Synthesis of Climate Change and Transportation Research Efforts at State DOTs, State Universities, and Federal Level

Requested by:

American Association of State Highway and Transportation Officials (AASHTO)

Standing Committee on the Environment

Prepared by:

ICF International
9300 Lee Highway
Fairfax, Virginia 22031

July 2011

The information contained in this report was prepared as part of NCHRP Project 25-25, Task 76, National Cooperative Highway Research Program, Transportation Research Board.

Acknowledgements

This study was requested by the American Association of State Highway and Transportation Officials (AASHTO), and conducted as part of the National Cooperative Highway Research Program (NCHRP) Project 25-25. The NCHRP is supported by annual voluntary contributions from the state Departments of Transportation. Project 25-25 is intended to fund quick response studies on behalf of the AASHTO Standing Committee on the Environment. The report was prepared by ICF International. The work was guided by a task group chaired by John Zamurs (NY DOT) which included Gina Campoli (VT DOT), Garth Hopkins (CA DOT), Alex Kasprak (MA DOT), Karin Landsberg (WA DOT), Jeff Houk (FHWA), Caroline Paulsen (AASHTO), John Thomas (US EPA) and Robert Kafalenos (FHWA). The project was managed by Nanda Srinivasan, NCHRP Senior Program Officer.

Table of Contents

1 INTRODUCTION

This white paper provides a synthesis of climate change and transportation research efforts at state DOTs, state universities, and the Federal government based on a recent study requested by the National Cooperative Highway Research Program (NCHRP) and American Association of State Highway and Transportation Officials (AASHTO).

The white paper begins with a brief background and overview of the study methodology. The remainder of the white paper is organized into two sections, *Climate Change Mitigation* (Section 2) and *Climate Change Adaptation* (Section 3). Each section provides a synthesis of recent climate change and transportation research at the Federal, state DOT, and university levels. Federal research is presented by the agency conducting the research, while state DOT and university research is presented by topic area. Where appropriate, research summaries and specific examples of research initiatives are provided.

Research gaps and needs are summarized at the beginning of each section and described in detail at the end of the mitigation and adaptation sections.

1.1 Background

Transportation is the second largest source of greenhouse gas (GHG) emissions in the United States, responsible for 26 percent of gross U.S. emissions.[1] Climate change has the potential to significantly impact transportation systems and infrastructure. For example, sea level rise could flood road networks, storm surges could damage bridges, and drastic temperature changes could increase the wear and tear of highways and rail lines. Therefore, it is important for the U.S. to examine potential mitigation strategies to reduce GHG emissions and begin to facilitate strategic adaptation planning and implementation.

Due to significant GHG emissions in the transportation sector and the risks posed by climate change impacts, the field of climate change and transportation is rapidly evolving and is the focus of considerable research. In October 2009, *Special Report 299: A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy* was completed by the Transportation Research Board (TRB) of the National Academies. *Special Report 299 (SR 299)* provides an overview of national research efforts being conducted by the federal government, identifies research gaps, and ultimately lays out a research plan for transportation and climate change focusing on several mitigation and adaptation research topics.

While *SR 299* provides a valuable overview of national initiatives, a similar analysis of state and local climate change and transportation research is essential to provide a full picture of the current research being conducted in this field. This white paper supplements *SR 299* by providing an overview of state DOT and university-led research efforts related to climate change and transportation in recent years. In addition, this white paper provides an update on federal research initiatives conducted since the release of

SR 299 in October of 2009. Using the mitigation and adaptation research topics described in *SR 299* as a foundation, this paper highlights a subset of recent and ongoing transportation and climate change research. In addition, the paper identifies topics on which research has recently focused significant resources and identifies major research gaps. Ultimately, this white paper will allow investigators to better understand research needs in the areas of climate change mitigation and adaptation as it relates to transportation at the federal, state and local level.

1.2 Study Methodology

To identify recent and ongoing climate change and transportation research, a literature review was conducted using the Transportation Research Board's *Research in Progress*, *Science Direct*, and *Academic Search Premier* databases. The field of transportation and climate change research is vast, so in order to gain insight into the areas of research relevant to NCHRP the literature review was confined to research conducted since 2005. The literature review focused primarily on ground transportation research.

Research initiatives were categorized by the mitigation and adaptation *topics* they addressed--defined in sections 2.1 and 3.1 of this report. In addition to the mitigation and adaptation topics addressed, studies were classified by *type* of research, as in *SR 299*. Research types include: foundational, policy, practitioner-oriented, and data/models/tools. Foundational research is "the development of expert synthesis of existing information into guidance for policy makers, practitioners, and researchers. These individual projects can be thought of as building blocks for subsequent policy decisions based on the best available information and as guides to subsequent research, analysis, and data collection."[2] Policy research addresses the effectiveness or implementation of specific policies to achieve mitigation or adaptation goals. Practitioner-oriented research is geared to aid transportation practitioners in the implementation of mitigation or adaptation strategies. Data, models and tools include both developing parameters for transportation and climate change modeling, and the development of models, collection of data, or other tools such as websites.

The literature review was supplemented by the results of an online survey of state DOTs conducted under NCHRP 25-25 (65) used to assess their energy data collection and GHG inventory efforts. As part of this survey, state DOTs were asked if they are conducting any research on climate change, as well as for information on research being conducted by universities in their state. Of the 28 state DOTs that participated in the survey, 12 state DOTs responded positively to conducting some research relating to climate change at their agency. In addition, 10 states responded that they were aware of either general research or specific research projects being conducted at universities in their state relating to climate change and transportation. Survey respondents, university researchers, and federal employees were also contacted to provide further clarification of research identified by the NCHRP 25-25 (65) survey and to expand on information found through the literature review.

SR 299 provided an overview of climate change and transportation research conducted by agencies at the federal level. As a follow-up to the work conducted for *SR 299*, research programs and initiatives undertaken by these federal agencies since the release of *SR 299* in October, 2009 were examined. In addition, this study discusses recent trends in federal climate change and transportation research.

The results of the literature review, survey, and subsequent follow up were used to identify existing research gaps for state DOTs, universities, and federal agencies. As this synthesis only represents a sampling of university research, certain gaps may be addressed by studies not identified in this analysis.

2 TRANSPORTATION RESEARCH PROGRAMS ADDRESSING CLIMATE CHANGE MITIGATION

Mitigation is an essential component of climate change research as it targets the cause of anthropogenic climate change—GHG emissions. Climate change mitigation policies aim to reduce sources of GHG emissions or to enhance GHG sinks in order to reduce the magnitude of anthropogenic climate change impacts in the future. According to the Intergovernmental Panel on Climate Change (IPCC), mitigation involves "technological change and substitution that reduce resource inputs and emissions per unit of output."[3] The primary driver of anthropogenic climate change is GHG emissions from the combustion of fossil fuels for energy use, and thus mitigation research tends to focus on reducing energy consumption.

For decades, transportation research has addressed energy use and pollution resulting from the transportation system. This includes a vast field of research ranging from models of multimodal transportation demand and land use patterns to detailed examinations of the materials used in roadside infrastructure and performance of specific engine technologies. This body of research has implications for climate change mitigation, as strategies to reduce energy use and tailpipe emissions from the transportation system inevitably reduce GHG emissions. Despite this connection, this synthesis focuses on the smaller body of work that directly addresses energy reduction strategies in the context of climate change. Therefore, the studies identified do not represent the entire field of research, but rather the studies encountered that address these topics *in the climate change context*. As an exception, a number of crosscutting-initiatives that address climate change as one component of broader research programs are also included, as well as studies that refer to emission reductions, whether or not those studies focus specifically on GHG emissions.

This section provides an overview of major mitigation research initiatives and trends identified through a robust sampling of recent state DOT, university, and federal research initiatives. Due to the considerable breadth and depth of transportation research being conducted, this synthesis is not intended to be a comprehensive review of all climate change mitigation and transportation research.

2.1 Mitigation Research Categorization and Summary Findings

Climate change and transportation mitigation research is classified into 7 categories or topics, which incorporate those identified in the mitigation research plan of *SR 299*: (1) measuring or estimating GHG emissions from transportation; (2) vehicle technology, (3) fuel technology; (4) construction, maintenance, and operations; (5) land use, planning and multimodal transportation; (6) regulatory instruments and pricing strategies; and (7) vehicle/highway system operations. Table 1 defines each of these topics and provides examples of mitigation strategies considered under each topic. Many research initiatives address multiple mitigation topics at once.

Table 1. Mitigation Topics: Definitions and Examples

Mitigation Topic	Definition	Examples
Measuring or Estimating GHG Emissions from Transportation	Research that quantifies emissions of CO_2, CH_4, or N_2O from transportation	Emissions models; vehicle performance testing
Vehicle Technology	Strategies that reduce the fuel consumption of internal combustion engine gasoline or diesel vehicles	Fuel efficiency improvements, hybrid internal combustion engine technologies
Fuel Technology	Initiatives that involve less carbon-intensive alternative transportation fuels to replace gasoline or diesel fuels.	Biodiesel, compressed natural gas (CNG), electric vehicles, hydrogen/fuel cell vehicles
Construction, Maintenance, and Operations	Initiatives that reduce GHG emissions associated with the life-cycle of transportation infrastructure and systems, including construction, maintenance, operations, and administration.	Construction equipment, pavement mixes, pavement practices, work-zone management, LED traffic lighting, LEED-certified transportation buildings, mowing practices, roadside vegetation
Land Use, Planning and Multimodal Transportation	Strategies to reduce GHG emissions through more compact land use, changing travel behavior to reduce passenger trips, or shift travel to more efficient modes such as intercity passenger bus, rail, and high speed rail	Land use planning, nonmotorized transportation, mode shift, transit carpooling, vanpooling, car-sharing, tele-working, tele-shopping, tele-education, tele-medicine
Regulatory Instruments and Pricing Strategies	Regulatory instruments and policies to encourage behavior changes that reduce GHG emissions. Pricing strategies include changing how much and how often drivers pay.	Vehicle feebates, GHG-based vehicle registration fees, congestion pricing, parking fees, pay-as-you-drive auto insurance, mileage-based user fees, tolls, fuel taxes
Vehicle Operations and Highway System	Strategies to reduce emissions through transportation system management and highway operations.	Speed management, congestion relief, incident management, bottleneck removal, traffic smoothing, roundabouts, traveler information services, air traffic routing, airport operations, anti-idling, logistics improvements

This study identified considerable climate change mitigation and transportation research being conducted at the federal, state DOT and university levels.[1] While state DOT and university research has addressed reducing energy use and minimizing impacts of transportation on the environment for decades, research that specifically addresses these topics in the context of GHG emissions and climate change is increasingly common in recent years.

Since the release of *SR 299*, more federal resources have been directed towards climate change mitigation research, and federal research initiatives are increasingly focusing specifically on climate change. The Department of Energy provides the largest amount of federal funding for climate change research, but the U.S. Department of Transportation and Environmental Protection Agency are also sponsoring a number of climate change and transportation research initiatives. The concept of sustainable communities and "livability" is a prominent theme in current federal transportation research, and these initiatives often incorporate climate change within their goals.

Research could focus on ways to better disseminate existing research findings to the public and to policy-makers at the state level through educational campaigns, case studies, and synthesis materials and resources.

There is a vast amount of research being conducted by state DOTs and universities on mitigation and transportation. The most common mitigation topic encountered in state DOT research was *Construction, Maintenance, and Operations* research, followed by *Vehicle Operations and Highway System*—suggesting that state DOTs are most interested in understanding the direct and indirect GHG effects associated with their transportation systems as well as options available to reduce these emissions. Sampled university research most commonly addressed *Measuring or Estimating GHG Emissions from Transportation* and *Fuel Technology*---suggesting that universities are heavily focused on the broad GHG reduction potential made available through new technologies as well as providing practitioners with the tools to quantify, and plan ways to reduce, GHG emissions.

While state DOT and university research was most common in these topic areas, research in all topic areas can be considered fair to strong. There are areas for improved research within mitigation topics, such as investigating outreach strategies for helping the public understand the link between their driving activities and climate change, and better understanding land-use and behavioral strategies for reducing passenger trips and encouraging more efficient modes of travel. Perhaps more importantly, however, there is a need for synthesizing findings to make the wealth of university-led research available as summaries to state DOT decision-makers. There is also a need for research into advanced mechanisms for resource and information sharing to improve collaboration and coordination among federal and state DOT initiatives.

This section, organized by federal, state, and university-led research initiatives, will more thoroughly explain the findings described above and provide specific examples of research encountered under each mitigation

[1] Climate change mitigation research is often a collaborative effort between federal agencies, state DOTs, and universities.

topic. Section 2.2 discusses federal research initiatives conducted since October of 2009, followed by recent state DOT (Section 2.3) and university (Section 2.4) research initiatives that correspond to the mitigation topics introduced in Table 1. This section concludes with a discussion of research needs and data gaps.

2.2 Federal Initiatives

The U.S. Department of Transportation (U.S. DOT), U.S. Environmental Protection Agency (EPA), and U.S. Department of Energy (DOE) perform the bulk of federal research related to transportation and GHG emissions. The Transportation Research Board's Cooperative Research Programs have also conducted a number of mitigation research studies since the release of *SR 299*. This section describes federal mitigation research being conducted by each of these agencies since *SR 299*.

In June 2009, a new interagency initiative, the Housing and Urban Development (HUD)-U.S. DOT-EPA Partnership for Sustainable Communities, was launched with a climate change focus within its goals. This partnership aims to promote sustainable/livable communities, and recognizes that providing multi-modal transportation choices and mixed use development is important to reducing GHG emissions. The concepts of livability and sustainable communities are a prominent theme among federal transportation research, and have been incorporated into the work of U.S. DOT's operating administrations and EPA. The livability and sustainable communities focus has been incorporated into the work of U.S. DOT's operating administrations. Although much of the program funding is allocated for grants and technical assistance, there has been some research performed under this program. For example, U.S. DOT released a research paper in March 2011 highlighting the current implementation of livability principles within the context of the federal-aid highway program. The report highlights challenges facing U.S. DOT's Federal Highway Administration (FHWA) and other transportation agencies in changing traditional planning approaches and evolving institutional frameworks to more effectively incorporate livability principles. It offers a sampling of strategies and tools for implementing livability through different programs and agencies, and across various scales as they pertain to highway program planning and development.[4]

2.2.1 U.S. Department of Transportation

Since the release of *SR 299*, U.S. DOT has continued to conduct and support research on various climate change topics and continues to provide technical assistance and outreach related to transportation and climate change. Below is a review of new research conducted by U.S. DOT's Center for Climate Change and Environmental Forecasting and by the main U.S. DOT operating administrations that focus on climate change, which includes the Federal Highway Administration, Federal Transit Administration, Federal Aviation Administration, and the Research and Innovative Technology Administration.

