed to make policy decisions.” See: Evaluating Federal Research Programs: Research and the Government Performance and Results Act (1999). Committee on Science Engineering and Public Policy. Washington, DC, National Academies Press.
may come in the form of knowledge advancement, knowledge application, human capital development, and mission advancement (for federal agencies) but that the unique characteristics of research investments mean that “expert review is the most effective mechanism\(^{10}\) for evaluating the quality, leadership, and relevance of research” (Evaluating Federal Research Programs 1999).

Because of the impediments to measuring research outcomes, the predominant paradigm—aside from periodic expert peer review—in transportation R&D involves assessing the results of research according to observable output metrics. As a transportation academic, Elizabeth Deakin, explained in testimony to the U.S. Congress,

> ...many transportation agencies evaluate the research they fund only on output measures (e.g., the main evaluation criteria are whether required products were produced on time and on budget, not whether the projects produced new knowledge, altered practice, or improved conditions. The same is true...for most on-the-ground transportation projects: they are evaluated on design compliance and whether they are on time or on budget much more often than they are graded on whether they actually improved services, the economy, or quality of life. (Deakin 2009)

Believing that an institutionalized emphasis on convenient metrics rather than on ultimate value creation from research and development activities is unhealthy for the system (establishing incentives that do not directly align with true R&D objectives), Deakin has argued that shifting toward outcome-focused expectations—metrics more closely reflecting the impact of research—could help to improve transportation R&D results (Deakin 2009). This belief in the importance

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\(^{10}\) The other mechanisms identified in the study were bibliometric analysis, economic rate of return, case studies, retrospective analysis, and benchmarking, each of which was judged useful for certain purposes but more limited in overall quality and scope than expert peer review.
of establishing expectations and metrics focused on ultimate goals rather than on easily-measured but imperfect proxy metrics is echoed elsewhere. The Transportation Research Board has found, for example, that “despite multiple sources of funding for research and technology development, the ability to estimate the relative benefits of various investments in highway research and technology development is often lacking” and that, subsequently, “the outcomes of research and technology development often are not used to determine future investment priorities” (Transportation Research Board 2009a). In another recent report, the National Research Council has identified a lack of appropriate performance metrics for infrastructure systems (like transportation) as a detriment to effective decision-making about investment in those systems; the NRC argues further that increased transparency as a result of these metrics would improve the quality of public dialogue about infrastructure issues: “If stakeholders are to understand fully what is at risk and what choices need to be made, the public dialogue needs to be recast as a discussion on how best to provide essential services—as opposed to its current focus on the merits and deficiencies of individual physical systems” (National Research Council 2009). While the NRC’s recommendations are focused on operational infrastructure systems, the shared themes with Deakin’s call for better performance measures in transportation R&D are clear. Devising and adopting outcome-based performance metrics can be no panacea, but in both research and practice, such a change could help shed light on the true benefits of investments and facilitate better-informed decision-making regarding similar future investments.

5.2 Coordination of R&D

Coordination of various R&D activities is a vital function of an effective R&D system, and it is one for which the U.S. transportation system has been frequently criticized. The clearest and broadest existing mandate for research oversight may lie with USDOT’s Research and
Innovative Technology Administration, which bears responsibility for overseeing all USDOT R&D activities, including specified coordination, facilitation, and evaluation roles. While RITA’s fulfillment of this mission appears to be improving, assessments of its performance have found that reality falls short of the coordination mandate (Government Accountability Office 2006). In 2007, a blue-ribbon commission created by Congress to study the problems of the national transportation system, after finding fault with existing transportation R&D coordination and oversight, included in their final report a recommendation for establishing a federal transportation program entitled, “Research, Development, and Technology: A Coherent Transportation Research Program for the Nation” – a wryly phrased suggestion clearly reflecting the commission’s dissatisfaction with the status quo (Transportation for Tomorrow 2007). This suggestion is in line with many observers who believe that the federal government, because of its position and resources, is best suited to undertake the role of gathering, synthesizing, and sharing information on the full range of transportation R&D activities undertaken nationally (and internationally) and that it should also take a lead role in identifying gaps in research and coordinating efforts to close those gaps. Improved coordination may also contribute to a reduction in potentially wasteful, unintentional duplication of activities, and increasing the flow of information among various actors in the R&D system may help to mitigate the detrimental effects of current segmentation (or fragmentation).

