# 1.0 Why Study Climate Change Impacts on Transportation?

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Transportation is such an integral part of daily life in the United States that few pause to consider its importance. Yet the Nation's strong intermodal network of highways, public transit, rail, marine, and aviation is central to our ability to work, go to school, enjoy leisure time, maintain our homes, and stay in touch with friends and family. U.S. businesses depend on reliable transportation services to receive materials and transport products to their customers; a robust transportation network is essential to the economy. In short, a sound transportation system is vital to the Nation's social and economic future. Transportation professionals – including planners, designers, engineers, financial specialists, ecologists, safety experts, and others – work hard to ensure that U.S. communities have access to safe and dependable transportation services.

Given the ongoing importance of the Nation's transportation system, it is appropriate to consider what effect climate change may have on this essential network. Through a regional case study of the central Gulf Coast, this report begins to examine the potential implications of climate change on transportation infrastructure, operations, and services. Investments in transportation are substantial and result in infrastructure that lasts for decades. Transportation plans and designs should, therefore, be carefully considered and well informed by a range of factors, including consideration of climate variability and change. Climate also affects the safety, operations, and maintenance of transportation infrastructure and systems. This research investigates the potential impacts of climate variability and change on transportation, and it assesses how planners and managers may incorporate this information into their decisions to ensure a reliable and robust future transportation network. This report does not contain recommendations about specific facilities or adaptation strategies, but rather seeks to contribute to the information available so that States and local communities can make more informed decisions when planning for the future.

Four key questions guide this investigation:

1. How important are the anticipated changes in climate?
2. Can we anticipate them with confidence?
3. What information is useful to transportation decisions?
4. How can decision makers address uncertainty?

The answers to these questions require first developing an understanding of how the climate is changing and the range of potential climate effects and then considering the relevance of these changes to transportation.

To set the context for this regional case study, this chapter first provides in section 1.1 an overview of how climate change is occurring globally, based on current scientific research. Section 1.2 introduces the questions these changes raise for the transportation sector and the research required to support effective responses to climate change. Section 1.3 provides a synthesis of the state of existing research regarding the impacts of climate change on transportation, discussing the focus of current investigations – both in terms of specific climate factors and individual transportation modes, major findings, and what entities are sponsoring and conducting this research. Section 1.4 draws conclusions from this literature review to identify what is known – and what research questions remain – on this multifaceted topic. Section 1.5 then discusses how the U.S. Department of Transportation (DOT) selected the Gulf Coast region for its first case study of the potential impacts of climate change on transportation and describes the objectives and organization of the research effort.

## ■ 1.1 The Climate is Changing

The natural "greenhouse" effect is an essential component of the planet's climate process. Naturally occurring greenhouse gases – carbon dioxide, methane, and nitrous oxide – effectively prevent part of the heat radiated by the Earth's surface from otherwise escaping to space. In the absence of these greenhouse gases, the Earth's temperature would be too cold to support life as we know it today.

However, atmospheric concentrations of greenhouse gases have increased markedly since the industrial age began. The concentration of carbon dioxide ($CO_2$) in the atmosphere has been increasing due to the combustion of fossil fuels and, to a lesser extent, land use changes. Direct atmospheric measurements made over the past 50 years have documented the steady growth in carbon dioxide concentrations. In addition, analysis of ice bubbles trapped in ice cores show that atmospheric carbon dioxide has increased by roughly one-third since 1750. Atmospheric concentration of $CO_2$ was 379 parts per million (ppm) in 2005, compared to a preindustrial level of 280 ppm (IPCC, 2007). Other heat-trapping gases – methane and nitrous oxide – also are increasing as a result of human activities. Finally, once in the atmosphere these greenhouse gases have a relatively long life time, on the order of decades to centuries, which means that the atmospheric warming taking place today will continue.

**Temperature has increased and is projected to continue to do so.** Temperatures have been rising over the last century, with more rapid increases since 1970 than earlier. According to the International Panel on Climate Change (IPCC) Working Group I Fourth Assessment Report (AR4), average global temperatures increased 0.74°C (1.33°F) during the past 100 years, with most of that increase – 0.65°C (1.17°F) experienced in the last 50 years. Recent years have set record highs; 11 of the past 12 years were the warmest years on record since 1850. While some of this change may be due to natural variability, human activities have contributed to the Earth's warming. The IPCC report finds with very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming. The last major challenge to whether the planet was warming or not was resolved in April 2006 with publication of "Temperature Trends in the Lower Atmosphere" (U.S. Climate Change Science Program, Synthesis, and Assessment Product 1.1, 2006). This study reconciled the remaining analytical issues regarding differences between surface and satellite temperature readings.

The climate models used to estimate temperature changes agree that it will be warmer in the future. According to the IPCC report, global average warming is expected to be about 0.4°C (0.72°F) during the next 20 years. Even if the concentrations of all greenhouse gases and aerosols had been stabilized at 2000 levels, warming of 0.2°C (0.36°F) would be expected during this period (IPCC, 2007). Over the longer term, the IPCC models project average global temperature increases ranging from 1.1°C (1.98°F) to 6.4°C (11.5°F) by the end of the 21$^{st}$ century, although climate responses in specific regions will vary. These projections are the result of reviewing a robust set of global climate models under a variety of future scenarios – using a range of assumptions for future economic activity and energy use – for the Earth as a whole.