Center for Climate Change and Environmental Forecasting

The Center for Climate Change and Environmental Forecasting (the Center),[5] which is overseen by senior executives from all of U.S. DOT's operating administrations, continues to serve as a focal point for multi-modal climate change research, technical assistance, partnerships, and outreach for all of the operating administrations within U.S. DOT. As mentioned in *SR 299*, one of the Center's major recent initiatives was the development of the Transportation and Climate Change Clearinghouse, which commenced in 2009 and is now fully developed.[6] The Clearinghouse provides general information about transportation and climate change and, more specifically, information about GHG inventories, forecasts, and transportation data; methodologies for analyzing GHG emissions from transportation; GHG emission reduction strategies; climate change impacts and adaptation; state/local actions and policies; and federal actions. The Center is intended to be a one-stop source of information for all levels of government, the private industry, and non-profits.[7]

The Center continues to support research on multi-modal strategies to increase energy efficiency and reduce GHG emissions, including emission comparisons for various modes of transportation. The Center also performs research for the development or improvement of modeling tools for transportation energy use. In April 2010, U.S. DOT released a *Report to Congress: Transportation's Role in Reducing U.S. Greenhouse Gas Emissions,*[8] which was prepared by the Center. This comprehensive report examines GHG emissions levels and trends from transportation and analyzes strategies to reduce GHG emissions. Identified strategies include: efficiency standards, market incentives, economy-wide price signal, research and development, and transportation planning and funding programs.

The Center is also performing outreach and is involved in partnerships with other agencies. For example, the Center is working with EPA to implement truck stop electrification on interstate corridors to reduce GHG emissions from idling, parked trucks.

Federal Highway Administration (FHWA)

In defining its role in climate change, FHWA states that it "is committed to improving transportation mobility and safety while protecting the environment, reducing GHG emissions, and preparing for climate change effects on the transportation system. FHWA is actively involved in efforts to initiate, collect, and disseminate climate-change-related research, and to provide technical assistance to stakeholders."[9] The Surface Transportation Environment and Planning Cooperative Research Program (STEP) funds research programs under FHWA. The FY2010 STEP Research Plan[10] provides a more detailed summary of climate change activities than the FY2009 STEP Research Plan,[11] indicating an expanded focus on climate change at FHWA since the release of *SR 299*. The FY2010 budget was slightly higher than the FY2009 budget ($1.59 million in FY2010 as compared to $1.25 million in FY2009). Additional climate-related activities highlighted in the FY2010 STEP Research Plan included disseminating information on climate change mitigation and adaptation; conducting a pilot project to investigate GHG emissions reduction potential from the integration of transportation, land use, and climate change; providing technical assistance to states to develop climate action plans; and developing a methodology for establishing GHG emissions targets.

Another new area in the FY 2010 STEP Research Plan was $150,000 for research efforts related to sustainable transportation.

In addition to the climate change efforts listed in the FY2010 STEP Research Plan, FHWA's transportation and climate change website[12] highlights the following ongoing and current research:

- VMT and GHG Emissions. This research is examining how new energy and GHG performance goals complement or conflict with transportation system performance. The research also examines how these performance goals inform the development of effective policy frameworks to slow vehicle miles travelled (VMT) growth and reduce GHG emissions.

- Sustainability and Transportation. This research focuses on incorporating sustainability into transportation planning to address challenges facing the nation's transportation infrastructure, including, among other challenges, climate change and GHG emissions.

- Transportation Planning and Energy Consumption. Research is being performed to develop tools to assist planners with reducing energy consumption from the transportation system. This research will assist with the development of a roadmap for implementing strategies to reduce transportation energy demand at a "megaregional" level (i.e., at a level that includes multiple metropolitan planning organizations [MPOs]).

FHWA has also supported other recent research initiatives including the development of a transportation and sustainability guidebook, a carbon sequestration pilot program, and research regarding the incorporation of climate change into transportation planning.

In the future, FHWA will be focusing more resources on moving past the conceptual idea of incorporating the reduction of GHG emissions into the planning process, and working towards the development of associated methodologies. FHWA is also exploring the role of intelligent transportation systems (ITS) in reducing GHG emissions.[13] FHWA has also increasingly focused on peer exchanges, workshops, and outreach to states and MPOs. For example, in 2010 and in 2011, FHWA is partnering with the American Association of State Highway and Transportation Officials (AASHTO) to conduct a series of webinars on climate change, as well as organizing a series of workshops for state DOTs and MPOs.[14]

Federal Transit Administration (FTA)

FTA has increasingly focused on climate change since the release of the *SR 299* report. FTA provides technical assistance, grants, and research and policy support to address climate change. As highlighted in *SR 299*, FTA funds research related to energy efficient vehicles. In FY2008, FTA developed an Electric Drive Strategic Plan for electric drive rail vehicles and buses. FTA has a 20-year vision for this program and will fund a five-year research program for transit electric drive beginning in 2010.[15] FTA also continues to fund the development of fuel cell bus technology through the National Fuel Cell Bus Program, a $49 million program in partnership with the Department of Energy that currently has demonstration projects running or

planned with several transit agencies.[16,17] FTA also performs policy research related to climate change. Recent reports include:[18]

- Public Transportation's Role in Responding to Climate Change.[19] FTA analyzed data from the National Transit Database, DOE, and EPA on ridership, fuel use, and emissions. This analysis, updated in January 2010, showed GHG savings from the use of public transportation.

- Transit Greenhouse Gas Emissions Management Compendium.[20] FTA sponsored research performed by the Georgia Institute of Technology to provide current information to transit operators, regional transportation planners, and decision-makers about how to incorporate GHG reduction strategies into decision-making. The report was released in January 2011.

- TCRP Synthesis 84: Current Practices in Greenhouse Gas Emissions Savings from Transit.[21] The 2010 FTA-funded report reviews transit agencies' role in reducing GHG emissions. The report also lists current practices for several agencies.

- Transit Green Building Action Plan.[22] Per a Congressional request, FTA performed an analysis of green transit buildings and identified ways to encourage the development of these buildings in FTA programs. The plan was submitted in July 2009.

- The Route to Carbon and Energy Savings: Transit Efficiency in 2030 and 2050.[23] This TCRP-funded project identifies a portfolio of strategies that transit agencies can take to reduce the energy use and GHG emissions of their operations and estimates the potential impacts of those strategies in 2030 and 2050. The report was completed in November 2010.

Along with FHWA, FTA also supported the development of the 2009 Moving Cooler[24] study, which reviews strategies to reduce transportation emissions through reduced VMT. Another new major FTA initiative is the Transit Investments for GHG and Energy Reduction (TIGGER) program. Through this program, FTA provides grants to transit agencies for investments in technologies that reduce GHG emissions.

Federal Aviation Administration

As noted in *SR 299*, the Federal Aviation Administration (FAA) has joined with National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) in an Aviation Climate Change Research Initiative (ACCRI). ACCRI supports the environmental goals of NextGen—FAA's overhaul of the National Airspace system—to mitigate the impact of aviation GHG emissions on global climate change.[25,26] ACCRI is focusing on the basic science associated with the effects of aviation on climate change and has identified the current state of research and research needs on these topics. In 2011, FAA plans to "develop and demonstrate the feasibility of use of alternative fuels in aircraft systems, including successful demonstration and quantification of benefits, and establish, develop, and implement metrics to better assess climate impacts from commercial aircraft operations."[27] The Continuous Lower Energy, Emissions and Noise (CLEEN) Program is a partnership with industry to address the

environmental goals of NextGen by developing and demonstrating clean, energy efficient technologies; demonstration and assessment of renewable alternative aviation fuels; and assessing engine retrofits or re-engines.[28]

FAA is also a participant in the Sustainable Aviation Guidance Alliance (SAGA), which in fall 2009 published a "Sustainable Aviation Resource Guide" and accompanying database of sustainable aviation practices, meant to be a living database for the aviation industry.[29] FAA also sponsors the Airport Cooperative Research Program (ACRP), which is sponsoring several projects to assess airports' ability to reduce their carbon footprint. The projects address practical GHG emission reduction strategies for airports, an analysis of legal hurdles to airport sustainability initiatives, a primer on carbon credits as a revenue stream for airports, and the potential for newer, quieter aircraft to use more fuel-efficient departure procedures without negatively impacting surrounding communities.[30]

Research and Innovative Technology Administration

The Research and Innovative Technology Administration (RITA) is advancing research into the GHG emissions reduction potential of ITS strategies through its "Applications for the Environment Real-Time Information Synthesis (AERIS). The program is intended to "generate and acquire environmentally-relevant real-time transportation data, and use these data to create actionable information that support and facilitate "green" transportation choices by transportation system users and operators." The program was formed in March 2010 and in October 2010 awarded seven projects to university research teams. The program roadmap currently runs through 2014.[31]

2.2.2 U.S. Environmental Protection Agency (EPA)

Climate change mitigation is a key focus area within EPA; it is one of the five priority goals of EPA Administrator Lisa Jackson.[32] Research related to transportation and climate change mitigation within EPA is mainly performed within the Office of Transportation and Air Quality (OTAQ) and the Office of Sustainable Communities (formerly the Office of Smart Growth). Details of current research are described below.

Office of Transportation and Air Quality (OTAQ)

OTAQ's Clean Automotive Technology Program,[33] which is operated within EPA's National Vehicle and Fuel Emissions Laboratory, conducts research and development of technologies related to engines, hydraulic hybrid vehicles, and alternative fuels. The goal of the program is to research and advance technologies that increase fuel efficiency and reduce emissions, including GHG emissions. Research under this program is performed in three main areas: engines that emit fewer GHG emissions, hydraulic hybrid vehicles (HHVs), and alternative fuels, such as alcohol fuels, which can potentially lower GHG emissions. Much of the research within the Clean Automotive Technology Program focuses on HHVs. EPA has worked with industry to demonstrate hydraulic hybrid delivery trucks and it is developing hydraulic hybrid

yard hostlers, vehicles that transport cargo at ports, rail yards, and warehouses. In January 2011, EPA announced that it was partnering with Chrysler to develop HHV technology for light-duty vehicles. EPA will work with Chrysler to develop a series of HHV minivans. EPA anticipates an increased fuel economy of up to 60 percent in city driving, and a 30-35 percent improvement overall. One of the program focuses is to demonstrate improved fuel economy and reduced GHG emission from HHV technology for the light-duty fleet.[34]

EPA also performs research for the development of models. For example, OTAQ developed the Motor Vehicle Emission Simulator[35] (MOVES) model which estimates emissions for mobile sources. In August 2010, EPA released a new version of MOVES, to incorporate new car and light truck energy and GHG rates. Similarly, the Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA), updated in 2010, estimates the cost of technologies that automobile manufacturers must apply to achieve varying levels of fleet-wide GHG emissions.[36] EPA recently updated the carrier model used to measure environmental performance under the SmartWay Transport Partnership as well. This program is a partnership between EPA and the freight industry to improve fuel efficiency and reduces emissions, including GHGs. Administrator Jackson lists emissions reductions from the SmartWay program as contributing to EPA's 2015 emissions reductions goal. [37]

EPA also recently released a report reviewing potential changes in emissions due to improvements in travel efficiency.[38] The purpose of this report is to establish a reliable and useful source of information on the effectiveness of transportation control measures (TCM) for changing travel activity and to quantify the potential national emission reductions that could result from those changes using EPA's MOVES2010 emission model. This study is intended to support a national policy-level assessment of TCMs by using actual metropolitan planning organization (MPO) travel demand modeling results and examining their effectiveness at a national scale.

EPA also performs research in support of rulemakings. There have been two major joint rulemakings related to climate change and transportation since 2009. In April 2010, EPA and U.S. DOT's National Highway Traffic Safety Administration (NHTSA) passed a joint rulemaking for a GHG and fuel economy program for light-duty vehicles. In November 2010, EPA and NHTSA proposed a new program to improve fuel efficiency and reduce GHG emissions for medium- and heavy-duty engines and vehicles.[39] One of the EPA-funded reports for the medium- and heavy-duty rulemaking was a study investigating costs for strategies to reduce GHG emissions for heavy-duty on-road vehicles. EPA also sets volume requirements of renewable fuel in transportation fuel through its National Renewable Fuel Standard. Regulations under this program are currently being updated.[40] As part of proposed revisions to the regulations, EPA reviewed lifecycle GHG emissions from increased renewable fuel use.[41]

Office of Sustainable Communities

EPA's Office of Sustainable Communities oversees the agency's work on smart growth policies and activities related to the Partnership for Sustainable Communities. Smart Growth promotes compact development, mixed land uses, and transit oriented development, all of which reduce VMT and GHG emissions. In recent years, the Office has focused largely on providing technical assistance and outreach to communities in the form of tools, guidebooks, and grants. However, the Office still performs some research relevant to transportation and climate change.

2.2.3 U.S. Department of Energy

The Department of Energy (DOE) has the largest federal investments in climate change research, spread across multiple sectors.[42] All of their work is focused on mitigation. DOE's climate change research directly related to transportation is focused on vehicle and fuel technologies, including hybrid vehicles, fuel cells, advanced combustion engines, and biofuels. DOE has been working to reduce transportation energy consumption and GHG emissions since the early 1990s and many of their programs are now quite mature, achieving mid-term targets for new technologies at this time. The biggest change in DOE programs over the past two years has been the funding infusion from the American Recovery and Reinvestment Act (ARRA) in 2009.

The newest research initiative at DOE is the newly funded Advanced Research and Projects Agency – Energy (ARPA-E). This is a major new initiative to overcome long-term and high-risk technical barriers for clean energy. The program was formed in 2007 but remained unfunded until it received $400 million from ARRA in 2009. As of spring 2010, the program had funded a series of projects within each project area. Relevant program areas to transportation include:

- Electrofuels – to advance new ways to make liquid transportation fuels that rely on microorganisms instead of petroleum or biomass (13 projects)
- Batteries for Electrical Energy Storage in Transportation (BEEST) – to develop a new generation of ultra-high energy density, low-cost battery technologies for long electric range plug in hybrid electric vehicles and electric vehicles (10 projects)
- Other Projects: Vehicle Technologies – a variety of projects, focused largely on electric or hybrid electric technologies such as electrical energy conversion, magnets, generators, fuel cells, and automobile waste heat recovery (6 projects)

Besides funding ARPA-E, ARRA provided $25 billion in funding to DOE. A total of $16.8 billion of that has gone to the Office of Energy Efficiency and Renewable Energy (EERE), the primary office within DOE whose research addresses transportation technology and climate change. Several vehicle and fuel technology projects received approximately $2.6 billion in funding.[43] These projects are generally expansions or continuations of existing DOE research areas and include:

- Heavy-Duty Truck and Passenger Vehicle Efficiency
- Alternative Fueled Vehicles Pilot Grant Program (through the Clean Cities program)
- Advanced Battery and Electric Drive Component Manufacturing Grants (the largest funding recipient)
- Transportation Electrification Projects
- Advanced Biofuels Research and Fueling Infrastructure
- Advanced Biorefinery Projects
- Fuel Cell Market Transformation

The National Laboratories are also major contributors to climate change research at DOE and other agencies. Their work largely supports DOE's project areas and many of their projects have been active for many years, like most of the DOE climate programs. In addition to research and development, the National Renewable Energy Laboratory has technology validation programs to "evaluate the performance of new vehicle and fuel technologies as they move into commercial use." This work includes hydrogen fuel cell bus evaluations in partnership with the Federal Transit Administration.