Coordination brings activities into common action and may take many forms, and it should not be confused with a formal command-and-control or hierarchical regime, which is but one method of coordinating activities within a system. In fact, command-and-control systems lie at one end of the range of coordination methods for economic and social systems; at the other end are pure market-based systems in which information is assumed to be complete and freely
available, enabling all agents within the system to make decisions, take action, and exchange goods and services according to individual incentive structures.

5.2.1 Government Leadership and Market Signals

Although the federal government has been seeking to strengthen its formal oversight and coordination mechanisms for its own transportation R&D activities, the Transportation Research Board has characterized the transportation research and development system overall as a market, utilizing a simple, stylized market model in which government buys “scientific and technological goods and services...from a variety of organizations and institutions” (Transportation Research Board 2009a). In the knowledge-driven economy of the United States, TRB notes, a critical question is whether markets and market signals are able to “stimulate...innovation at the level necessary” to achieve desired transportation-related objectives. In the highway sector especially, TRB has found that “technology development and innovation have often not kept pace with the growth in traffic and its attendant challenges,” and that the “relationship between government and markets in promoting or impeding the identification and diffusion of solutions...remains a conundrum with many conflicting answers” (Transportation Research Board 2009a).

As in the operational transportation system, the transportation R&D system is fragmented, following “any other division or segmentation of the traditional markets” (Transportation Research Board 2009a). Generally speaking, the infrastructure market segment is driven primarily by the public sector, while operations and equipment markets are more heavily influenced by private sector stakeholders. Citing the collective goods nature of much transportation innovation (especially in the transportation infrastructure sector) and associated free-rider problems as the primary economic justification for government intervention in the transportation R&D market, TRB argues that public sector leadership is necessary to mitigate the
risks of certain R&D activities and to facilitate partnerships that provide private-sector researchers with incentives to undertake R&D with potential public benefit that, because of the difficulty of appropriating benefits to the investor (or inventor), would be underprovided by the private markets alone.

In Table 10, a summary of the characteristics of the national highway innovation system, first prepared and published by the TRB, is reproduced. Several of these items foreshadow themes that will be further discussed in Chapter 5, but for now it is important to note that the TRB assessment concludes that high levels of public sector involvement at multiple levels generally complement rather than substitute for market-based coordination and that, measured by several innovation-related metrics, the system remains fairly inefficient or ineffective at producing breakthrough innovations and/or integrated, systems-level improvements.

5.2.2 Plans, Frameworks, and Visions as Coordinating Mechanisms

Market-based mechanisms are well-entrenched in the transportation R&D community, and resistance to stronger top-down control (by, for instance, the federal government) is high. According to TRB, “Public research proposals compete for funding, while local groups and business groups seek to influence decisions for the content and use of earmarked funds according to their vast array of competing and diverging interests...nonmarket-based coordination is relatively lacking, with no centralized process by which a research agenda is defined” (Transportation Research Board 2009a). There is growing emphasis, though, on strengthening coordination mechanisms that rely primarily on information gathering and dissemination while preserving most entrepreneurial research opportunities. Such mechanisms may take the form of strategic plans and roadmaps, research frameworks, and vision statements intended to communicate high-level priorities or articulate common goals around which the R&D
Table 10: The U.S. National System of Highway Innovation
Adapted from: (Transportation Research Board 2009a)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>U.S. Surface Transportation Innovation System</th>
<th>TRB Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authority sharing between federal and state governments</td>
<td>Considerable and increasing</td>
<td>FHWA shares authority with 50 states and Congress</td>
</tr>
<tr>
<td>Involvement with the public sector</td>
<td>High</td>
<td>Federal system of innovation interactions with other sub-national public research programs through initiatives such as the Pooled Fund Research Program</td>
</tr>
<tr>
<td>Nonmarket coordination</td>
<td>Limited to absent</td>
<td>Government is relatively passive and disjointed</td>
</tr>
<tr>
<td>Specificity of innovations</td>
<td>Considerable</td>
<td>Federal government has particular emphasis on applied technology</td>
</tr>
<tr>
<td>Discontinuity of innovations</td>
<td>Varies, but typically is significant</td>
<td>Some innovation streams are integrated; others are not. Use of roadmaps is intended to increase continuity of research.</td>
</tr>
<tr>
<td>Systemic nature of innovations</td>
<td>Very often quasi-public institutions such as TRB stimulate integrated research</td>
<td>Historically the nature of innovation development was reductionist – roadmaps and strategic planning leading to more systemic view of innovations</td>
</tr>
<tr>
<td>Extent of intermodal research</td>
<td>Varies, but has been historically low</td>
<td>Recent efforts have been made at the highest levels of the Department of Transportation to promote intermodal research.</td>
</tr>
</tbody>
</table>