The average increase in temperature may not be as important to the transportation community as the changes in extreme temperature, which also are expected to increase. Over the last 50 years, the frequency of cold days and nights has declined, while hot days, hot nights, and heat waves have become more frequent. The number of days with temperature above 32°C (90°F) and 38°C (100°F) has been increasing since 1970, as has the intensity and length of periods of drought. The IPCC report finds that it is virtually certain that the next century will witness warmer and more frequent hot days and nights over most land areas (IPCC, 2007).

**Precipitation patterns are changing, and more frequent intense precipitation events are expected.** Over the past century precipitation amounts have increased in several regions – including the eastern parts of North and South America – while drying has been observed in other regions in Africa and Asia. During the 21$^{st}$ century, the IPCC (2007) anticipates that increases in the amount of precipitation are *very likely* in high latitudes, while decreases are likely in most subtropical land regions, continuing observed patterns in recent trends. While total average levels of precipitation will vary by region, the incidence of extreme precipitation events is expected to increase.

According to NOAA analyses, the magnitude of the highest precipitation events has been increasing since 1970. A Simple Daily Intensity Index that examines the total precipitation for the United States divided by the number of days with precipitation clearly demonstrates an increase in average intensity from 1970 to 2005. These observed increases in extreme precipitation are not only in keeping with observational analyses but also with model projections for the future. The IPCC AR4 (2007) concludes that heavy precipitation events will continue to become more frequent during the coming decades.

**Sea level is rising, and the rate of change is likely to accelerate.** As the Earth warms, two changes are occurring that are causing sea levels to increase: glacial melting and thermal expansion of the oceans. Sea level rise is perhaps the best documented and most accepted impact of climate change. The IPCC reports that – on a global level – the total 20$^{th}$ century rise is estimated to be 0.17 m (0.56 ft) and that global sea level rose at an average rate of 1.8 mm (0.07 inches) per year between 1961 and 2003. Excluding rapid changes in ice flow, the IPCC model-based projections for global sea level rise over the next century across multiple scenarios range from 0.18 to 0.59 m (0.59 to 1.94 ft). Should the melting of the land-based polar ice caps accelerate, sea level could rise much higher.

**The intensity of severe storms is expected to increase**. It is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and heavier precipitation (IPCC, 2007). (There is insufficient evidence to identify changing trends for other storm phenomenon, such as tornadoes, hail, and lightning [IPCC, 2007]; these types of storm activity are not addressed by this report.) There are several aspects of tropical storms that are relevant to transportation: precipitation, winds, and wind-induced storm surge. All three tend to get much worse during strong storms. Strong storms tend to have longer periods of intense precipitation, and wind damage increases exponentially with wind speed. The primary concern with hurricanes is for strong storms of Categories 3, 4, and 5. These storms have considerably more destructive energy. For example, a Category 5 storm may have winds only twice as fast as a Category 1 storm, but its kinetic energy is over four times that of a Category 1 storm.

Chapter 3.0 of this report provides a detailed discussion of how the climate is changing in the central Gulf Coast study area.

## ■ 1.2 How Will Changes in Climate Affect Transportation?

That the climate is changing leads to a number of intriguing and critically important questions for transportation. For the transportation community – the planners, engineers, builders, operators, and stewards of our Nation’s roads, airports, rail, transit systems, and ports – the primary question is how such changes will affect infrastructure and associated services and the trillions of dollars of investment these facilities represent. Transportation services are vital to our economy and quality of life. Individuals use transportation not only to get to and from work but for a wide variety of personal travel. Further, as producers seek to reduce warehousing costs through “just-in-time” delivery, transportation systems increasingly are functioning in effect as mobile warehouses. This places new stresses on service providers to make sure that economic goods are delivered on time. As the number of vehicles – and miles traveled – continues to grow, congestion on our roadways is an increasing concern.

Nationally, we invest about $110 billion annually in highways and transit alone. Federal investment in passenger rail approaches $2 billion a year. Add to this the considerable investment made by the private sector in freight rail, airports, and ports, and it is clear that the value that we place on these systems is enormous. Any disruption to the goods and services provided through the U.S. transportation network can have immediate impacts ranging from the annoying, such as flight delays due to severe weather, to the catastrophic, such as the chaos wrought by Hurricanes Katrina and Rita.

The question of how a changing climate might affect transportation infrastructure and services led the U.S. DOT, under the auspices of its Center for Climate Change and Environmental Forecasting (hereafter “the Center”), to hold a first-ever workshop on October 1-2, 2002. Cosponsored by the Environmental Protection Agency, the Department of Energy, and the U.S. Climate Change Science Program, the workshop brought together noted climate scientists, top transportation executives and practitioners, and experts in assessment research, environment, planning, and energy. This interdisciplinary group was charged to explore the potential impacts of climate change for transportation and to delineate the research necessary to better understand these implications. In preparation, the Center commissioned a series of white papers on overviews of climate change, regional case studies, potential system impacts, and environment and planning. The workshop participants identified significant gaps in the knowledge and processes necessary to fully incorporate climate science information into transportation decisions and developed a framework to pursue future research in this multifaceted area of investigation. The two-day session deepened practitioners’ understanding of the significance of climate change for transportation and led to a firm commitment by the U.S. DOT to pursue needed research. The current Gulf Coast Study was designed to begin to address the research needs identified at this important forum.

### 1.2.1 What are the Challenges to Research?

Several research challenges must be met to successfully incorporate climate information into transportation decisions. Framing this new area of research is a complex undertaking that requires a new style of interdisciplinary work among scientists, planners, engineers, and policy makers.