2.2.4 Transportation Research Board – Cooperative Research Programs

The Transportation Research Board (TRB) of the National Academy of Sciences manages cooperative research programs in highways, transit, airports, and freight for the states, transit agencies, and airports. TRB also manages the Strategic Highway Research Program 2 (SHRP 2) which has work related to climate change. TRB currently maintains a climate change specialty page that "serves as a gateway to TRB activities and products addressing transportation and climate change."[44] The page includes a link to related projects from the Research in Progress database, used to compile state DOT and university research in this study, and to related TRB reports.

As of April 2011, Cooperative Research Programs (CRP) had 26 active or completed research projects and 37 reports related to climate change and transportation, nearly all published since 2009. Some of these projects have been discussed above under their sponsoring agencies. CRP research projects generally focus on mitigation strategies in planning and operations, though some also deal with quantification and modeling methods and the interface between transportation GHG reduction and existing regulations. The majority of the cooperative research projects were for the National Highway Cooperative Research Program (NCHRP), including the active committees addressing long-range strategic issues for the transportation industry (20-83), planning (08-36), and the environment (25-25).

2.3 State DOT Initiatives

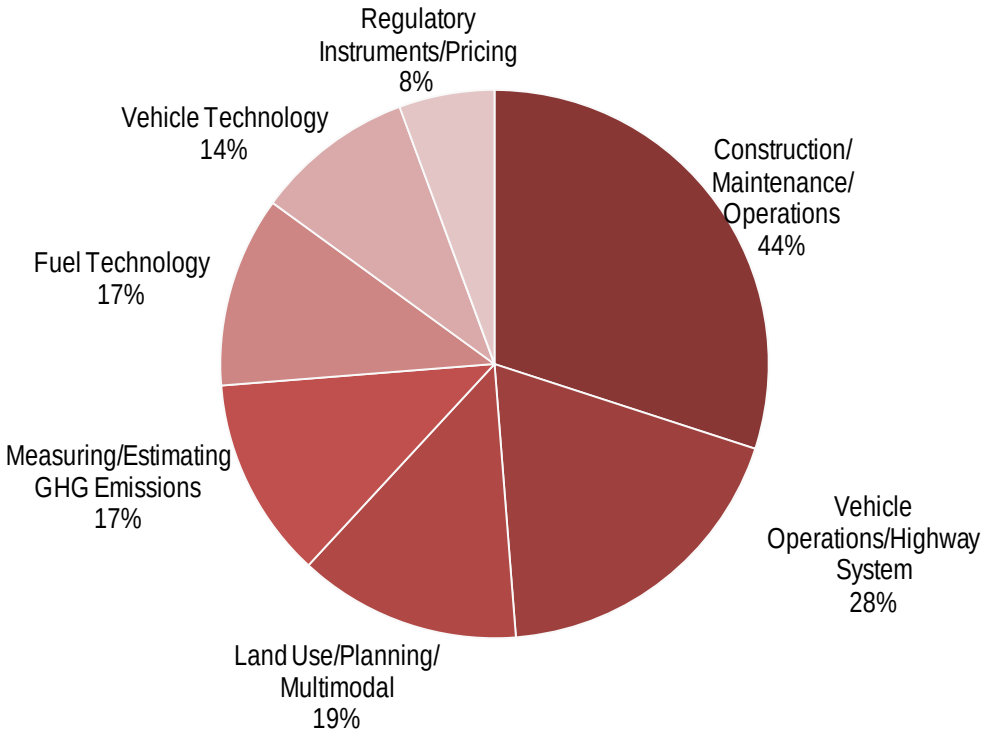
Over 100 state DOT climate change transportation mitigation research projects or initiatives were identified for this analysis. The primary mitigation focus area being addressed by state DOTs is *Construction,*

Maintenance and Operations, which includes GHG emissions associated with transportation infrastructure such as streetlights and highways. The second-most addressed mitigation research topic of state DOTs is *Vehicle Operations and Highway System*, which includes strategies to reduce emissions through transportation system management and operations, such as congestion relief and speed management. The third most common research topic encountered under mitigation was *Land Use, Planning, or Multimodal Transportation.* The percent of state DOT research projects that address each topic is shown in Figure 1; as many research initiatives addressed multiple mitigation topics, the sum of these percentages is greater than 100.

Box 1 - State DOT Mitigation Research at a Glance

- Over 100 research initiatives identified
- Primary Focus Area: Construction, Maintenance, and Operations

Figure 1 - Percent of State DOT Studies that Address Each Mitigation Topic



Below is a description of the types of projects encountered under each mitigation topic, as well as an illustrative list of example state DOT projects. The projects are organized into the following sections, corresponding to the relative number of research projects surveyed that fell within each mitigation topic, as shown in Figure 1:

- Construction, Maintenance, and Operations;
- Vehicle Operations and Highway System;
- Land-Use, Planning, and Multimodal Transportation;
- Measuring or Estimating GHG Emissions;
- Fuel Technology;
- Vehicle Technology;
- Regulatory Instruments and Transportation Pricing; and
- Cross-Cutting Initiatives.

Each section provides a brief overview of the types of research surveyed, and provides a few example projects that demonstrate the topic.

Construction, Maintenance, and Operations

Of the research initiatives surveyed, 44 percent of studies addressed GHG emissions in construction, maintenance, and operations. The most common topic of research under construction, maintenance and operations is the GHG emissions impact and performance of various construction materials--including pavement and concrete (see Figure 1). Other programs under the construction, maintenance and operations category include training DOT staff to reduce GHG emissions and energy use associated with DOT operations, replacement of DOT fleet vehicles with more efficient or alternatively fueled vehicles, and developing a GHG footprint of state DOT operations. For example, California, New York, and Florida have implemented anti-idling programs to reduce emissions from heavy equipment during construction and maintenance of transportation infrastructure.

Box 2 - Research Spotlight: GHG Emissions from Construction Materials

At least 7 state DOTs are examining the energy or GHG impact of construction materials such as asphalt and concrete. For example:

- Utah DOT is optimizing the cementitious materials content in concrete for transportation applications
- Michigan's DOT is establishing a service lifetime carbon footprint for hot mix asphalt (HMA)and Portland Cement Concrete Pavements for reconstruct and rehabilitation projects
- New York and Washington DOTs are examining the energy and environmental benefits of using recycled asphalt and concrete for highway construction
- California, Nebraska and South Dakota DOTs are examining the performance and application of warm mix asphalt in their regions

Some key example construction, maintenance, and operations projects are described briefly below.

- *Identifying Excessive Vehicle Idling in the Caltrans Fleet,* California DOT (2007).[45] This research quantified the fuel savings and emissions reductions that could be achieved by applying idle shutdown systems to the Caltrans fleet.

- *Environmental Management Systems for Transportation Maintenance Operations,* New Jersey DOT and Rutgers Center for Advanced Infrastructure and Transportation (2009).[46] This study developed a system for monitoring carbon emissions produced during DOT operations and maintenance activities.

- *Green and Economic Fleet Replacement Modeling,* Oregon DOT and Oregon State University (2009).[47] This research examined the green fleet replacement criteria being used by state DOTs in the U.S., with the ultimate goal of developing replacement models that use GHG emissions and equipment energy source as replacement criteria.

Vehicle Operations and Highway System

The second most encountered state DOT mitigation research topic was vehicle and highway system operations, which includes strategies to reduce emissions through transportation system management and operations such as congestion relief and speed management. For example, a number of state DOTs have programs, research projects, or pilot studies on intelligent transportation systems (ITS) and congestion relief strategies. Other examples of research initiatives or programs under this category are: traffic calming methods (District of Columbia), general traffic operations research (Washington), and assessing the carbon footprint of highway travel (New York). Of the identified state DOT research initiatives, 28 percent addressed vehicle and highway system operations.

Below are examples of research being conducted relevant to vehicle and highway system operations.

- *Reducing Energy Usage through Transportation Planning for Mega Regions*, South Carolina DOT and Clemson University (2008). This research produced tools that enable comparisons of planning scenarios to reduce the energy consumption, and thus emissions, of the transportation system.[48]

- *Carbon Highway Footprinting Research,* New York DOT (2008). This research identified areas of high commercial vehicle energy consumption and emissions, and produced a model to identify and help correct "poorly designed" roadways in order to gain emissions and other environmental benefits.

Land Use, Planning and Multimodal Transportation

The third most common state DOT research topic encountered under mitigation was land use, planning, or multimodal transportation. This topic was addressed in about 19 percent of state DOT research initiatives surveyed. Examples of types of research encountered under this category are: transit-oriented development (California) and development of planning models that incorporate GHG emissions estimates (e.g., California and Oregon). Examples include:

- *Sustainability Impact of Multimodal Corridor Improvements in Urbanized Area,* Maryland State Highway Administration and University of Maryland (2011).[49] This research project will develop

methods to estimate the impact of multimodal corridor improvements on GHG emissions, as well as other sustainability metrics.

- *Davis Shopping Study*, California DOT and the University of California, Davis (2009).[50] This research examined the impact of a new Target store on the Davis community's shopping driving behavior and vehicle miles traveled.

- *Climate Change Decision Tools in Multimodal Transportation*, New Mexico DOT (2004).[51] This study developed a policymaking framework for GHG mitigation in a multimodal transportation setting, including addressing innovative approaches that could be adopted by NMDOT professionals in terms of multimodal operations, construction, design, and maintenance.

Measuring or Estimating GHG Emissions

Research that involved the measurement or estimation of GHG emissions typically overlapped with at least one of the other mitigation categories. For example, a number of construction, maintenance, and operations studies involved the quantification of GHG emissions from different construction materials (see Box 1). About 17 percent of state DOT research studies encountered involved quantifying GHG emissions. Several of the example studies listed under the previous topics also quantified GHG emissions; an additional example is described below (this example is also classified under construction, maintenance, and operations).

- *Carbon Footprint for Hot Mix Asphalt and Portland Cement Concrete Pavements,* Michigan DOT (2009). This study established a life-cycle carbon footprint for both hot mix asphalt and Portland cement concrete for reconstruct and rehabilitation projects.

Fuel Technology

The primary types of alternative fuel research encountered were for biodiesel, hydrogen fuel cells, and plug-in hybrid electric vehicles. These alternative fuel technologies were evaluated primarily in the context of department-owned vehicles, although some (e.g., California DOT's Sustainable Transportation Energy Pathways Program) evaluated alternative fuels for vehicles in general. In addition to vehicles, some studies also addressed the development of refueling infrastructure to support alternative fueled vehicles. Below are examples of research conducted under the fuel technology category.

- *Evaluation of Biodiesel in Department Vehicles,* Arkansas State Highway and Transportation Department (2008).[52] This study examines the cost-effectiveness of using biodiesel in the DOT's fleet by testing four vehicles, two using diesel and the other two using biodiesel.

- *Evaluation of Fuel Cell Transit Buses*, Connecticut DOT (2009).[53] This report describes Connecticut's experience with a demonstration prototype fuel cell bus in Connecticut Transit's fleet in comparison with three new diesel buses.

Vehicle Technology

Of the state DOT research initiatives in this study, only about 9 percent addressed reducing the fuel consumption of vehicles. Examples of vehicle technology research are:

- *Studies in Consumers and Automotive Fuel Economy: A Qualitative Field Test of the Effects of Driver Feedback on Automotive Fuel Consumption,* California DOT and the University of California, Davis (2007).[54] This study examines the effect of energy use feedback on drivers of conventional LDVs and hybrid-electric vehicles.

- *Dual-Drive Production Prototype Project,* New Jersey DOT and Rutgers University (2008).[55] This program develops fuel-efficient vehicle retrofits, with a goal of producing a plug in hybrid electric vehicle with a 30 to 40 mile range.

Regulatory Instruments and Transportation Pricing

Regulatory instruments and transportation pricing was the least common category of mitigation research encountered in this study, suggesting that state DOTs are more focused on researching technologies and practices than on the effects of potential regulatory instruments. Examples of research that was identified include:

- *Innovative Contracting Strategies for Combating Climate Change,* Maryland DOT (2009).[56] This project investigated innovative green contracting strategies and project-level implementation plans for reducing GHG emissions in Maryland.

- *Carbon Pricing Policies and Their Effect on Greenhouse Gas and Criteria Emissions,* California DOT and the University of California Davis (2010).[57] This research studies the impact of pricing GHGs on emissions in the transportation sector.

Cross-cutting Initiatives

In addition, several cross-cutting initiatives were encountered that addressed climate change as part of a broader program, or focused on sustainable transportation as a whole with implications for climate change. As an example:

- *Assembly Bill (AB) 32: Global Warming Solutions Act Transportation Sector White Paper and Stakeholder Workshop,* California DOT (2008).[58] This research examined the emissions impact of intelligent transportation systems, mobility, and land-use management strategies.

Many state DOTs are conducting research on sustainability that directly relates to GHG emissions reductions through reduced energy use, although climate change is not always directly mentioned in these studies. For example, a number of state DOTs mention energy use reduction strategies in their long-term transportation plans which will impact GHG emissions.

Finally, state DOTs perform a large portion of their research in collaboration with universities. Research initiatives that are sponsored by state DOTs but conducted by universities were discussed in this section. However, there is also a vast field of research being conducted by universities outside of their work with state DOTs. University-led mitigation research initiatives are discussed in the following section.

2.4 University Initiatives

Thousands of universities in the United States are conducting transportation research to some degree, whether through regional or national transportation research centers; in individual university departments such as Civil and Environmental Engineering, Planning, and Public Policy departments; or through the work of individual professors. University transportation research projects are often conducted in collaboration with state DOTs, other universities, federal research programs, or private/nongovernmental organizations.