As noted in Table 10, TRB believes that use of technology roadmaps and strategic planning is already facilitating a shift towards a more systemic approach to innovation. However, critics argue that
the strategic plans put in place by USDOT in recent years remain too limited in scope to catalyze real change—and that, in any case, USDOT’s low level of interaction with other relevant stakeholders and agencies would doom a broadly-framed strategic plan if one was developed. As Deakin has pointed out,

Compared to the EU and other economically advanced countries, the USDOT’s strategic plan is narrowly framed; for example, there is no clear mention of global warming or many other environmental issues, and such matters as transportation’s role in economic development, in social equity, and in quality of life are not given much attention. Further, the scope of the USDOT’s collaborations with other federal agencies is quite limited and appears to be narrower in some cases than Congress apparently contemplated. (Deakin 2009)

Others have focused not on the role of formal strategic plans or roadmaps but rather on the use of less-prescriptive frameworks and visions. For instance, the National Research Council has advocated development of a framework to guide efforts to renew critical infrastructure—a crucial and daunting challenge in transportation as well as other infrastructure sectors. In the NRC’s words:

Although technological advances, community-based initiatives, and financing options offer the promise of new ways to approach critical infrastructure renewal, they have often been ad hoc, often focusing on one issue, one type of system, or one set of solutions. By concentrating on single projects, technologies, financing mechanisms, or narrowly defined objectives, ad hoc efforts run the risk of wasting scarce resources and increase the probability of serious, unintended consequences. A framework is needed to create a structure within which ongoing activities, knowledge, and technologies can be aligned and leveraged to support critical infrastructure renewal and also to help achieve some of the nation’s 21st century imperatives. (National Research Council 2009)
While further developing and utilizing holistic planning approaches seems to be a promising strategy for increasing coordination and improving results in transportation R&D, it is important to note that the success of any such approach is likely to be highly dependent on the degree to which it has been inclusive of a wide range of transportation stakeholders, including end-users of the transportation system (USDOT 2008). In a market-based system, a vision can provide direction only so long as the actors within that market share the vision and are motivated to work within its guiding framework.

5.3 Systems Integration in Transportation and Infrastructure R&D

Improving coordination is one potential step toward improving the transportation R&D system, but, narrowly defined, such a strategy does not address more fundamental issues regarding the organization of the system or the scope of research projects and programs conducted within it. As has been stated previously, the extensive segmentation of the nation’s transportation system—a characteristic which heavily influences the organization of R&D activities as well as transportation practice—contributes to the formation and perpetuation of “silos” of information, expertise, and decision-making that raise barriers to high-level systems optimization. Promoting advances toward substantive integration—that is, redesigning structural boundaries rather than simply improving the linkages between existing divisions—of transportation R&D activities offers a strategy that is conceptually differentiable (although not wholly independent of) the support of better coordination. This section discusses two systems-integration related perspectives that, if used to guide transportation R&D, might provide promising ideas for performance improvement strategies.
5.3.1 Transportation as an Integrated System

As stated in an earlier chapter, the transportation field is well-accustomed to the use of systems concepts, and five possible levels at which transportation can be studied have been identified: component, modal subsystem, modal system, multi-modal system, and enterprise. Most work in transportation has been done at the modal system level or below, but there is growing momentum toward raising the emphasis on multi-modal and enterprise-wide analysis and decision-making. Various forms of the term “integration” have become popular keywords in transportation planning, but in practice integration remains more of an aspirational goals statement than an objective description of fact. The USDOT operates under a mission statement that explicitly promotes integrated solutions; it states that the USDOT’s purpose is to “foster innovations leading to effective, integrated, and intermodal transportation solutions” (USDOT 2006b). Expanding on this, the USDOT strategic plan states that:

USDOT should look at the transportation enterprise from a multimodal and department-wide perspective as a larger system in which interactions and interdependencies occur among modes, as they do between transportation and other large-scale societal and natural systems such as the economy, land use, national defense, and the environment. The nine modal agencies – with their own statutory requirements and narrow missions – seldom take such a broad and systems-level approach to programming their RD&T. (USDOT 2006b)

Thus, USDOT recognizes both the desirability of improving systems-level integration of the national transportation system at a level higher than is common today and the entrenched organizational and cultural barriers to implementing such a reform. The 1991 passage of the Intermodal Surface Transportation Efficiency Act was a landmark for its promotion of intermodal transportation analysis and policy, but progress towards fully-integrated multi-modal
approaches to transportation system planning, design, and management has been slow. More aggressively encouraging R&D stakeholders to embrace multi-modal and enterprise-wide perspectives in their work may provide a transitional step toward realizing benefits from multi-modal integration in practice.