- **Articulating data and information needs –** First, transportation practitioners need to be able to articulate the types of climate data and model projections that will be relevant to transportation decisions: *What information could lead a public or private transportation agency to change a transportation investment plan, road location, or facility design?* Determining what climate information is useful includes identifying the appropriate regional scale and timeframe for climate scenarios, as well as the types of climate factors that could result in a revised decision. Generating this practical information may require scientists to analyze and portray existing data in different ways in order to be useful to transportation decisions.

- **Identifying most relevant climate information –** At the same time, climate scientists need to be able to explain to transportation and planning professionals what information is available today that may be relevant to transportation decisions. The pace of climate science is advancing rapidly, and new and increasingly reliable climate findings are being released regularly. The sheer volume of significant climate information poses a major challenge to the scientific community: How can scientists effectively translate the findings of basic research into information that can be understood by other professions – and the general public – and be applied to the choices transportation managers need to make?

- **Integrating multiple environmental factors –** Further, climate factors need to be considered, not in isolation, but as part of a broader set of social and ecological factors that provide the context for thoughtful and informed transportation decisions. This will require that natural scientists and geospatial specialists work with transportation planners to integrate climate information into maps and data addressing other environmental factors. Incorporating new types of information – including longer-range climate scenario projections – may require the transportation community to adopt new approaches to planning and visioning exercises that engage a broader range of stakeholders and subject matter experts.

- **Incorporating uncertainty –** An additional challenge is learning how to incorporate uncertainty in transportation decisions – how to assess risk and vulnerability of the transportation system and individual facilities given a range of potential future climate conditions. While transportation practitioners historically have planned and designed to meet established standards – for weight loads, flood levels, temperature extremes, etc. – today's transportation planner needs to consider the most effective strategies to ensure a robust transportation system across a broader range of possible futures, potentially encompassing longer timeframes and a wider variety of impacts. This challenge may require new approaches to design and investment that use probabilistic, rather than deterministic, analysis.

To begin to explore these complex research questions, the team conducted a review of existing literature regarding climate change impacts on transportation to determine the state of science.

## ■ 1.3 State of Science Regarding Climate Change Impacts on Transportation

What is the state of knowledge about climate change impacts on transportation? The research team undertook a review of the literature to assess the depth and breadth of existing research that specifically examines changes in climate and the resulting implications for transportation infrastructure and services.

Although there is a large body of research concerning climate change and how transportation contributes to greenhouse gas emissions, less work has been done concerning the impacts of climate change on transportation. A review of existing literature indicates that the impacts of climate change on transportation is an emerging area of research and one that is growing steadily more sophisticated. As a new field, the level of analysis given to the variety of subtopics within this broad area of research has been uneven; some aspects of climate change impacts on transportation have received much greater scrutiny than others depending on the particular concerns of individual authors and research sponsors.

### 1.3.1 Overview of State of Practice

Although there are relevant studies going back at least two decades, the pace of investigation has accelerated in more recent years. Several studies were conducted in this field in the late 1980s and early 1990s as international agreements on climate change were first under serious discussion (Marine Board, 1987; Hyman, 1989; Black, 1990; Irwin and Johnson, 1990). However, citations from this period are relatively infrequent, and as recently as 1998, the U.S. Federal Highway Administration (1998) found relatively little literature on this topic. Since then, the citations show growing recognition of climate impacts on transportation as an issue; research on this topic was highlighted in the United States' Third National Communication (U.S. Department of State, 2002). In fact, the majority of references cited are from the new millennium (table 1.1).

In addition to the growing number of research efforts, the analytic rigor of studies – particularly in the use of climate information – has progressed as well. While early discussions tend to be exploratory in nature, recent work has incorporated more sophisticated climate information and model outputs, addressed issues of uncertainty, and begun to examine the implications of climate factors on specific regions and infrastructure. This trend is likely to continue as awareness of the issues grows within the transportation community and decision makers seek improved information and tools to assess risks and adaptation strategies.

The literature encompasses a wide variety of studies conducted for different time periods, sponsored by a range of organizations, and undertaken for different purposes. General characteristics of the literature reviewed are described below:

- **Key climate factors examined –** The major climate factors most often discussed in the literature in terms of transportation impacts are temperature, precipitation, and sea level rise. Some articles explicitly dealt with storm activity or storm surge. (These climate factors are also analyzed as significant drivers in the Gulf Coast Study.) Many northern studies also examined permafrost thawing and navigation issues relating to ice cover on seaways and inland waterways.

- **Modal focus –** Information on modes is uneven. The majority of articles dealt with highways and marine transport; other modes such as rail, aviation, and transit were not as well represented. Relatively few articles addressed pipelines or emergency management issues in the context of climate change.

- **Geographic focus –** Much of the work done in this field has a national or regional focus; only the IPCC (1996 and 2001) has considered the topic at a truly global level. The Arctic Climate Impacts Assessment (Instanes et al., 2005) is a rare example of transnational regional study, in that it focused on impacts throughout the Arctic nations.

In addition, some studies focused on specific urban areas (Kirsten et al., 2004; Suarez, 2005; Greater London Authority, 2005).

- **Climate zones examined –** The literature does not examine all climate zones equally or in proportion to the amount of transportation infrastructure present. In particular, transportation in Arctic climates received substantial study, as warming impacts already are being observed in those regions. Many other studies looked at temperate climates, as in the United States or Europe. Australian studies were among the few that examined desert climates or hot climates. In addition, most of the literature focused on the industrialized world.