The U.S. DOT's Research and Innovative Technology Administration (see Mitigation: Federal Initiatives) provided $5.9 million in funding to over 60 university transportation centers in fiscal year 2008.[59] Several highly active contributors to climate change transportation research include UTCs located at the:

- University of California – UCTC (includes UC Davis, UC Berkeley, UCLA, UC Irvine)
- University of Washington
- Oregon Transportation Research and Education Consortium

Box 3 -University Mitigation Research at a Glance

- Over 150 research initiatives identified
- Primary Focus Areas: Quantifying GHG Emissions and Alternative Fuels

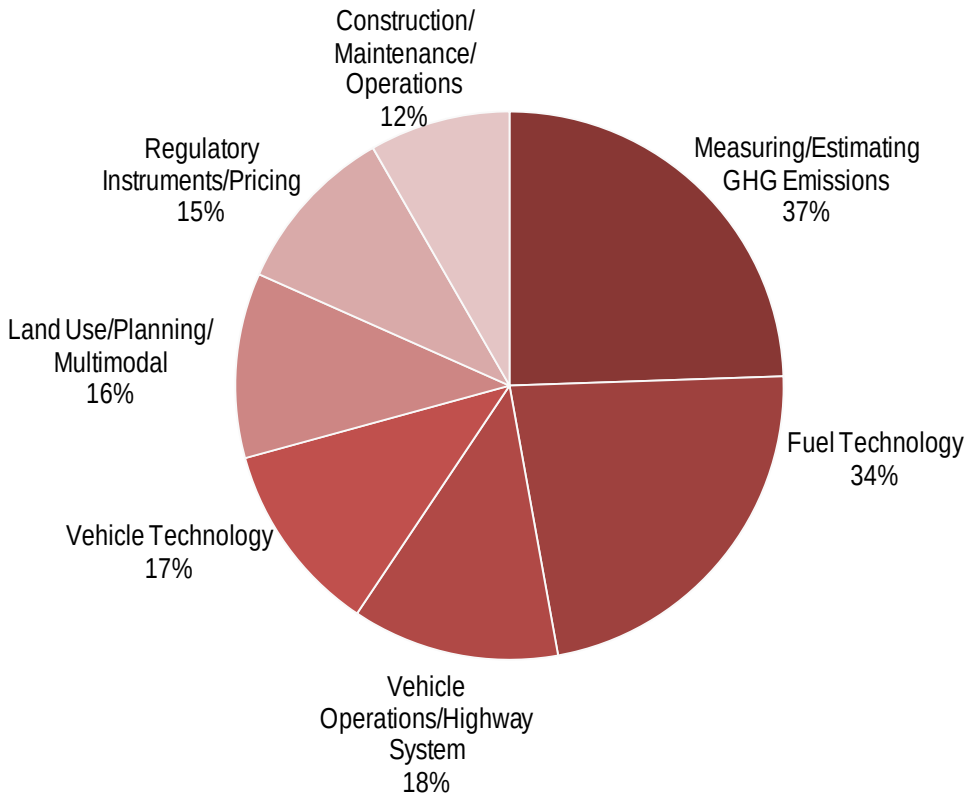
This synthesis focused on research being conducted at UTCs, in particular the UTCs from the universities noted above, as well as other research initiatives identified through a literature review which included an examination of the research contained in the TRB's *Research in Progress* database,[60] *Academic Search Premier,*[61] and *Science Direct.*[62]

Over 150 relevant university research initiatives were identified by this sampling. The largest mitigation research topic identified in these studies was *Measuring and Estimating GHG Emissions*. The second-most encountered mitigation research topic by universities was *Fuel Technology*.

The remaining mitigation topics were relatively evenly spread, addressed by between 12 and 18 percent of studies encountered. As with state DOTs, a number of studies also addressed "sustainable transportation," but did not always explicitly mention climate change. Unlike state DOTs, however, the emphasis of university-led research was the measurement or estimation of GHG emissions and fuel technologies, while the most common state DOT topic—Construction, Maintenance, and Operations of Transportation Infrastructure—was the least-encountered university-led research topic. This may indicate that universities

are focused on accounting methods and assessing the viability of various technological options while state DOTs are more focused on real-world applications of this knowledge. The percent of university research initiatives that addressed each mitigation topic is shown in Figure 2 - Percent of University Studies that Address Each Mitigation Topic . As with state DOT initiatives, most studies surveyed addressed multiple mitigation topics, and thus the sum of the percentages in Figure 2 - Percent of University Studies that Address Each Mitigation Topic are greater than 100.

Figure 2 - Percent of University Studies that Address Each Mitigation Topic



Examples of research addressing each mitigation topic are provided below. The projects are organized into the following sections, corresponding to the relative number of research projects surveyed that fell within each topic shown in Figure 2 - Percent of University Studies that Address Each Mitigation Topic :

- Measuring or Estimating GHG Emissions;
- Fuel Technology;
- Vehicle Operations and Highway System;
- Vehicle Technology;
- Land-Use, Planning, and Multimodal Transportation;
- Regulatory Instruments and Transportation Pricing; and
- Construction, Maintenance, and Operations;

- Cross-Cutting Initiatives.

Each section provides a brief overview of the types of research encountered, and provides a few example projects that demonstrate each mitigation topic.

Measuring and Estimating GHG Emissions

The quantification of GHG emissions was the most common mitigation topic encountered in university studies, addressed by about 37 percent of university research initiatives. As with state DOT research, studies that quantified GHG emissions typically overlapped with other mitigation topics. Two main types of studies were encountered under this category: research that quantifies the CO_2, CH_4, or N_2O emissions from specific vehicle technologies, and research that estimates the GHG emissions from fleet composition or other transportation scenarios. For example, the University of California system researched multiple scenarios for achieving an 80 percent reduction in GHG emissions by 2050, a stated goal of the state of California. Several examples of research quantifying GHG emissions are provided below.

- *An Evaluation of Mobile Source Greenhouse Gas Modeling Approaches for Traffic Management Assessment,* Texas Southern University and Texas A&M (2009).[63] This research collected data and modeled GHG emissions from three traffic management strategy scenarios: electronic toll collection, high occupancy vehicle (HOV) lanes, and traffic signal coordination.

- *Optimizing the Supply Chain for Cost and Carbon Footprint,* University of Minnesota, Minneapolis (2009).[64] This research developed supply chain models that minimize cost or maximize profit while minimizing or restriction carbon emissions.

- *The Transportation Greenhouse Gas Inventory: A First Step toward City-Driven Emissions Rationalization,* University of California, Berkeley (2008).[65] This study proposed a new inventory methodology for estimating city GHG emissions, including life-cycle transportation emissions and attributing emissions to trip ends, as opposed to geographically.

- *Regional On-Road Vehicle Running Emissions Modeling and Evaluation for Conventional and Alternative Vehicle Technologies,* North Carolina State University (2009).[66] This study presents a methodology for estimating on-road vehicle CO_2 and other pollutant emissions from alternative fuels and alternative propulsion technologies.

- *Development and Validation of a Testing Protocol for Carbon Sequestration Using a Controlled Environment,* Texas A&M (2010).[67] This research will conduct initial measurements and testing in order to carbon sequestration, which will be applicable to vegetation on state DOT right-of-ways.

Fuel Technology

Many fuel technology studies also involved quantifying GHG emissions from alternative fuels. The types of alternative fuel research being conducted addresses hydrogen and fuel cell technologies, biofuels, plug-in

hybrid electric vehicles, battery electric vehicles, and compressed natural gas. A number of studies evaluated multiple alternative fuels and compared their relative GHG emissions (for example, the University of California and the University of Minnesota have *Low Carbon Fuel* research initiatives). In addition to the GHG emissions of the fuel technologies themselves, a number of studies also included research about the market penetration of alternative fueled vehicles into the vehicle fleet, and development of an alternative transportation refueling structure. Examples of university fuel technology research are provided below.

- *Minnesota Low Carbon Fuels Study,* University of Minnesota (2009).[68] This study develops a modeling analytical framework to compare economic and environmental implications of low carbon fuel standards in Minnesota.

- *Electric Bus and Inductive Power Research and Demonstration,* Kansas University (2007).[69] This project studies the feasibility of pairing a Wampfler Inductive Power charging system with an electric bus in a series of real-world scenarios.

- *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet,* MIT Laboratory for Energy and the Environment (2007).[70] This study modeled potential emissions reductions that could be achieved through the use of electric and hybrid-electric powertrains, such as plug-in hybrid vehicles, gasoline hybrid-electric vehicles, fuel-cell vehicles, and battery-electric vehicles.

- *Comparison of Flexible Fuel Vehicle and Life-Cycle Fuel Consumption and Emissions of Selected Pollutants and Greenhouse Gases for Ethanol 85 versus Gasoline*, NC State University (2009).[71] This study compared the fuel consumption and tailpipe emissions of flex fuel vehicles that use E85 versus gasoline.

- *Transit Bus Fleet Management and Optimization Models Addressing New Engine Technologies and Emissions Constraints,* Portland State University in collaboration with King County Metro (2010).[72] The purpose of this research is to develop a new generation of fleet replacement model that incorporates new engine and alternative fuel types, which can then be applied to a case study King County Metro's bus transit fleet.

- *Energy and Greenhouse Gas Impacts of Biofuels: A Framework for Analysis,* University of California, Davis (2007).[73] This study reviewed the energy and climate change impacts of biofuels.

Vehicle Operations and Highway System

Vehicle operations and highway system research includes studies of intelligent transportation systems, the impact of freeway removal, and congestion and traffic flow issues. About 18 percent of university research initiatives involved vehicle and highway system operations. Examples of university mitigation research under this category are:

- *Incorporating Vehicular Emissions into an Efficient Mesoscopic Traffic Model: An Application to the Alameda Corridor, CA*, University of California, Irvine (2011).[74] This research created a tool for generating information on traffic dynamics and pollutant emissions on large scale networks.

- *Real-World Carbon Dioxide Impacts of Traffic Congestion,* University of California, Riverside (2010).[75] This study evaluated the traffic congestion and its impact on CO_2 emissions using detailed energy and emissions models linked to real-world driving patterns and traffic conditions.

- *"Intelligent" Ways to Cut Transportation's CO_2 Emissions,* University of California, Riverside (2010).[76] This research analyzes the impact of intelligent transportation systems on GHG emissions.

Vehicle Technology

Of the university initiatives examined, approximately 17 percent addressed reducing fuel consumption and GHG emissions through changes in vehicle technology, including the following examples:

- *Assessing the Fuel Consumption and GHG of Future In-Use Vehicles,* MIT Laboratory for the Energy and Environment (2010).[77] This research paper provides a methodology for developing plausible future transportation scenarios of vehicle technology and use and fuels on GHG emissions and energy use.

- *Understanding Household Preferences for Alternative Fuel Vehicle Technologies,* San Jose State University and the University of California, Irvine (2009).[78] This research project sampled an internet panel using the contingent ranking stated preference technique in order to quantify household preferences and tradeoffs people are willing to make for hybrid-electric vehicles.

- *Quantifying the Benefits of Hybrid Vehicles,* University of California, Davis (2006).[79] This research report described hybrid vehicle technologies and analyzed the impact of hybrid-electric vehicles on the climate and other environmental metrics.

Land Use, Planning and Multimodal Transportation

Land use, planning, and multimodal transportation research themes included the examination of bicycle infrastructure, mode shift to alternative modes of transportation, and transportation planning. Examples of research initiatives include:

- *Climate Change Considerations in Transportation Planning,* Georgia Institute of Technology (2008).[80] This research reviewed MPO and international city transportation plans to determine if climate change considerations are being addressed by transportation planning.

- *Costs and Equity of Reducing GHG Emissions through Land Use and Transportation Measures: A Comprehensive Review of the Advanced Modeling Literature for Practical Application in California*,

San Jose State University and the University of California, Berkeley (2009).[81] This research initiative expanded on a previous study that modeled scenarios of strategies to reduce vehicle miles traveled to include the cost-effectiveness, economic efficiency, and equity effects of GHG, VMT, and congestion reduction by policy and geographic area.

- *Effect of Low-Impact Sustainable Transportation Design as a Strategy for Alleviating Stormwater Runoff and Reducing GHG Emissions*, University of Connecticut (2010).[82]

Regulatory Instruments and Transportation Pricing

This category includes studies of fuel economy standards, auto pricing strategies, and other policy tools for reducing GHG emissions from transportation, such as:

- *Model of Alaska Transportation Sector to Assess Energy Use and Impacts of Price Shocks and Climate Change Legislation,* University of Alaska (2009).[83] The purpose of this research was to develop a model of Alaska's transportation sector in order to assess the impacts of GHG legislation that could affect fuel consumption or fuel prices.

- *A Review of the International Modeling Literature: Transit, Land Use, and Auto Pricing Strategies to Reduce Vehicle Miles Traveled and Greenhouse Gas Emissions,* University of California, Davis (2008).[84] This report reviews international modeling literature addressing land use, transit and auto pricing policies in order to determine a range of potential VMT and GHG reductions that could occur under these policies.

- *Use of Performance Measurement to Include Air Quality and Energy into Mileage-Based User Fees,* Texas A&M University (2010).[85] This research began to develop a pricing framework based on performance measurement incorporating air quality goals to help monitor GHG reduction and mitigation performance of vehicle mileage fee systems.

- *The Design and Estimation of a Household Vehicle Evolution and Composition Model for Assessing the Impact of Transportation Policies on Global Climate Change and Air Quality*, University of Texas, Austin and Texas A&M (2010).[86] This research developed a comprehensive vehicle fleet composition, utilization, and evolution simulator to help forecast household vehicle ownership and VMT by vehicle type.

Construction, Maintenance, and Operations

About 12 percent of university initiatives addressed emissions from construction, maintenance and operations. This does not include university research conducted in collaboration with state DOTs, which is discussed in the previous section. Examples include:

- *Feasibility of Solar Powered Traffic Signs in Houston – A Step Toward Sustainable Control Devices,* Texas A&M University (2010).[87] This project analyzes the number, types, and cost of

current traffic signs in Houston and the potential and cost of converting to solar-powered traffic signs.

- *Evaluating and Optimizing Recycled Concrete Fines in PCC Mixtures Containing Supplementary Cementitious Materials*, University of Washington (2009).[88] This research project tested the use and effectiveness of recycled concrete fines, fly ash, or granulated blast furnace slag used to reduce the carbon footprint of Portland cement concrete.

- *Roadway Construction Sustainability Impacts: A Review of Life-Cycle Assessment,* University of Washington (2010).[89] This research reviewed 14 roadway construction life-cycle analysis papers to identify main findings on the energy and GHG emissions impacts of roadway construction.

As with state DOT research, much of the research encountered addressed multiple mitigation topics at once. A few illustrative examples of cross-cutting initiatives that addressed a wide range of mitigation topics are provided below. In addition, Box 4 describes a common type of cross-cutting research, which evaluates scenarios of multiple mitigation strategies to reduce GHG emissions from the transportation sector.

- *Strategies for Reducing the Impacts of Surface Transportation on Global Climate Change: A Synthesis of Policy Research and State and Local Mitigation Strategies* - University of Minnesota (2008).[90] This research, prepared for the Transportation Research Board, suggested strategies for reducing GHG emissions in surface transportation via vehicle efficiency, VMT, construction, maintenance, and operation and administration of transportation systems using a scenario analysis.

- *An Action Plan for Cars: The Policies Needed to Reduce U.S. Petroleum Consumption and Greenhouse Gas Emissions*, MIT (2009).[91] This report provides a portfolio of policies to create a sustainable transportation sector, including near-term fuel economy standards, feebate incentive programs, fuel tax increases, driver educations, and the evaluation of alternative fuel life-cycle impacts on GHG emissions.

- *Achieving Deep Reductions in U.S. Transport Greenhouse Gas Emissions: Scenario Analysis and Policy Implications,* University of California, Davis (2009).[92] This research paper evaluates potential scenarios for reaching 50-80% reductions of GHG emissions below 1990 levels by 2050.

- *Good Practice in the Exploitation of Innovative Strategies in Sustainable Urban Transport: City Interview Synthesis*, University of California, Berkeley (2009).[93] This report included a literature review and interviews in 11 cities of the transfer of innovative sustainable transportation policies across cities.