5.3.2 **Infrastructure Integration: A Multi-Systems View**

Building on this concept, extending the systems integration paradigm beyond the transportation sector may offer even more possibilities to facilitate improvements in the transportation system; transportation is just one of the complex systems sectors that characterize a modern economy, and looking to these other sectors may provide useful ideas for research and innovation in transportation. For instance, an important area of work in the systems domain is the expansion of knowledge about interdependencies among different infrastructure systems. Interdependencies exist among components and subsystems of a given infrastructure system as well as among different types of infrastructure systems, yet these linkages have traditionally received little attention from researchers, designers, or operators of infrastructure. In transportation, interactions and interdependencies among different modes have a significant effect on the efficiency and performance of the transportation system as a whole, but most transportation knowledge and authority is vested in modally-oriented institutional structures. Accidents, acts of terrorism, and natural disasters have served as stark reminders that interdependencies among different infrastructure systems, like power and transportation, are critical vulnerabilities in these systems, and better understanding these interdependencies may not only facilitate improved security and reliability but also may provide opportunities to reconfigure infrastructure systems in ways that improve efficiency or fundamentally alter the delivery of services.
Higher-level integration should not be pursued blindly, however; as noted earlier, both centralized, system-level planning and more decentralized approaches have theoretical costs and benefits, and informed choices among these trade-offs should be the basis of selecting the scale and scope for system-level analysis, design, and management. Gifford writes that, “On the one hand, strong system level planning may enable the achievement of system level changes that would otherwise be difficult to achieve. On the other, system level choices may suppress diversity and may lead to ‘wrong’ decisions being universally or widely applied” (2005).

Carefully conceived systems integration incorporating a multi-sector view of infrastructure systems may create opportunities to develop new approaches for rationalizing existing infrastructure systems, for enhancing the capabilities of legacy infrastructure systems, and for redefining roles and responsibilities at various levels of government and across public and private sectors to improve infrastructure service delivery. Championing such an approach, the National Research Council has written:

A world of new possibilities and approaches to infrastructure renewal will open up if we choose to think about critical infrastructure more holistically, in terms of the services that these systems provide—water, wastewater removal, power, mobility, and connectivity—and as part of a strategy for meeting other national imperatives. To paraphrase Albert Einstein, “the significant problems we face cannot be solved at the same level of thinking we were at when we created them. (National Research Council 2009)

5.4 A Conceptual Model for Guiding Infrastructure Research and Development

Research, development, and eventual deployment of new policies, technologies, and strategies will be critical to the success of any serious effort to develop and implement solutions to transportation and infrastructure challenges. A conceptual framework (shown in Figure 14),
which organizes infrastructure issues into three domains, may be a useful tool for developing R&D strategies. In the framework, each of the three dimensions is informed by the broad perspective on infrastructure outlined previously in this paper, and the three dimensions should be viewed as integrated parts of a holistic approach to infrastructure systems development and provision. Although the relationships between the three domains can be quite complex, a basic conceptual understanding that technologies are integrated into systems, which are in turn enabled and governed by policies, provides a starting point for discussion.

The policy domain includes activities such as identification and evaluation of presently available infrastructure policies, associated institutions, organizational structures, and financing mechanisms. Policy-focused analysis can address demand-side management of infrastructure, although policy has significant implications for supply-side alternatives as well. Infrastructure policy choices establish the framework within which many stakeholders interact to deliver infrastructure services, including establishing the missions of public-sector agencies and governing the conduct of business and formation of partnerships with private sector entities. Particularly in the public sector, further exploring the merits of emphasizing delivery of
infrastructure services over provision of infrastructure facilities is an important part of policy
domain activities.