- **Timeframe examined –** Most studies examined time horizons of 50- to 100-years into the future, consistent with the timescale of projections and scenarios often used in the climate literature. Though this is well beyond the 20- to 30-year planning horizons typically used in transportation planning, it was noted in the literature that some infrastructure (such as bridges) is designed with life expectancies of 100 years or more (Eddowess et al., 2003; Wooler, 2004; Norwell, 2004). Other researchers eschewed timescales and instead chose specific thresholds to consider. For instance, Marine Board (1987) chose to examine the impacts of 0.5-, 1.0-, and 1.5-m (1.6-, 3.3-, and 4.9-foot) rises in sea levels, without specifying a projected year for when these might take place. Finally, several Arctic studies focused on changes *presently* occurring, as in Grondin's (2005) study of the effect of thawing permafrost on airfields and roads in Nunavik due to increasingly warmer winters.

### 1.3.2 Major Sponsors Conducting Related Research

Studies on the impacts of climate change on transportation have been conducted by a variety of researchers and organizations, including governmental agencies, academic researchers, and the private sector, reflecting the range of stakeholders with an interest in the topic. These studies incorporate a variety of approaches and can be found as stand-alone assessments of transportation impacts or as one aspect of a broader examination of climate impacts.

Two very significant impact assessment efforts have dealt with this issue in a limited fashion. The IPCC's multivolume assessment reports (IPCC, 1996; IPCC, 2001) discussed the topic in general terms, particularly noting the vulnerability of transportation infrastructure in coastal zones and permafrost regions to climate impacts, with the 2001 report broadly discussing some transportation operations impacts and more detail on Europe-specific concerns, such as impacts to aviation operations and river navigation.

Similarly, the U.S. National Assessment, which represents one of the broadest examinations of climate impacts to date in the U.S., did not include transportation as a sector of interest (National Assessment Synthesis Team, 2000). However, some of the regional studies conducted under the umbrella of the national assessment process did examine transportation impacts, most notably the Metro East Coast and Alaska studies (Zimmerman, 2002a; Weller et al., 1999). The 2002 U.S. DOT report, *The Potential*

*Impacts of Climate Change on Transportation: Summary and Discussion Papers*, contains 15 discussion papers addressing potential climate impacts on various modes of transportation across the Nation and a summary of priority research needs. The importance of weather and climate and its potential impacts on the Nation's transportation system was studied in *Weather Information for Surface Transportation: A National Needs Assessment Report* (OFCM, 2002). The report established national needs and requirements for weather information associated with decision-making for surface transportation operation modes including highway, transit, rail, marine, pipeline, and airport ground operations. It was issued as part of the cross-agency Weather Information for Surface Transportation (WIST) initiative, supported by the Federal Committee for Meteorological Services and Supporting Research (FCMSSR) and the agencies it represents.

The United Kingdom (U.K.) Climate Impacts Programme, an initiative similar to the U.S. National Assessment, specifically included impacts on the transportation sector in the overall assessment and in each of the regional reports prepared under its umbrella. The Canadian and Australian governments also have commissioned studies to examine transportation impacts of special interest to them – Canada with permafrost concerns and interest in the opening of the Northwest Passage; Australia with dry land salinity impacts due to its unusual soil and climatic conditions (Andrey and Mills, 2003; Norwell, 2004). References to research on this topic also were seen for New Zealand, Finland, and the Netherlands (Kinsella and McGuire, 2005; Ministry of Housing, Spatial Planning, and the Environment, 2001). A small number of city agencies also have commissioned studies examining impacts to their own transportation networks, such as in Seattle and London (Soo Hoo, 2005; Greater London Authority, 2005).

Many studies also were identified in engineering and transportation journals, ranging from transportation-specific publications such as the National Academy of Science Transportation Research Board's (TRB) *Transportation Research Review* to more general sources such as *Civil Engineering – ASCE* or the *Journal of Cold Regions Engineering*, and even some transportation trade journals (Barrett, 2004). A small number of private sector reports, all from the U.K., were identified, including one study from a ports company and two from the insurance industry (ABP Marine Environmental Research, Ltd., 2004; Dlugolecki, 2004; Climate Risk Management and Metroeconomica, 2005).

Finally, though many nongovernmental organizations (NGO) are engaged in research and policy advocacy related to climate change, we found few NGOs producing literature on climate impacts on transportation. For instance, the Union of Concerned Scientists (UCS) and the Pew Center on Global Climate Change have both published multiple reports on impacts and adaptation (see the UCS regional impact studies[1] and Easterling, 2004), yet transportation implications have received little direct attention in these reports.

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[1] http://www.ucsusa.org/global_warming/science.

### 1.3.3 State of Technical Analysis

The level of technical analysis in current research regarding their use of climate data and modeling varies, depending both on when the study was done and the magnitude of the study. Early studies, for instance, focused on $CO_2$-doubling scenarios (i.e., examining an equilibrium state at an unspecified point in the future), because standardized emissions and climate change scenarios had not yet been developed for researchers to use (Hyman, 1989; Black, 1990; Irwin and Johnson, 1990). Later studies took advantage of the climate projections developed by the IPCC process or by other large modeling efforts, such as the United States and United Kingdom national assessments. Several studies demonstrated advanced approaches to climate modeling, making use of multiple climate models and regional models to generate projections of climate variables (Instanes et al., 2005; Kinsella and McGuire, 2005; National Assessment Synthesis Team, 2000; Entek UK Limited, 2004). Other studies took more simplified approaches, using global temperature or sea level rise projections as the basis for examining potential impacts. A few studies did not use climate modeling at all, instead relying on historical trend data (Sato and Robeson, 2006; ABP Marine Environmental Research Ltd., 2004).