Box 4 - Research Spotlight: Evaluating Scenarios to Meet GHG Reduction Goals in the Transportation Sector

In the last several years, a number of state-level policies and initiatives have emerged that set GHG emissions reduction targets for transportation and other sectors. A number of universities are conducting research on how to meet these state-level reduction targets, or how to reduce transportation emissions in the US transportation sector as a whole. These include, among others:

- *Meeting U.S. Passenger Vehicle Fuel Economy Standards in 2016 and Beyond,* MIT Laboratory for Energy and Environment (2010). This project models scenarios of changes to the U.S. vehicle fleet that are required to meet future fuel economy standards.
- *Meeting an 80% Reduction in Greenhouse Gas Emissions from Transportation by 2050: A Case Study in California,* University of California, Davis (2009). The purpose of this paper was to evaluate potential strategies for California to reduce transportation GHG emissions to 80% below 1990 levels by 2050 to meet the target set by the state of California.

2.5 Research Needs and Data Gaps

The above sections summarized the types of research and example initiatives conducted by federal agencies, state DOTs, and universities. This sampling of research initiatives was combined with existing literature and information from the field to identify potential research needs and data gaps in mitigation research. This section discusses federal research needs as identified by previous gap analyses, as well as state DOT and university research needs identified through this study.

2.5.1 Federal

In addition to *SR 299*, two recent reports identified research needs on the subject of transportation and climate change. In January 2010, TRB sponsored a climate change research needs workshop to review, prioritize, and refine research needs statements prepared for the workshop. This resulted in 36 discrete research proposals with more detail than *SR 299*.[94] The second report, in June 2010, was the TRB 2010 Environment and Energy Workshop: *Better Delivery of Better Solutions*. In preparation for the workshop, U.S. DOT's Volpe National Transportation Systems Center prepared a series of four white papers on research needs in climate change, sustainability, energy, and livability based on feedback from 13 TRB committees, FHWA, and AASHTO.[95]

- Between these three reports, research needs at the federal level have been well-defined for the near future. Research needs brought out through these identification projects are identified below, presented by the mitigation topics identified for this study.

- Measuring or Estimating GHG Emissions from Transportation
    - There are still substantial requests for improved understanding of certain aspects of transportation's impacts on climate change and the effectiveness of various strategies in mitigating climate change. Topic areas of interest include life cycle analysis of materials and construction, and cost-effectiveness of mitigation strategies.
    - There are needs to integrate climate change considerations into transportation models used to guide many planning and design processes. These include mode shift considerations, induced demand, and land use and transportation interactions.
    - There is a need for evaluation tools and guidance on how to properly apply various GHG emission reduction strategies.
- Fuel Technology
    - There are several research needs identified around alternative fuels, such as infrastructure needs, social costs and benefits, life-cycle GHG impacts, and policy options.
- Land Use, Planning and Multimodal Transportation
    - There is interest as well in the potential for alternative energy generation within transportation ROW or projects.
    - Planning processes need to be able to incorporate climate change considerations. This ranges from incorporating climate change into transportation scenario planning to more specific NEPA guidance on how to address GHG emissions and mitigation.

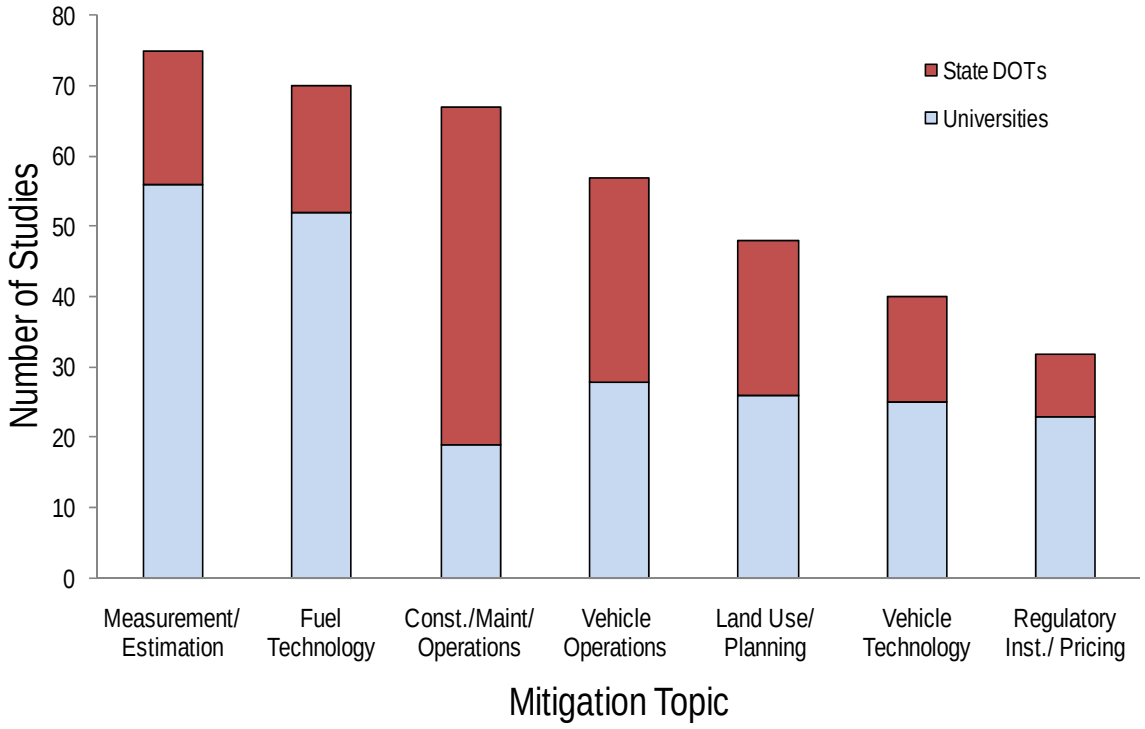
In addition to the needs identified above, there is an overarching need for improved outreach. Effective outreach will be necessary to have the public better understand the linkages between transportation and climate change and to involve the public in efforts to mitigate GHG emissions. As an example, researchers are looking for means to better disseminate their findings to policymakers and the public, including finding ways to address uncertainties around climate change. Also, educational materials and campaigns are needed to help people understand the link between transportation to climate change, and to understand the role that a community can play in mitigating climate change impacts. Research is also needed to provide decision-makers with guidance about public participation through programs and projects that deal with climate change issues.

2.5.2 State DOTs and Universities

Similar to research at the Federal level, there is a considerable amount of mitigation research being conducted at the state DOT and university level. However, this study found that research for both state DOTs and universities was most often in the form of data, models, or other tools—indicating that state DOTs are increasingly interested in methods and tools to help them with planning efforts. State DOTs appear to be focusing on practitioner-oriented research—or research into techniques for implementing mitigation strategies—while universities appear to be focusing on foundational research—development of materials to support guidance for decision-makers, practitioners, and researchers. This indicates that universities may be dealing more with the broad, foundational questions related to climate change mitigation in the transportation sector, whereas state DOTs appear to be investing more resources into mitigation research that directly relate to their activities. This finding may indicate that state DOTs are looking for ways to implement direction and guidance from federal and state initiatives as well as the recommendations that stem from university-based foundational research. As such, research that synthesizes information to provide practical steps for implementation may prove most useful to state DOTs.

Figure 3 summarizes the state DOT and university mitigation research initiatives identified by mitigation category. Each column represents a category of mitigation research that covers a broad suite of studies. The most common mitigation topic encountered was the *Measurement or Estimation of GHG Emissions*.

Figure 3 - State DOT and University Mitigation Research Distribution



The field of transportation mitigation research is well-established and vast.[2] Overall, each mitigation topic was addressed by a significant number of university and state DOT research initiatives surveyed. Even the least-encountered mitigation topic, *Regulatory Instruments and Transportation Pricing Policies*, was addressed in over 12 percent of state DOT or university initiatives. Thus, each of the mitigation topics identified is being researched.

As can be seen in Figure 3, the number of university studies surveyed outnumbered those of state DOT studies. Of the research projects sampled, state DOT research initiatives focused less on *Regulatory Instruments and Transportation Pricing* (8 percent of state DOT studies identified). As for university studies, *Construction, Maintenance, and Operations* research was mainly addressed in collaboration with state DOTs, and less by the studies led only by universities.

Research under the *Measurement or Estimation of GHG Emissions* mitigation topic was commonly conducted by universities to establish parameters for models and by both state DOTs and universities to

[2] This synthesis of climate change and transportation research represents a sampling of the vast amount of research being conducted by universities and state DOTs in the U.S. on climate change and transportation. While some sustainable transportation research initiatives or programs were included in this survey, there is a significant body of relevant research being conducted on topics directly relevant to climate change, but not within the context of climate change, that were not surveyed here.

measure the impact of changing vehicle or fuel technology, as well as traffic management strategies, on reducing GHG emissions. Most research focused on highway (light duty) vehicles, however, with fewer studies found on freight/rail or heavy duty vehicles. This finding suggests that there is a potential gap of measuring and estimating GHG emissions from freight and heavy duty vehicles.

State DOTs and universities have conducted considerable research into the various types of alternative *Fuel Technologies* available. University-led research often focuses on determining the GHG reduction potential of these fuels as well as the alternative fuel's performance as a replacement fuel. Moving forward, state DOTs will likely benefit from a synthesis of research findings that will help them quickly determine appropriate replacement fuels. Side-by-side comparisons of the costs and benefits of using replacement fuels—particularly comparisons that are case-study based—will also prove useful for state DOTs as they look to implement alternative fuel projects.

State DOTs, in collaboration with universities, are conducting research on the impact of alternative materials on GHG emissions and energy use under the *Construction, Maintenance, and Operations* mitigation topic. Previous research gap analyses[96] have recognized a need for increased attention to the energy and emissions of construction and maintenance materials over their full life cycle. In addition, this field of research would benefit from a synthesis of best practices and results for evaluating the emissions, energy saving potential, and other environmental benefits from alternative construction materials.

Future research could continue to focus on providing state DOTs with more case studies and practical approaches for implementing various mitigation measures. As an example, mitigation measures within the *Vehicle Operations and Highway System* mitigation topic area are well-researched, but could be strengthened by a synthesis of case studies that highlight effective measures to reduce GHGs through improved travel demand management, decreased congestion and idling, and effective use of technologies such as traveler information services.

The field of *Land Use, Planning, and Multimodal Transportation* encompasses a broad range of studies. One research need identified through this analysis was the coordination of land use and transportation planning scenarios between local communities and regional land use models. Several studies highlighted a need for incorporating travel behavior into MPO land use modeling at a more localized level as regional models often use average regional travel behavior parameters, which does not capture the impact of localized land use changes. There was also an expressed need to evaluate the effectiveness of public outreach and educational campaigns in encouraging mode shift to reduce GHG emissions, as well as empirical data on GHG emissions intensities of alternative modes of travel.

Increasingly, state DOTs and MPOs are looking for opportunities to promote the use of fuel-efficient vehicles, such as allowing hybrid vehicle access to HOV lanes. Research to date into *Vehicle Technology* has explored the efficiency gains of improvements to the internal combustion engine. Future research could focus on how these improvements can be transferred to on-the-ground projects and programs that

state DOTs can implement to encourage use, and to support development of performance measures for gauging the effectiveness of these projects and programs.

While the *Regulatory Instruments and Pricing* mitigation topic was less well researched than other mitigation topics for the sample reviewed by this study, there is still a fair amount of research that assesses the impacts of pricing mechanisms, such as carbon taxes, and regulatory instruments. Future research could continue to scale national models down to better understand the regional effects of regulatory instruments as well as options available to state DOTs. In particular, state DOTs may benefit from research that examines fuel-price tipping points that lead to increased multimodal transportation and reduced passenger trips due to rising fuel costs for planning purposes.

3 TRANSPORTATION RESEARCH PROGRAMS ADDRESSING CLIMATE CHANGE ADAPTATION

The second component of this white paper discusses transportation research initiatives that address climate change adaptation. Regardless of the level of future mitigation actions, changes in the frequency, intensity, and timing of climatic processes will occur. A large portion of these projected changes, such as sea-level rise, increasing temperatures, and changes in precipitation patterns will impact transportation assets, operations, and plans. The act of responding to climate impacts, either anticipatorily or reactively is referred to as climate change adaptation.

The IPCC defines adaptation as "an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Adaptation activities can be technological (such as increase sea defenses), policy-based (such as improved risk management), behavioral (such as the sparing use of water in times of drought), or managerial (such as improved forest management)". Likewise, the UNFCCC defines adaptation as "actions by individuals or systems to avoid, withstand, or take advantage or current and projected climate changes and impacts. Adaptation decreases a system's vulnerability, or increases its resilience to impacts".

In order to facilitate anticipatory adaptation and mitigate climate impacts on transportation there is a need to invest in a suite of adaptation research initiatives that are wide in scope, robust, and abundant. This chapter attempts to summarize the current transportation research initiatives that are either related or potentially relevant to climate change adaptation. The analysis will provide perspective on the state of climate change adaptation research by highlighting the most robust areas of research and identifying research gaps at the federal, state and university level.

The remainder of this Adaptation section is organized as follows:

- Adaptation Research Categorization and Summary Findings
- Federal Initiatives
- State DOT Initiatives
- University Initiatives
- Research Needs and Data Gaps

3.1 Adaptation Research Categorization and Summary Findings

Climate change and transportation adaptation research is classified into 7 categories or topics, which incorporate those identified in the adaptation research plan of *SR 299*: (1) climate change impact data and analysis, (2) risk and vulnerability assessment, (3) monitoring, (4) operational adaptation responses, (5) design standard and material adaptation responses, (6) evaluation, and (7) decision support tools. There were a number of research initiatives that addressed several adaptation topics simultaneously, and were therefore considered to be crosscutting initiatives. Table 2 below provides a brief definition and demonstrative examples for each of these adaptation topics.