The technology domain emphasizes R&D in areas like new materials, new infrastructure
construction technologies, and novel technologies to make transportation rolling stock more
efficient. Technology-focused R&D includes both basic and applied research into new
technologies as well as technology transfer and adaptation (e.g., scans of other economic sectors
or international markets for promising technologies not yet integrated into U.S. infrastructure
systems).

Finally, research and related development and deployment activities in the systems
dimension emphasize the interactions of different systems and sub-systems within the broad
domain of physical infrastructure, including exploration of the potential to reorganize or
transform systems for provision of better services. The confluence of technology and market
factors has in the past demonstrated the ability to spur significant technological and structural
change in industries that did not previously appear to have much interaction or integration. For
example, television, telephone, computer, and other telecommunications and media industry
segments historically each have had separate trajectories and business models, but the interaction
of technologies, market forces, and policies has fundamentally reshaped the telecommunications
and media industries in the past two decades. Vertical integration and distinct technology
solutions for each of these sectors have weakened, and horizontal organizations providing
technology platforms, software, or consumer interfaces have grown in prominence. The
potential may exist to leverage technological developments and complementary policies or
strategies to effect similar changes in infrastructure systems. True multi-modal integration of the
transportation system might yield levels of mobility and access that cannot be delivered by the present system, which is dominated by vertical integration along modal lines.
CHAPTER 6:
CONCLUSIONS

Infrastructure systems are central to quality of life and economic competitiveness in nations worldwide, but daunting challenges stand in the way of providing systems capable of delivering needed infrastructure services. In the United States, the transportation system, which is widely considered to be the nation’s largest infrastructure system, provides a case study of the complex investment, design, and operations-related problems of infrastructure service provision. An effective and efficient research and development system is needed to support efforts to devise solutions to these problems; the nation is served by a large and well-developed transportation R&D system, but given the magnitude of outstanding needs for new packages of technologies, systems, and policies and the persistence of resource shortfalls, it is appropriate to re-examine all aspects of the transportation R&D enterprise in search of strategies for improving its performance.

Transportation R&D activities are funded and performed by a large number of organizations, but the decentralization and deficiency in proactive coordination of this effort make it difficult to quantitatively assess the magnitude of the investment with confidence. The federal government, which is the largest source of funding in this sector, spends in excess of one billion dollars annually, with air transportation R&D receiving the largest share of investment. At the USDOT, R&D budget levels have fluctuated in real terms, but a gradual decline in the R&D share of USDOT’s budget is evident over the last decade. Two very limited assessments of transportation R&D intensity compared to other industries and other federal mission sectors both show low levels of R&D in transportation compared to all of the other points of comparison.
This result might logically lead to the conclusion that transportation R&D expenditures should be increased, which is indeed a common position within the transportation R&D community. With complex challenges ahead in the transportation and infrastructure sectors, the effectiveness of R&D will be critical, and increasing investment in R&D might well be beneficial. Spending more, however, provides no guarantee of better results, especially in the realm of research and development; and the nature of the investment in transportation research and development will be as crucial as its magnitude in determining its ultimate effect. Although funding may dominate much of the policy discourse in transportation research and practice, the potential value of ‘rethinking the system’ has received some notable attention as well. For instance, in testimony before a Congressional committee in 2009, a former director of USDOT’s Research and Innovative Technology Administration argued strongly in favor of systemic reforms:

“In order [to shape a National Transportation Research program that has the potential to transform how we move people and goods across the nation and indeed re-establish our global position as leaders of a new, innovative and efficient transportation paradigm], we will need to rethink our approach to transportation research…and establish structural improvements that can ensure the level of innovation that is often promised but rarely realized.” (Brubaker 2009)

The best research program one can imagine cannot guarantee desired performance outcomes; the transfer of research results into the operational transportation system is a complicated process, and its efficacy is crucial to realization of system performance goals. Furthermore, a general lack of accessible data and transparency in transportation R&D funding is an impediment to making objective policy decisions regarding R&D investment levels and
priorities. Improved data collection and analysis could provide a better factual basis for policy decisions and improve the prospects for R&D coordination and performance-based management.

Ultimately, facilitating a paradigm shift toward more effective provision of infrastructure services and the development of infrastructure systems is an unavoidably complex task, and there is no single formula that, if followed, will bring about the needed changes. As policy-makers continue to debate the merits of alternative approaches, it is vital that they consider the role of research and development not in the context of a static R&D system but rather with an understanding of the possibilities that would arise from improving R&D coordination, integration, and similar characteristics.
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