In many cases, climate variables produced by global or regional climate models were used as inputs into secondary effects models relevant for specific transportation questions. For example, Cheng (2005) used permafrost models to assess the impact of rising temperatures on road and rail structures in Tibet. Lonergan et al. (1993) integrated climate projections into snowfall and ice cover models for northern Canada to understand climate impacts on freight shipments via ice roads and waterways.

On the whole, relatively few studies attempted to quantify the estimated costs, benefits, or effects on performance resulting from climate change; more commonly, they identified potential impacts without a quantitative assessment. Some examples of the kinds of quantitative analyses performed include:

- Hyman et al. (1989) estimated that it would cost more than $200 million (in 1989 dollars) to elevate affected Miami streets to compensate for rising groundwater levels due to sea level rise and that increases in winter temperatures and decreases in snowfall would reduce Cleveland’s snow and ice control budget by 95 percent (about $4.4 million, or nearly 2 percent of the city’s operating budget).

- Kirshen et al. (2004) estimated an 80 percent increase in traveler delays due to increased incidence of flooding in the Boston area. They also tested overall monetary and environmental costs for three adaptive strategies, finding that aggressive adaptation strategies proved less costly in the long run than doing nothing.

- Kinsella and McGuire (2005) estimated the approximate cost of retrofitting or redesigning New Zealand’s road bridges to accommodate increased precipitation (and higher stream flows). They found that although designing for climate change increased initial costs by about 10 percent, over the life of the structure the incremental cost was small (less than 1 percent) due to the decreased probability of climate-related damage.

- Olsen (2005) conducted a Monte Carlo simulation of total annual losses to shippers on the Mississippi River from having to switch to more expensive modes of transport when barge travel is restricted due to low or high water flows. He found that future losses could range from $1.5 million to $41 million per year, compared to an historical average of $12 million per year.

- Associated British Insurers used insurance catastrophe models to examine the financial implications of climate change through its effects on severe storms (Climate Risk Management and Metroeconomica, 2005), estimating that climate change could increase the annual costs of flooding in the United Kingdom almost 15-fold by the 2080s under high-emissions scenarios.

Studies also have been done on the cost of severe storms on transportation networks, which will provide useful data for future studies relating them to climate change. For instance, Grenzeback and Lukmann (2006) summarize some costs to the transportation network resulting from Hurricane Katrina. Although they do not attempt a full accounting of these costs, they note that infrastructure restoration costs will run into the billions of dollars – replacement of the I-10 Twin Span Bridge between New Orleans and Slidell, LA, alone will cost $1 billion and of the CSX rail line another $250 million.

### 1.3.4 Impacts, Assessment, and Adaptation

A review of the literature indicates that the potential impacts of climate changes on transportation are geographically widespread, modally diverse, and may affect both transportation infrastructure and operations. Indeed, numerous transportation impacts were discussed in the literature. However, the degree to which a study discussed an impact varied; some studies addressed impacts at length, while others gave an impact only a passing mention. A complete list of impacts and adaptations addressed in the literature, along with references, can be found in table 1.1.

Four major categories of climate change factors are addressed most frequently in the literature. These closely parallel the major factors addressed later in this report’s study of the Gulf Coast region. These climate factors and their major impacts are:

1. **Increasing temperatures,** which can damage infrastructure, reduce water levels on inland waterways, reduce ice cover in the Arctic, and melt permafrost foundations;

2. **Increasing precipitation,** which can degrade infrastructure and soil conditions;

3. **Rising sea levels,** which can inundate coastal infrastructure; and

4. **Changes in storm activity,** which can damage infrastructure and operations due to increased storm intensity, though winter snowstorms may decrease in frequency.

A summary of the literature findings regarding these impacts, and their corresponding adaptation measures, is presented below. This is followed by a brief discussion of the indirect or secondary impacts on the economy, environment, population, and security of a region.

[INSERT TABLE 1.1 Impacts of Climate Change Identified in the Literature 1987-2006]

### 1.3.5 Direct Climate Impacts on Transportation Addressed in Existing Literature

***Increasing Temperatures***

Increasing temperatures have the potential to affect multiple modes of transportation, primarily impacting surface transportation. The transportation impacts mentioned most often in the literature included pavement damage; rail buckling; less lift and fuel efficiency for aircraft; and the implications of lower inland water levels, thawing permafrost, reduced ice cover on seaways, and an increase in vegetation. These are discussed in greater detail below:

- **Pavement damage –** The quality of highway pavement was identified as a potential issue for temperate climates, where more extreme summer temperatures and/or more frequent freeze/thaw cycles may be experienced. Extremely hot days, over an extended period of time, could lead to the rutting of highway pavement and the more rapid breakdown of asphalt seal binders, resulting in cracking, potholing, and bleeding. This, in turn, could damage the structural integrity of the road and/or cause the pavement to become more slippery when wet. Adaptation measures mentioned included more frequent maintenance, milling out ruts, and the laying of more heat resistant asphalt.