Table 2. Adaptation Topics: Definitions and Examples

Adaptation Topic	Definition	Examples
Climate Change Impact Data and Analysis	Efforts to understand our current climate conditions, assess how climatic processes (e.g., temperature, precipitation, SLR) will likely change in the future, and gauge how these changes will affect other weather-related hazards (e.g., flooding, soil stability, drought).	Historical analogues, global circulation models, downscaling methods, and integrated assessment models.
Risk and Vulnerability Assessments	Initiatives that aim to assess the vulnerability (a function of exposure, sensitivity and adaptive capacity) of transportation assets to specific climate change impacts and/or quantify climate risk (function of consequence and likelihood).	Tools, frameworks, or guidance that identify vulnerable assets and/or locations, assess exposure, sensitivity and adaptive capacity (or resilience), or characterize risk. This may include understanding the change in life of facilities or identifying the modes and consequence of failure.
Monitoring	Efforts that involve monitoring technologies, which measure stresses and strains on key infrastructure and provide warning of pending failures.	Equipment or tools that measure stress, thresholds, or
Operational Adaptation Responses	Efforts that identify operational alternatives, which would reduce asset vulnerability/risk or more effectively respond to asset failure.	Strategies that manage maintenance and repair needs in a changing climate, ways of integrating emergency response systems and processes into existing operations
Design Standards and Material Adaptation Responses	Initiatives that identify transportation alternatives, which are less vulnerable to climate change because of changes in design or material.	Strategies and tools that modify existing methods, codes and standards to more effectively respond to climate change impacts
Evaluation	Efforts that assess the effectiveness of	Processes, tools, or methods that are used to

	adaptation strategies.	evaluate implemented adaptation responses
Decision Support Tools	Initiatives that focus on building, improving, altering, or using adaptation-focused decision support tools.	Techniques for integrating impact and adaptation information into long term transportation plans or procedures for identifying and sharing best practices in asset management

In sum, this study finds that the state of federal, state, and university-led transportation related adaptation research has advanced significantly since the TRB white paper was released. Research initiatives were found to occur at the federal, state, and university level in various adaptation topics. In particular, the majority of initiatives fell under the adaptation topics of *Climate Change Impact and Data Analysis* and *Risk and Vulnerability Assessment*, while a portion of initiatives also addressed *Design Standards and Material Adaptation Responses*, and *Decision Support Tools*. This study finds that none of the initiatives specifically addressed the *Evaluation* topic, which covers efforts to assess the effectiveness of adaptation strategies. The topics researched to date are in line with the sequence of steps outlined in most adaptation frameworks, therefore, as the field progresses it is likely that evaluation mechanisms will be developed.

Furthermore, this study finds that collaboration and information exchange are critical in streamlining adaptation into transportation planning. Collaboration is encouraged between federal, state, and universities as they each provide unique contributions that will progress the field. Intra-regional collaboration is also important because the impacts of climate change will differ significantly from region to region and the sharing of regional best practices will help to reduce barriers to adaptation in transportation planning. Finally, it is also important for research initiatives to target citizens and local stakeholders as the local context of adaptation is one of the most effective types of information.

This section, organized by federal, state, and university-led research initiatives, will more thoroughly explain the findings described above. The initiatives are characterized by adaptation topic, as well as, other characteristics, such as type of research and format and target audience.

3.2 Federal Initiatives

This section provides a review of federal level transportation initiatives related to climate change adaptation since the release of *SR 299* by referring to various U.S. government agency websites and consulting with experts in the field. U.S. DOT was the main agency found to have record of transportation-related adaptation initiatives.

The study conducted to develop this white paper found that climate change adaptation has begun to gain significant interest at the federal level, as seen by the Climate Change Adaptation Task Force highlighted in the text box to the right. Furthermore, adaptation has become particularly relevant to federal government agencies since President Obama both signed an Executive Order requesting that the Task Force "recommend how the policies and practices of Federal agencies can be made compatible with and reinforce a national climate change strategy"[97] and subsequently called for all federal agencies to perform planning for climate change adaptation.

Box 5 - Adaptation in the Federal Government

In the spring of 2009, an Interagency Climate Change Adaptation Task Force convened in recognition of the fact that the federal government plays a key role in adaptation. The Task Force is co-chaired by the Council on Environmental Quality (CEQ), the National Oceanic Atmospheric Administration, and the Office of Science and Technology Policy.

Climate change adaptation is of special interest to the U.S. DOT due to its mission to oversee the nation's transportation system, including transportation infrastructure, which could be at risk from climate change impacts. Adaptation as related to transportation is less applicable to the EPA and the DOE who mainly fund transportation research related to fuel efficient technologies, vehicles, and fuels.

Most of the work on adaptation at U.S. DOT has been spearheaded by FHWA. The research funded under FHWA is through the Surface Transportation Environment and Planning Cooperative Research Program (STEP), which has targeted climate change adaptation as a research area in their FY2010 STEP Research Plan.[98] More specifically, the STEP Research Plan states that FHWA will research (1) transportation infrastructure vulnerabilities to climate change impacts; and (2) adaptation strategies that minimize climate change impacts. This research will assist transportation planners in adapting the transportation system to climate change impacts. Specific research areas identified in the 2010 STEP plan include: developing FHWA's adaptation strategy; describing FHWA's key climate change adaptation focus areas; providing technical assistance to states that use FHWA's climate change vulnerability framework, currently being developed; and providing technical assistance on the effects of climate change. In addition to performing research on climate change adaptation, FHWA and AASHTO have been holding peer exchanges on climate change adaptation, which they plan to continue.

Although a large majority of adaptation work has come from FHWA, FTA has also set its own adaptation goals and begun to develop an adaptation plan. FTA has also begun a synthesis study by: reviewing the anticipated climate impacts on the transportation system and reviewing climate change adaptation efforts, risk management tools, and the incorporation of adaptation into transit agencies. FTA plans to fund partnerships to perform risk assessments and reviews of adaptation options, hold workshops and webinars, and align FTA policies and programs with adaptation goals.[99]

As seen by the examples provided above, many federal-level adaptation initiatives address the suite of adaptation topics outlined in this study. The integrated and comprehensive nature of these initiatives demonstrates U.S. DOT's leadership, forethought, and ability to provide guidance on transportation-related adaptation issues. Due to the fact that these initiatives are heavily cross-cutting, a sampling of other federal transportation-related adaption initiatives identified in this study is highlighted generally below.

- *Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region,* EPA.[100] A study that assessed the effects of sea-level rise on coastal environments. The report, released in 2009, includes an assessment of the effects of sea-level rise on transportation infrastructure and identifies challenges to adapting to sea-level rise.
- *Developing a Climate Change Effects Typology*, U.S. DOT. A study that reviews and synthesizes relevant climatological studies, which will be used by U.S. DOT to inform future analysis of climate change impacts on transportation.
- *Regional Climate Change Effects: Useful Information for Transportation Agencies,* FHWA.[101] FHWA released a report that reviews the projected climate change effects on the highway system at the regional level. This research will be used for an assessment of risks and vulnerabilities that the transportation system faces from projected climate change impacts.
- *Gulf Coast Study – Phase 2*, FHWA.[102] For Phase 2 of the study of the Gulf Coast, U.S. DOT performed an in-depth assessment of transportation assets across all modes for a single Gulf Cost metropolitan planning organization to (1) identify critical assets, (2) assess climate impacts on those assets, (3) assess vulnerability, (4) perform detailed engineering assessments of vulnerable infrastructure, including a review and analysis of adaptation options. The results of this MPO-specific research and analysis informed the development of risk management tools, templates, and architectures for the planning agency in the study region to use in deciding what infrastructure or transportation programs need protecting, and prioritizing efforts to protect, accommodate, or relocate assets.
- *Adaptation Conceptual Model Pilots,* U.S. DOT.[103] U.S. DOT is funding pilots for state DOTs and MPOs to implement conceptual models that perform vulnerability and risk assessments of transportation infrastructure to the projected climate change impacts.
- *Literature Review: Climate Change Vulnerability Assessment, Risk Assessment and Adaptation Approaches*, FHWA.[104] This literature was released by FHWA in July 2009.

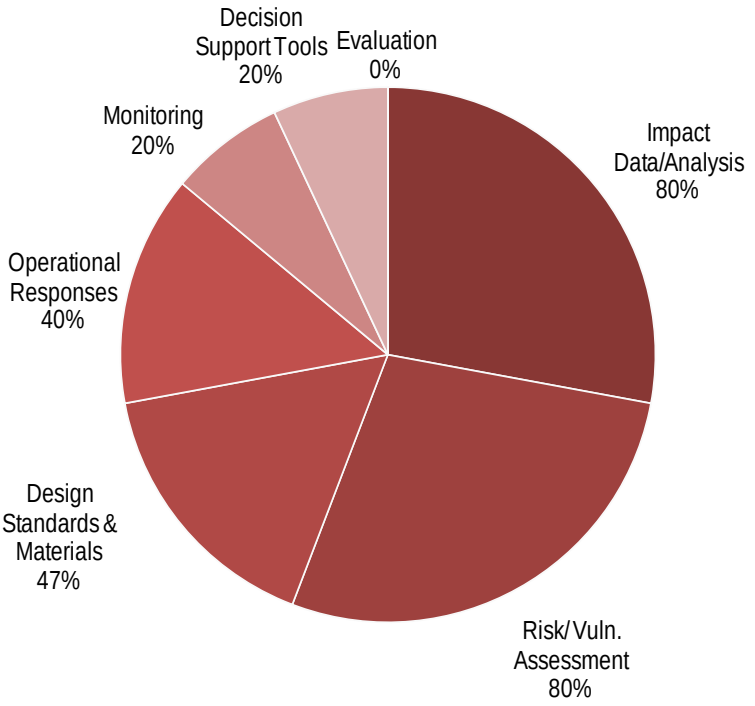
- *Adaptation Framework,* U.S. DOT. U.S. DOT is funding the development of a framework to analyze climate and weather-related impacts on highway infrastructure and to incorporate risk management adaptation approaches into all aspects of highway management.
- *Climate Change and the Highway System: Impacts and Adaptation Approaches*, NCHRP 20-83 (05).[105] The purpose of this research is to begin to assess potential impacts of climate change on highway systems, identify vulnerable infrastructure by region, and recommend institutional arrangements and technical tools to address the future interactions of climate change and highway systems.

3.3 State DOT Initiatives

This section describes recent state-level transportation initiatives related to climate change adaptation. Out of the 50 U.S. states inventoried, approximately 25 percent were found to have a record of transportation-related adaptation initiatives. State DOTs are often intimately connected with the research being conducted by their state universities through a variety of mechanisms, such as sponsorship, financing, and technical expertise. This is particularly pertinent for adaptation research, as adaptation responses are governed by local impacts and context. For example, Columbia University is working with New York DOT to mainstream climate change adaptation strategies into New York DOT's operations using local knowledge of transportation systems and projected impacts. Although this study categorizes a research initiative by the entity performing the research, states should also be recognized for their contribution to university performed initiatives, which will be described in the university-led research section below.

The primary adaptation research topic seen in state transportation initiatives is climate change impact data and analysis. However, states have also been heavily involved with risk and vulnerability assessments. Figure 4 shows the distribution of adaptation topics being addressed by the state DOT research initiatives identified in this study. When compared to that of the larger adaptation field, we find that this distribution is in line with the typical adaptation framework process, which generally follows the subsequent procession: understand climate impacts, assess vulnerability and risk, monitor climate conditions, identify and implement adaptation options, and evaluate and improve performance.

Figure 4 - Percent of State DOT Studies that Address Each Adaptation Topic



This adaptation process, or framework, of 1) understanding climate impacts, 2) assessing vulnerability and risk, 3) monitoring climate conditions, 4) identifying and implementing adaptation options, and 5) evaluating and improving performance, is demonstrated through the U.S. DOT initiative, Adaptation Conceptual Model Pilots. This U.S. DOT initiative, which is included as an example in the federal initiatives section above, funds helps state DOTs and MPOs implement conceptual models that guide vulnerability and risk assessments of transportation infrastructure to projected climate change impacts. U.S. DOT intends for these pilots to facilitate a consistent and robust approach for transportation agencies to make decisions when addressing vulnerability and risk to climate change. Through such initiatives, it is likely that impact analysis and risk and vulnerability assessments will become more common and frequent, thereby, encouraging state DOTs to further adaptation planning by implementing design standard, material, and operational adaptation strategies. Box 6 identifies the agencies that were selected to participate in the pilot of this U.S. DOT initiative. [106]

Box 6 – Research Spotlight: U.S. DOT Adaptation Conceptual Model Pilots

- San Francisco Bay Metropolitan Transportation Commission
- New Jersey DOT/North Jersey Transportation Planning Authority
- Virginia DOT – Hampton Roads
- Washington State DOT
- The Island of Oahu's Metropolitan Planning Organization

In addition to the adaptation topic classification provided in Figure 4, state DOT initiatives were sorted by the type of research they were addressing, the format and the target audience. This study found that state DOT initiatives differed in regard to the type of research that was addressed. For example, most initiatives fell into the foundational research classification—the development of expert synthesis of existing information into guidance or other materials—while others were classified as data, models, and other tools research—research focused on developing models and tools to support adaptation analyses.

This study also found that, in comparison to universities, a large number of state DOT initiatives are presented as parts of policies, plans, reports, or strategies rather than as formal research within the topic areas highlighted by this study. Therefore, although many of these initiatives touched on the adaptation research topics mentioned introduced in this study, they were not necessarily being implemented or tested through research and development. Instead, these types of initiatives, such as Hawaii DOT Climate Change Adaptation Framework, more generally discuss potential strategies or frameworks for conducting climate change adaptation research or provide guidance for how practitioners and policy-makers should start considering climate change impacts and adaptation. Finally, all of the state DOT initiatives targeted practitioners and policy makers.

As mentioned above, adaptation is notably dependent on local impacts; therefore, this study finds that the research identified addressed impacts that were threatening to their local context. For example, as a warming temperature will contribute to the melting of permafrost, many of Alaska's initiatives involved climate impacts related to soil stability. It should also be noted that because climate change is projected to impact regions and states in different ways and with varying magnitudes, those states with a greater risk of being affected by climate change would be expected to invest in adaptation research, while those that are less threatened would be expected to direct their resources elsewhere.

In order to provide more insight into the identified adaptation research initiatives conducted by state DOTs, an illustrative list is provided below. While most of the identified research initiatives address at least two types of adaptation research, the list below highlights the components of each initiative specific to the adaptation topic category.

The example projects are organized into the following sections, corresponding to the relative number of research projects surveyed that fell within each adaptation topic shown in Figure 4:

- Climate Change Impact Data and Analysis;
- Risk and Vulnerability Assessment;
- Design Standards, Material, and Operational Adaptation Responses;
- Decision Support Tools; and
- Monitoring.

Each section provides a brief overview of the types of research surveyed, and provides a few example projects that demonstrate the adaptation research topic.

CIimate Change Impact Data and Analysis

These initiatives explored a variety of climate impacts, including, changes in precipitation, temperature, flooding, and SLR. Two examples are:

- *Climate Change Impact on Coastal River Estuaries in Oregon*, Oregon DOT.[107] The physical processes and roadway features of the Salmon River Estuary will be monitored to understand the possible effects of sea level rise and climate change. The results will help form the foundation for ODOT's efforts to maintain functionality when faced with climate impacts.
- *Long-Range Transportation Plan for the State of Connecticut, 2009-2035*, Connecticut DOT.[108] The ConnDOT LRTP provides a relatively robust discussion of climate change, including a specific section dedicated to the consideration of potential impacts of climate change on transportation infrastructure and services.

Risk and Vulnerability Assessment

While risk and vulnerability assessments were most often discussed generally with regard to climate change, some initiatives mentioned specific risks, such as risk to transportation services or LRTPs or risk of modeling methods performing under various climate scenarios.

- *Integrated Assessment for Effective Climate Change Adaptation Strategies in New York State,* New York DOT.*[109]* This report aims to provide decision-makers, including transportation planners, with cutting edge information on the state's vulnerability to climate change.
- *Final I-70 Mountain Corridor Programmatic Environmental Impact Statement (*PEIS), Colorado DOT.[110] The Final PEIS begins to address the risks to transportation services from climate change.

Decision Support Tools

Adaptation decision-support tools are in their infancy, but are likely to be a rapidly expanding field. Increasingly, research will focus on applying decision-support tools to develop local or regional scenarios. An example is:

- *Design-Flood Flows in a Changing Climate,* Maine DOT.[111] In order to test the applicability of design-flood flow models to future scenarios, this project will employ four detailed rainfall/runoff models for four watersheds in coastal Maine to model future annual peak flows under multiple global-climate-model scenario projections and compute future design-flood flows.

Design Standards, Material, and Operational Adaptation Responses

The development of adaptation options was often discussed generally through strategies, frameworks or plans in the context of future development and implementation. This suggests that some state DOTs recognize the importance of adaptation planning and are beginning to familiarize themselves with adaptation frameworks.

- The Michigan Department of Transportation has proposed a study for 2012 to determine transportation infrastructure, maintenance, and operational adaptation needs[112].

- *A preliminary study of climate change adaptation issues for the statewide transportation system in Arizona,* Arizona DOT.[113] The purpose of this study is to identify key vulnerabilities and discuss important elements of an organizational adaptation strategy within the transportation system.

Monitoring

Monitoring was only mentioned with regard to a sample of climate impacts, including stream flow trends, temperature, and precipitation, suggesting that state DOTs have not begun widely planning or implementing monitoring procedures. Rather, those state DOTs that are addressing climate change adaptation are in the design and framework development stages.

- *Analysis of Pavement Response Data and Use of Nondestructive Testing for Improving Pavement Design*, Maine DOT.[114] For this analysis, field tests, applicable for different climatic regions, traffic and construction materials will collect in-place data to provide information for proper design and rehabilitation of pavements.

3.4 University Initiatives

This section discusses recent university–led research related to adaptation. Transportation related research occurs at over sixty University Transportation Centers (UTCs) in the U.S. and hundreds of university-specific departments. In order to capture the most relevant university-level adaptation transportation research, this study identified UTCs that are considered to be the most active in climate change and transportation research based on experience. This study cataloged climate change initiatives being conducted at these UTCs by searching the identified UTC's websites and the TRB's *Research in Progress* database. The most active universities conducting research on this topic include:

- The University of Delaware, Newark;
- The University of Alaska, Fairbanks; and
- Texas A&M University, College Station.

Other universities, such as Georgia Institute of Technology, Oregon State University (Corvallis), Portland State University, The University of Washington (Seattle and Pullman) and The University of New Orleans also focus on this topic. The sponsor organizations for these research initiatives are even more diverse and include state DOTs, other universities, university transportation centers, local organizations (such as Watershed Councils and County DOTs) and the USDOT. As mentioned previously, because this study classified each initiative under the performing

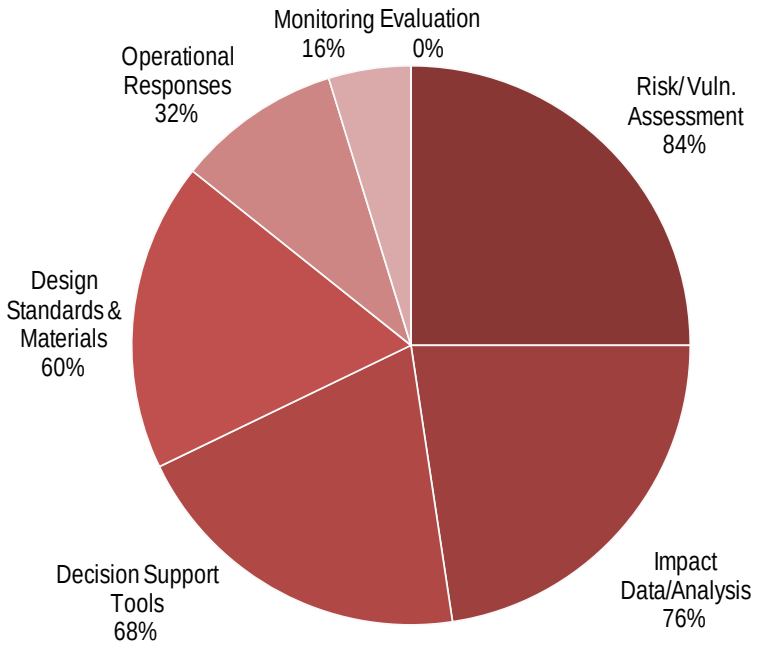
Box 7 – Research Spotlight: Understanding the State of Climate Science at the State and Regional Level

Texas A&M University's *Climate Change/Variability Science and Adaptive Strategies for State and Regional Transportation Decision Making* study aims to generate a baseline understanding of current policy response to climate change and to understand the role scientific information plays at the state and regional level. The final report will provide guidance for integrating climate science into the decision and planning process and will include a list of "best practices" for

organization, state DOT-sponsored research being conducted by universities is captured under the university initiatives section of this report. Box 7 uses an example to demonstrate the integrated relationship of university research and state and regional action.

Similar to the findings for federal and state-led adaptation transportation research, university-led research mainly centered on the adaptation topics of climate change impact data and analysis and risk and vulnerability assessment. In addition, university-led research was found to also have a significant presence in decision support tools and design standards and material adaptation strategies. The percent of university-led research that addressed each adaptation topic is found in Figure 5.

Figure 5 - Percent of University Studies that Address Each Adaptation Topic



Similar to state initiatives, university research initiatives were also classified according to the type and format of research being performed and the target audience. This study found that university research was typically classified as foundational and often co-classified as foundational and data, models, and other tools. For example, The University of Alaska, Fairbanks' Impact of Groundwater Flow on Permafrost Degradation and Transportation Infrastructure Stability study is conducting foundational research by developing a relationship between groundwater flow, permafrost degradation and embankment stability, which will ultimately act as a decision support tool. Two initiatives were classified as practitioner research; the first of which was Columbia University and NYSDOT's collaboration on mainstreaming climate change adaptation strategies into transportation operations, which was mentioned above. The other initiative was Texas A&M University's *Managing Freeway Operations During Weather Events* initiative,[115] which helped

TxDOT develop a structured and systematic approach for managing traffic during weather events. Furthermore, the large majority of university initiatives were categorized as R&D and targeted toward practitioners and policy makers.

Two general caveats apply to university-led adaptation research. First, the theme of local context is also important to university-led research. In particular, the study finds that university research will either focus on those areas of vulnerability that are particularly important for the state that university is found in or more general, national assessments or reports. For example, research in coastal states often focused on the stability of bridges to hurricane forces while research in Alaska was centered on permafrost stability. Second, university research is often guided by the sponsoring organization. Therefore, due to funding decisions, the results of this study should not be viewed as a hard indication of university priorities but instead as an indication of their capability to conduct adaptation related transportation research.

In order to provide more insight into the identified adaptation research initiatives conducted by universities, an illustrative list tailored to each adaptation topic is provided below. The projects are organized into sections that correspond to the relative number of research projects surveyed that fell within each adaptation topic, as shown in Figure 5:

- Risk and Vulnerability Assessment;
- Climate Change Impact Data and Analysis;
- Decision Support Tools;
- Design Standards and Materials;
- Operational Responses; and
- Monitoring.

Each section provides a brief overview of the types of research surveyed, and provides a few example projects that demonstrate the adaptation topic. Unlike mitigation research, the adaptation topics addressed by universities are addressed with the same relative frequency as state DOTs, with the exception of *Design Standards* and *Decision Support Tools*. This may indicate that both states and universities are in the early stages of conceptualizing and developing the various elements of an adaptation framework. They are therefore focused primarily on identifying climate change impacts and local or regional vulnerabilities. Universities are beginning to develop models and tools to help with decision-making as state DOTs and others integrate impact and vulnerability understandings into their planning documents.

Risk and Vulnerability Assessment

In many instances, risk and vulnerability assessments examined transportation infrastructure as a whole. However, in certain circumstances assessments focused on, specific types of transportation infrastructure and components; these include bridges, design standards, pavement performance, road intersections, and transportation flows.

- *Future Flooding Impacts on Transportation Infrastructure and Traffic Patterns Resulting from Climate Change,* Portland State University.[116] This research will use water models and vulnerability

and traffic analysis to identify transportation infrastructure that is vulnerable to flooding and associated road failure and congestion impacts.

- *Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska,* Portland State University & University of Alaska, Fairbanks.[117] The objective of the study is to conduct a preliminary assessment of the risks and vulnerabilities climate change poses to the surface transportation infrastructure system in the region.
- *Assessing the Vulnerability of Delaware's Coastal Bridges to Hurricane Forces,* University of Delaware.[118] In this study, a vulnerability assessment will be conducted for a sample of Delaware's coastal bridges to hurricane forces.

Climate Change Impact Data and Analysis

These initiatives address a suite of climate change impacts including SLR, precipitation, water runoff, flooding, temperature, permafrost, and storm surge, suggesting that universities are seeking to explore the broad array of impacts to transportation systems posed by climate change.

- *Assessing the Long-term Impact of Subsidence and Global Climate Change on Emergency Evacuation Routes in Coastal Louisiana,* University of New Orleans.[119] This study will work to create a subsidence forecast model for coastal Louisiana that will estimate the change in evacuation road elevations for 2015, 2025, 2050, and 2100.
- *Development of a Methodology for the Assessment and Mitigation of Sea Level Rise Impacts on Florida's Transportation Modes and Infrastructures*, Florida DOT.[120] This project includes inventorying data sources and methods for forecasting SLR in Florida, analyzing the advantages and disadvantages of these data sources and methods, and making recommendations.
- *The Implications of Climate Change on Pavement Performance and Design,* University of Delaware, Newark.[121] This research is meant to explore the impacts, uncertainty and affect of climate change on pavement performance deterioration by identifying important climatic factors and understanding their uncertainties associated with frequency, severity, and duration.

Decision Support Tools

Universities are working with a diverse set of decision-support tools including models (e.g., wave load, storm surge, transportation flows), management, preparation, response, and recovery tools, and workbooks for using climate science, which demonstrates that universities are seeking to improve modeling capabilities to better understand the impacts of climate change and inform adaptation response strategies.

- *Effect of Climate Change on Transportation Flows and Inland Waterways due to Climate-Induced Shifts in Crop Production Patterns,* Texas A&M University.[122] This project will analyze changes in transportation flows caused by climate change-induced shifts in crop production patterns by linking a US agricultural sector and international grain transportation model. The results will help planners in forecasting demand for Mississippi river transport facilities and capacity.
- *Low Impact Development and Transportation Stormwater Practices,* University of Washington, Seattle.[123] The project combines research, design, and best practices to develop a design decision

tool that can be used by Region X transportation designers to make informed decisions with regard to stormwater in the wake of future climate change impacts.

Design Standards and Materials

As mentioned above, adaptation is typically referenced in a general sense but specific mention was given to coastal bridges, transportation infrastructure, construction materials, structures, roads and pavement. This demonstrates that universities are beginning to develop methods and standard for incorporating climate change considerations into the transportation system design and planning.

- *Design Standards for U.S. Transportation Infrastructure: The Implication of Climate Change,* Georgia Institute of Technology.[124] This project is researching the ways in which engineering design practices may need to be altered under a changing climate; it includes an assessment of how robust and flexible design standards are to coping with climate induced changes.
- *Identification and Evaluation of Major Issues Involving the Impact of Global Climate Change on Transportation Systems*, University of Southern California, Los Angeles.[125] This study will compare the historical and future hydrological conditions over the Palouse River basin to create a methodology for designing sustainable transportation infrastructure.

Operational Responses

Typically, adaptation is mentioned generally but specific operational responses include risk management, advisory, control and treatment, and process strategies.

- *Understanding the Impacts of Climate Change on the 1-95 Corridor in Maryland and Delaware,* University of Delaware.[126] This research will result in the development of guidelines for states and MPOs to recognize how design and construction practices may be adapted to mitigate the impacts of climate change.

Monitoring

The identified initiative mentions the following types of weather monitoring: winds, rains, snow, ice storms, temperature and hydrological properties of soils.

- *Measurement of Temperature and Soil Properties for Finite Element Model Verification,* University of Alaska, Fairbanks.[127] This project will measure temperature data and thermal and hydrological properties of soils to provide a complete data set for ground-truthing 2-D thermal modeling results.

3.5 Research Needs and Data Gaps

Using the results of the literature review, research needs and data gaps in adaptation research were determined and are presented below. This section will first describe the research needs and data gaps for federal initiatives, and then for state and university initiatives combined. Finally, a separate section explains research needs and data gaps that were found across federal, state, and university initiatives.

3.5.1 Federal

As with the mitigation section, prior TRB and FHWA reports have already identified a range of research needs. There are fewer identified topics on adaption in those reports, reflecting the more recent shift in focus to adaptation that seen at U.S. DOT.

These reports state that there is a need for: better understanding the impacts of climate change on transportation infrastructure; models that provide meaningful outputs for assessing climate risks and adaptation strategies; and frameworks for evaluating and making decisions collaboratively around climate change issues.

Furthermore, there is a stated need in planning and design in the following areas:

- Methods that include climate risk analysis in transportation investment policies, promote vulnerability assessments, and as needed, transportation design standards.
- Research is needed to understand the potential for population displacement, with particular emphasis on environmental justice communities and their transportation needs.
- Planners need to be able to include climate impact and adaptation considerations in transportation planning; particularly scenario planning and NEPA project development.

This study finds that there are certain communication and information exchange gaps in the adaptation field. More specifically, it is important to encourage collaboration between stakeholders across the country to develop a better understanding of transportation-related adaptation, disseminate lessons learned, and expand the pool of creativity when developing methods, tools, and adaptation strategies. Finally, there is an identified need to overcome the perception that the uncertainties regarding climate change should limit the implementation of adaptive measures.