- **Rail buckling –** Railroads could encounter rail buckling more frequently in temperate climates that experience extremely hot temperatures. If unnoticed, rail buckling can result in derailment of trains. Peterson (2008) noted, "Lower speeds and shorter trains, to shorten braking distance, and lighter loads to reduce track stress are operational impacts." Adaptation measures included better monitoring of rail temperatures and ultimately more maintenance of the track, replacing it when needed.

- **Vegetation growth –** The growing season for deciduous trees that shed their leaves may be extended, causing more slipperiness on railroads and roads and visual obstructions. Possible adaptation measures included better management of the leaf foliage and planting more low-maintenance vegetation along transportation corridors to act as buffers (Wooler, 2004).

- **Reductions in aircraft lift and efficiency –** Higher temperatures would reduce air density, decreasing both lift and the engine efficiency of aircraft. As a result, longer runways and/or more powerful airplanes would be required. However, one analyst projected that technical advances would minimize the need for runway redesign as aircraft become more powerful and efficient (Wooler, 2004).

- **Reduced water levels –** Changes in water levels were discussed in relation to marine transport. Inland waterways such as the Great Lakes and Mississippi River could experience lower water levels due to increased temperatures and evaporation; these lower water levels would mean that ships and barges would not be able to carry as much weight. Adaptation measures included reducing cargo loads, designing vessels to require less draft, or dredging the water body to make it deeper.

- **Reduced ice cover –** Reduced ice cover was generally considered a positive impact of increasing temperatures in the literature. For example, a study conducted by John D. Lindeberg and George M. Albercook, which was included in the *Report of the Great Lakes Regional Assessment Group for the U.S. Global Change Research Program*, stated, "the costs of additional dredging [due to lower water levels] could be partially mitigated by the benefits of additional shipping days on the [Great] Lakes caused by less persistent ice cover" (Sousounis, 2000, p. 41). Additionally, arctic sea passages could open; for example, the *Arctic Climate Impact Assessment* noted, "projected reductions in sea-ice extent are likely to improve access along the Northern Sea Route and the Northwest Passage" (Instanes et al., 2005, p. 934). However, negative environmental and security impacts also may result from reduced ice cover as well from as the increased level of shipping. These are discussed below in the subsection on indirect impacts (Section 1.3.6.).

- **Thawing permafrost –** The implications of thawing permafrost for Arctic infrastructure receive considerable attention in the literature. Permafrost is the foundation upon which much of the Arctic's infrastructure is built. The literature consistently noted that as the permafrost thaws the infrastructure will become unstable – an effect being experienced today. Roads, railways, and airstrips are all vulnerable to the thawing of permafrost. Adaptation measures vary depending on the amount of permafrost that underlies any given piece of infrastructure. The literature suggested that some assets will only need rehabilitation, other assets will need to be relocated, and different construction methods will need to be used, including the possibility of installing cooling mechanisms. According to the Arctic Research Commission, "roads, railways, and airstrips placed on ice-rich continuous permafrost will generally require relocation to well-drained natural foundations or replacement with substantially different construction methods" (U.S. Arctic Research Commission Permafrost Task Force, 2003, p. 29).

- **Other –** Other impacts of increasing temperatures included a reduction in ice loads on structures (such as bridges and piers), which could eventually allow them to be designed for less stress, and a lengthening of construction seasons due to fewer colder days in traditionally cold climates.

### *Increasing Precipitation*

Increases in precipitation will likely affect infrastructure in both cold and warm climates, although in different ways. Increases in the frequency and intensity of the precipitation could impact roads, airstrips, bikeways/walkways, and rail beds. The literature suggested most of the impact would be felt in the more rapid deterioration of infrastructure. According to a report released by Natural Resources Canada (2004, p. 138), “accelerated deterioration of these structures may occur where precipitation events and freeze-thaw cycles become more frequent, particularly in areas that experience acid rain.” Other impacts of increased flooding include subsidence and heave of embankments (ultimately resulting in landslides), and deterioration in water quality due to run-off and sedimentation. Adaptation measures included monitoring infrastructure conditions, preparing for service delays or cancellations, and replacing surfaces when necessary (Warren, 2004). Although mentioned less frequently, some attention was given in the literature to bridge scour from increased stream flow. Bridge scour could cause abutments to move and damage bridges.

### *Rising Sea Levels*

Sea level rise could impact coastal areas. While incremental sea level rise impacts may not be as immediate or severe as the storm activity, the impacts could nevertheless affect all modes of transportation. Low-level roads and airports are at risk of inundation, and ports may see higher tides. Titus (2002, p. 139) concluded “the most important impact of sea level rise on transportation concerns roads. In many low-lying communities, roads are lower than the surrounding lands, so that land can drain into the streets. As a result, the streets are the first to flood.” Adaptation measures include more frequent maintenance, relocation, and the construction of flood-defense mechanisms (such as dikes) (Titus, 2002). Although mentioned less often in the literature, deeper water caused by sea level rise could permit greater ship drafts in ports and harbors.

### *Changes in Storm Activity*

Storm activity was discussed as an issue for all climates, impacting both inland areas and coastal areas. Impacts most frequently mentioned in the literature include storm surges that could potentially cause damage to coastal areas and a decrease in winter snowstorms (with more winter precipitation falling as rain). These are discussed in greater detail below:

- **Increased storm activity or intensity –** In coastal areas, increased storm activity or intensity could lead to an increase in storm surge flooding and severe damage to infrastructure, including roads, rails, and airports. These effects could be exacerbated by a rise in sea level. In addition, coastal urban areas, like New York City, could potentially see storm surges that flood the subway system. As Zimmerman (2002a, p. 94) noted, “transportation systems are traditionally sited in low-lying areas already prone to flooding.” She went on to state that, “New York City alone has over 500 miles of coastline, much of which is transgressed [sic] by transportation infrastructure – roadways, rail lines, and ventilation shafts, entrances and exits for tunnels and transit systems, many are at elevations at risk of being flooded even by traditional natural hazards” (p. 94). Adaptation measures included construction of barriers to protect against storm surges, relocating infrastructure, and preparing for alternative traffic routes (Zimmerman, 2002a).

Other impacts related to storm activity included an increase in wind speed and an increase in lightning. Increased wind speeds could damage signage and overhead cables. Increased lightning strikes could cause electrical disturbances disrupting electronic transportation infrastructure, like signaling.

- **Reduced snowfall –** A decrease in winter snowstorms could potentially relieve areas that typically see large amounts of snow from some of the cost of maintaining winter roads. Natural Resources Canada concluded, "empirical relationships between weather variables and winter maintenance activities indicate that less snowfall is associated with reduced winter maintenance requirements. Thus, if populated areas were to receive less snowfall and/or experience fewer days with snow; this could result in substantial savings for road authorities" (Warren et al., 2004, pp. 138-139).

### 1.3.6 Indirect Climate Impacts on Transportation Addressed in Existing Literature

Four secondary, or indirect, impacts were addressed to some degree in the literature: economic, environmental, demographic, and security impacts.

***Economic***

The economic impact of climate change received considerable attention. Some studies made an attempt to approximate the cost of replacing infrastructure or to place a monetary figure on loss of specific aspects of system performance, such as traffic disruptions. For example, Suarez et al. (2005, p. 240), when discussing the effects flooding could have on the Boston Metro area, stated, "over the period 2000 to 2100, the results indicate that delays and trips lost (i.e., canceled trips) increased by 80 percent and 82 percent under the climate change scenario. While this is a significant increment in percentage terms, the magnitude of the increase is not enough to justify a great deal of infrastructure improvements."

The economic implications of impacts on freight were particularly studied. Three climate factors were analyzed in most depth: changing inland water levels, specifically on the Great Lakes; thawing permafrost and warmer temperatures in traditionally colder climates; and the potential opening of the Northwest Sea Passage through the Canadian Arctic as a result of sea ice melt. These are discussed in greater detail below:

- **Changing inland waterway levels –** Quinn analyzed the economic impacts of lower water levels in the Great Lakes, which would require ships to lighten their loads because of lower water levels. According to Quinn (2002, p. 120), "a 1,000-foot bulk carrier loses 270 tons of capacity per inch of lost draft." If lower water levels occur on a regular basis, Great Lakes shippers are likely to see less profit and will run the risk of the freight being transported by competing modes (e.g., rail or truck). A few analyses considered the impacts of rising inland water levels (Olsen, 2005).

- **Increasing temperatures in northern regions –** Other analysts assessed the economic impacts of warming temperatures on trucking in northern regions. Typically, trucks are allowed to carry more weight when the underlying roadbeds are frozen, and some Arctic regions are served by ice roads over the tundra in winter. If temperatures increase and northern roads thaw before their usual season, truckloads may have to be reduced during the traditionally higher weight-limit trucking season. This impact already is occurring in some regions of the United States and Canada. As a result, a few highway authorities are adjusting their weight restrictions based on conditions, rather than linking them to a given date (Clayton et al., 2005).

- **Opening of the Northwest Passage –** The literature indicated that the reduction of waterway ice cover and the eventual opening of an Arctic Northwest Passage have by far the largest economic consequences of all the impacts. The passage could provide an alternative to the Panama Canal and stimulate economic development in the Arctic region (Johnston, 2002).

***Environmental***

A small number of environmental impacts have been addressed in the literature to date, focusing on the effects of specific adaptation responses to changing climate and weather conditions. These included the potential of increased dredging of inland waterways, reduced use of winter road maintenance substances, and the environmental impact increased shipping could have on the Arctic.

- **Dredging –** Dredging of waterways – in response to falling water levels – could have unintended, harmful environmental impacts. According to the Great Lakes Regional Assessment, "in a number of areas the dredged material is highly contaminated, so dredging would stir up once buried toxins and create a problem with spoil disposal" (Sousounis, 2000, p. 30).

- **Increased shipping in the Arctic –** The transportation benefits of the Northwest Passage could be offset by the negative environmental impacts associated with its use, particularly oil spills (Struck, 2006). Johnston (2002, p. 153) noted that there is "serious concern on the part of many Inuit and other residents that regular commercial shipping will, sooner or later, cause serious harm to the Arctic ecology."

- **Reduced winter maintenance –** Some positive environmental impacts also were mentioned, particularly in relation to milder winter weather in northern regions. For example, according to Warren et al. (2004, p. 139) "less salt corrosion of vehicles and reduced salt loadings in waterways, due to reduced salt use" during winter months could positively impact the environment. According to Natural Resources Canada, "experts are optimistic that a warmer climate is likely to reduce the amount of chemicals used, thus reducing costs for the airline industry, as well as environmental damage caused by the chemicals" (Warren et al., 2004, p. 139).