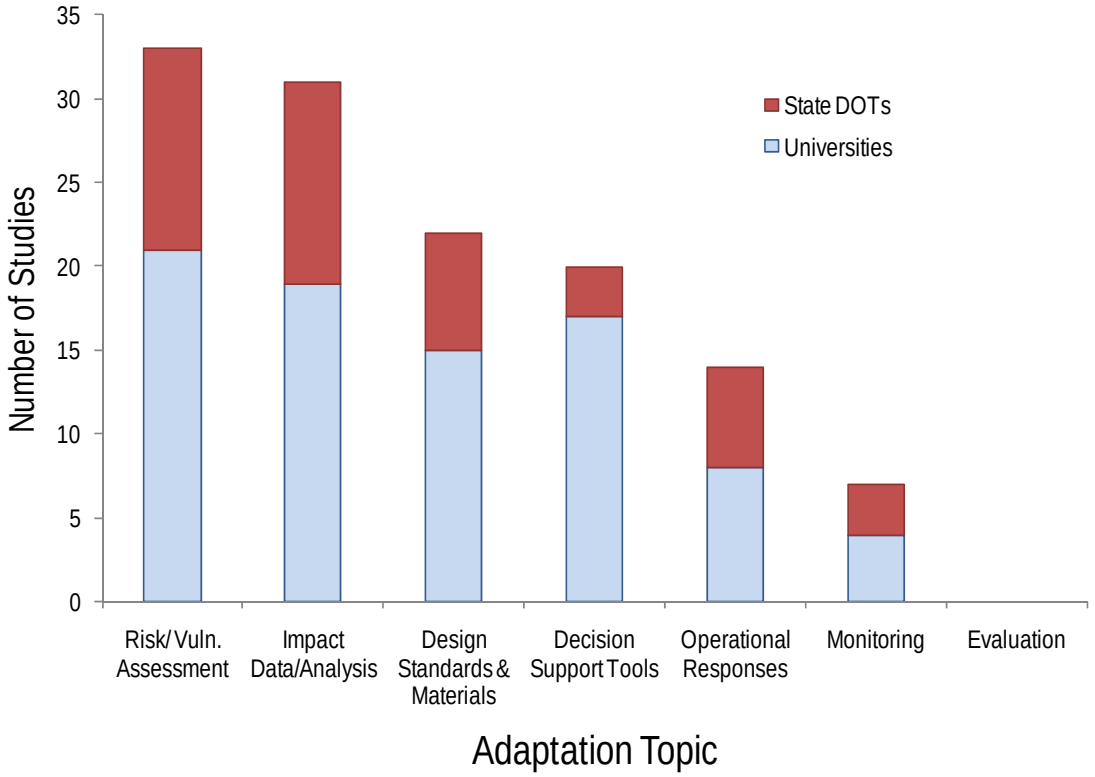
Box 8 – Research Spotlight: Climate Change Considerations in Transportation Planning, Georgia Institute of Technology

This study's objective was to determine whether climate change considerations are being incorporated into the transportation planning process. The review revealed that climate change considerations have not yet been included in a majority of cases in the transportation planning process, especially with regard to adapting transportation systems to the potential effects of climate change.

3.5.2 State DOTs and Universities

A summary of state DOT and university climate change adaptation research projects are shown in Figure 6, which demonstrates the spread of climate change adaptation research topics across state DOTs and universities.

Figure 6 - Distribution of Adaptation Research Projects



The majority of the transportation-related adaptation initiatives identified at the state and university-level were focused on the beginning stages of the adaptation framework process. Furthermore, similar to the state DOT mitigation section, state DOTs are found to mainly focus on reports, plans or guidelines, thereby demonstrating that state DOTs have conducted only modest primary research, lack established programs, and implemented few transportation policies related to climate change adaptation. Although these examples demonstrate various gaps in state DOT and university initiatives it is important to consider transportation-related adaptation as an integrated sector. In other words, this study sees an opportunity to capitalize on the strengths of federal programs, states, and universities to effectively share information without unnecessary reproduction. This section provides a few examples of these types of collaboration.

The section above demonstrates that federal research initiatives have been more all-encompassing in the adaptation topics they address than state and university research. Therefore, there is an opportunity for states and universities to capitalize on the existing knowledge of federal programs by utilizing lessons learned and best practices identified in these initiatives, thereby encouraging states and universities to build off of existing capabilities and experience when beginning to move forward in the adaption framework process, specifically in topics related to adaptation and evaluation research.

It is evident from the description of state initiatives above, that little state- and university-level research has focused on the evaluation of specific policies or programs due to the shortage of transportation-related

adaptation program and policy implementation. Therefore, this study identifies a need for states to begin implementing and integrating adaptation into programs and planning. As states move forward, it is important that they utilize information gained from university and federal research to move forward on policy development and program implementation.

To ensure the information learned from university research can be used effectively, it is important for universities to continue working collaboratively with state DOTs, especially when conducting more localized research. While there are a notable number of universities engaging in adaptation initiatives, a stronger collaboration between those states seen as most vulnerable to climate impacts and local universities is encouraged.

Furthermore, regional collaboration will also be important, as certain areas of the country will typically be faced with similar problems. For example, the southwest is projected to feel a warmer, drier climate, while the southeast is expected to experience more frequent and intense hurricanes. Partnerships between universities and regional UTCs will be critical for the effective spread of quality climate information and adaptation strategies.

This study also finds that the one adaptation topic in particular that has not been addressed explicitly by federal, state or university research is *evaluation*. Therefore, as adaptation options are being tested, it is important for evaluation processes to be documented and improved through adaptive management.

Finally, there is a need to engage not only policy-makers and practitioners in transportation-related adaptation initiatives, but also stakeholders and citizens. This is particularly important because these populations have established a foundational relationship with transportation assets, systems, and operations from their everyday use. Their local knowledge and understanding of climate change adaptation initiatives may further benefit the adaptation process.

4 Endnotes

[1] U.S. EPA (2011). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009. http://www.epa.gov/climatechange/emissions/usinventoryreport.html

[2] TRB, Special Report 299: A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy (2009).

[3] IPCC Climate Change 2007: Synthesis Report, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_appendix.pdf

[4] http://www.fhwa.dot.gov/livability/state_of_the_practice_summary/research2011.pdf

[5] http://climate.dot.gov/

[6] TRB, Special Report 299: A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy (2009)

[7] U.S. DOT, Transportation and Climate Change Clearinghouse, http://climate.dot.gov/about-the-clearinghouse.html

[8] http://ntl.bts.gov/lib/32000/32700/32779/DOT_Climate_Change_Report_-_April_2010_-_Volume_1_and_2.pdf

[9] http://www.fhwa.dot.gov/hep/climate/index.htm

[10] http://www.fhwa.dot.gov/hep/step/fy2010rp.htm

[11] http://www.fhwa.dot.gov/hep/step/fy09rp.htm

[12] http://www.fhwa.dot.gov/hep/climate/index.htm

[13] Personal communication, Robert Hyman (FHWA), 4/14/2011.

[14] Personal communication, Robert Hyman (FHWA), 4/14/2011

[15] FTA Multi-Year Research Program Plan (FY 2009-FY 2013)

[16] http://fta.dot.gov/documents/Flyer_ClimateChange_2010.pdf

[17] http://fta.dot.gov/documents/Flyer_ClimateChange_2010.pdf

[18] http://www.fta.dot.gov/planning/planning_environment_12125.html#FTA_Reports

[19] http://www.fta.dot.gov/documents/PublicTransportationsRoleInRespondingToClimateChange2010.pdf

[20] http://www.fta.dot.gov/documents/GHGCompendGTv2.pdf

[21] http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_syn_84.pdf

[22] http://www.fta.dot.gov/documents/Transit_Green_Building_Action_Plan.pdf

[23] http://www.fta.dot.gov/planning/planning_environment_12125.html

[24] http://www.movingcooler.info/

[25] http://www.faa.gov/about/office_org/headquarters_offices/apl/research/

[26] Brasseur, Guy P. and Mohan Gupta. "Impact of Aviation on Climate: Research Priorities." *American Meteorological Society*, vol. 91, no. 4 (April 2010): 461-463

[27] http://www.faa.gov/about/plans_reports/media/FPP_Flight%20Plan%202008-2012.pdf

[28] http://www.faa.gov/about/office_org/headquarters_offices/apl/research/cleen/

[29] http://www.airportsustainability.org/resources

[30] See the TRB Research Projects link on the TRB Specialty Page on Climate Change, http://www.trb.org/main/SpecialtyPageClimateChange.aspx

[31] http://www.its.dot.gov/aeris/index.htm

[32] U.S. EPA, FY 2011-2015: EPA Strategic Plan, 43.

[33] http://www.epa.gov/oms/technology/

[34] http://www.epa.gov/oms/technology/partners-milestones.htm

[35] http://www.epa.gov/otaq/models/moves/index.htm

[36] http://www.epa.gov/otaq/climate/models.htm

[37] U.S. EPA, FY 2011-2015: EPA Strategic Plan, 43.

[38] http://epa.gov/otaq/stateresources/policy/420r11003.pdf

[39] US EPA, Climate Change – Regulatory Initiatives, http://www.epa.gov/climatechange/initiatives/index.html

[40] http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm

[41] http://www.epa.gov/oms/renewablefuels/420f09024.htm

[42] TRB, Special Report 299: A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy (2009)

[43] "American Recovery & Reinvestment Act" DOE Office of Energy Efficiency & Renewable Energy website, accessed April 2011. http://www1.eere.energy.gov/recovery/

[44] TRB, Special Report 299: A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy (2009)

[45] http://rip.trb.org/browse/dproject.asp?n=27736

[46] http://rip.trb.org/browse/dproject.asp?n=26700

[47] http://otrec.us/project/305 http://rip.trb.org/browse/dproject.asp?n=22854

[48] http://rip.trb.org/browse/dproject.asp?n=20298

[49] http://rip.trb.org/browse/dproject.asp?n=27135

[50] http://rip.trb.org/browse/dproject.asp?n=28189

[51] http://www.nmshtd.state.nm.us/main.asp?secid=14815

[52] http://rip.trb.org/browse/dproject.asp?n=18664

[53] http://www.nrel.gov/hydrogen/pdfs/45670-2.pdf

[54] http://rip.trb.org/browse/dproject.asp?n=13141

[55] http://cait.rutgers.edu/files/FDU-RU4474_0.pdf

[56] http://rip.trb.org/browse/dproject.asp?n=23175

[57] http://rip.trb.org/browse/dproject.asp?n=28177

[58] http://rip.trb.org/browse/dproject.asp?n=22913

[59] http://utc.dot.gov/publications/progress_report/pdf/entire.pdf

[60] Rip.trb.org.

[61] Academic Search Premier database

[62] Science Direct database, http://www.sciencedirect.com/

[63] http://rip.trb.org/browse/dproject.asp?n=23458

[64] http://rip.trb.org/browse/dproject.asp?n=25901

[65] http://www.uctc.net/papers/879.pdf

[66] http://dx.doi.org/10.1021/es900535s

[67] http://swutc.tamu.edu/projectdescriptions/476660-00028.htm

[68] http://rip.trb.org/browse/dproject.asp?n=26020

[69] http://rip.trb.org/browse/dproject.asp?n=24911

[70] http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/kromer_electric_powertrains.pdf

[71] http://secure.awma.org/JOURNAL/Abstract.aspx?id=2115

[72] http://rip.trb.org/browse/dproject.asp?n=27176

[73] http://rael.berkeley.edu/node/734

[74] Qijian Gan, Jielin Sun, Wenlong Jin, UC Irvine, February 2011 (UCTC-FR-2011-02). http://www.uctc.net/research/papers/UCTC-FR-2011-02.pdf

[75] http://www.uctc.net/research/papers/UCTC-FR-2010-11.pdf

[76] http://www.uctc.net/research/briefs/PB-2010-03.pdf

[77] http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/Heywood_ESD-14.pdf

[78] http://transweb.sjsu.edu/mtiportal/research/projects/rpd/rpd2809.html

[79] http://pubs.its.ucdavis.edu/publication_detail.php?id=1055

[80] http://rip.trb.org/browse/dproject.asp?n=21320

[81] http://rip.trb.org/browse/dproject.asp?n=21963

[82] http://rip.trb.org/browse/dproject.asp?n=26678

[83] http://www.iser.uaa.alaska.edu

[84] http://www.arb.ca.gov/planning/tsaq/docs/rodier_8-1-08_trb_paper.pdf

[85] http://rip.trb.org/browse/dproject.asp?n=24803

[86] http://swutc.tamu.edu/projectdescriptions/161120.htm

[87] http://rip.trb.org/browse/dproject.asp?n=27161

[88] http://rip.trb.org/browse/dproject.asp?n=26621

[89] http://tris.trb.org/view.aspx?id=910627

[90] http://www.cts.umn.edu/Research/ProjectDetail.html?id=2009066

[91] http://web.mit.edu/sloan-auto-lab/research/beforeh2/actionplan/index.html

[92] http://pubs.its.ucdavis.edu/publication_detail.php?id=1353

[93] http://www.uctc.net/papers/880.pdf

[94] Special Task Force on Climate Change and Energy, *Research Needs Statements for Climate Change and Transportation*, Transportation Research Circular E-C144, Transportation Research Board, April 2010.

[95] Volpe National Transportation Systems Center, *Research Needs Workshop White Papers on Climate Change, Sustainability, Energy, and Livability*, Prepared for the 2010 Transportation Research Board Environment and Energy Research Conference, May 2010.

[96] 2010 Transportation Research Board Environment and Energy Research Conference: Research Needs Workshop White Papers on Climate Change, Sustainability, Energy, and Livability. http://itre.ncsu.edu/cte/EEConference/workshop/VolpeWhitePapers.pdf

[97] http://www.whitehouse.gov/sites/default/files/microsites/ceq/Interagency-Climate-Change-Adaptation-Progress-Report.pdf

[98] http://www.fhwa.dot.gov/hep/step/fy2010rp.htm

[99] Personal communication, Tina Hodges (FTA), 4/19/2011

[100] http://www.epa.gov/climatechange/effects/coastal/sap4-1.html

[101] http://www.fhwa.dot.gov/hep/climate/climate_effects/effects00.cfm

[102] http://www.fhwa.dot.gov/hep/climate/gcs.pdf

[103] http://www.fhwa.dot.gov/hep/climate/pilots.htm

[104] http://www.fhwa.dot.gov/hep/climate/ccvaraaa.htm

[105] http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2631

[106] http://www.fhwa.dot.gov/hep/climate/pilots.htm

[107] http://rip.trb.org/browse/dproject.asp?n=21593

[108] http://www.ct.gov/dot/cwp/view.asp?a=1383&q=259760

[109] http://www.nyserda.org/programs/environment/emep/10851_project_update.pdf

[110] http://www.coloradodot.info/projects/i-70mountaincorridor/final-peis

[111] http://rip.trb.org/browse/dproject.asp?n=22909

[112] NCHRP 25-25 (65) state DOT survey results

[113] http://rip.trb.org/browse/dproject.asp?n=26108

[114] http://rip.trb.org/browse/dproject.asp?n=14529

[115] http://tti.tamu.edu/documents/0-5278-1.pdf

[116]http://www.otrec.us/project/257

[117] http://www.otrec.us/project/383

[118] http://www.ce.udel.edu/UTC/Mertz.html

[119] http://rip.trb.org/browse/dproject.asp?n=27917

[120] http://rip.trb.org/browse/dproject.asp?n=25898

[121] http://rip.trb.org/browse/dproject.asp?n=26893

[122] http://rip.trb.org/browse/dproject.asp?n=24804

[123] http://rip.trb.org/browse/dproject.asp?n=26623

[124] http://onlinepubs.trb.org/onlinepubs/sr/sr290Meyer.pdf

[125] http://www.metrans.org/research/2008/08-19.htm

[126] http://rip.trb.org/browse/dproject.asp?n=23136

[127] http://ine.uaf.edu/autc/projects/measuring-temperature-and-soil-properties-for-finite-element-model-verification/