***Demographic***

Demographic shifts were rarely addressed in the literature. A few reports raised the potential for shifts in travel destinations and mode choices. For instance, in a U.K. Climate Impacts Programme Report on the West Midlands it was noted: "higher temperatures and reduced summer cloud cover could increase the number of leisure journeys by road. There could be a possible substitution from foreign holidays if the climate of the West Midlands becomes more attractive relative to other destinations, reducing demand at Birmingham International Airport" (Entek UK Limited, 2004, p. 24). In addition, the Arctic regions, located near the Northwest Passage, could see an influx of population (Entek UK Limited, 2004).

***Security***

Security was identified as an issue in relation to the Northwest Passage. Given the enormous changes the development of the Northwest Passage would precipitate, it is no surprise that global diplomacy, safety, and security is of concern. Johnston (2002, p. 152) stated, "even if the remoteness of the Northwest Passage seems to make it an unlikely target for terrorists, security concerns will centrally have to be factored in to any major undertaking in the Arctic or elsewhere that would be perceived by enemies as an important component of the North American economy." If the Northwest Passage does become practical for shipping, security, ownership, maintenance, and safety of the waterway will become an issue. Indeed, the U.S. Navy already had begun thinking about the implications of an ice-free Arctic during a symposium held in April 2001 (Office of Naval Research, 2001). Sovereignty issues also will need to be resolved to clarify whether the passage will be considered international or Canadian waters (Johnston, 2002).

### 1.3.7 Decision Making Processes and Tools

Until recently, studies typically concluded with recommendations for additional analysis of uncertainty, thresholds, and prioritization of actions. Recent work has begun to respond to this need, but the field still has a long way to go. Some reports have begun to make suggestions for institutional changes necessary to integrate climate impacts into the decision making processes for transportation planning and investment. Studies have suggested some approaches to more adequately dealing with uncertainty. Finally, several studies have attempted to develop methodologies that can integrate potential climate impacts into risk prioritization processes, decision trees, and other decision support tools.

The following sections discuss institutional changes that were identified in the literature, evaluate the manner in which uncertainty and probability was addressed, and present four case studies highlighting different methodologies used in risk analysis and impact assessment.

### *Institutional Changes*

On the whole, analysis and recommendations concerning needed changes in standard design practice or institutional changes are beginning to emerge but are at a nascent stage. A few recent studies illustrate this point:

- **Urban-scale planning –** Two recent studies developed recommendations for London and Seattle. The Greater London Authority (2005) urged transportation decision makers to incorporate climate into routine risk management procedures, build adaptation measures into new infrastructure when appropriate, and make certain that whatever measures are taken are flexible and easily adaptable to future climatic changes. However, the report gave little direction on how they should go about this; suggestions about how and when officials should incorporate these adjustments were not well defined. Likewise, a 2005 Seattle study, authored by the city auditor, recommended that the Seattle Department of Transportation "identify, prioritize, and quantify the potential effects of climate change impacts; and plan appropriate responses to changes in the region's climate" (Soo Hoo et al., 2005, p. 12). A specific institutional recommendation made was the synchronization of sea level rise assumptions among Seattle's various city agencies (for instance, in the assumptions made for construction of seawalls) (Soo Hoo et al., 2005).

- **Arctic maritime regulatory regime –** For the Arctic, several studies identified the need for a new regulatory system to govern ships in Arctic waters. Johnston (2002) recommended a new "transit management regime" be developed for the Northwest Passage to clarify Canadian and international responsibilities and jurisdiction over maritime passage, and the Arctic Marine Transport Workshop (Brigham, 2004) suggested the development of harmonized safety and environmental measures for the larger Arctic region.

- **General planning considerations –** Several other reports recommended that as a first step a process be developed for including climate impacts in planning. For instance, the Northern Ireland assessment recommended that a formalized policy on climate impacts be developed within three years (Smyth et al., 2002), and Associated British Ports indicated that it planned to periodically re-examine potential impacts to ports in order to see if their assessment changes with new information (ABP Marine Environmental Research Ltd., 2004). Interestingly, Norwell (2004) noted that planning for sea level rise already has been incorporated into planning documents in several Australian States.

  In general, the mismatch between typical planning horizons and the longer-term timeframe over which climate impacts occur appears to be a barrier to incorporating climate change factors in decision making. For example, Kinsella and McGuire (2005) concluded that for infrastructure with replacement horizons of less than 25 years, there was no need to consider longer-term climate effects in the present day, as the infrastructure would turn over before it became a problem.

### *Uncertainty and Probability*

The literature indicates that only recently have analysts begun to address the issue of transportation risk assessment and decision making under uncertainty. Even now, the analytical sophistication of studies that attempt to address these concerns is in its infancy. The studies consistently showed awareness of the uncertainty of climate projections, quoting ranges for potential climate changes. However, probabilistic approaches were not implemented in the literature reviewed and were rarely discussed. Nor was there a focus on the development of "robust" strategies that can bear up under multiple possible futures or other strategies designed specifically to deal with decision making under uncertainty. Dewar and Wachs (forthcoming) note that this is a gap in transportation planning more generally and not simply in the matter of climate change. They call for a paradigmatic shift in transportation planning approaches.

Several studies did discuss possible approaches to the issue of uncertainty and decision making, without applying them to specific cases. For example, Meyer (forthcoming) noted that, "in recent years, many engineering design analyses have been incorporating more probabilistic approaches into their design procedures that account for uncertainty in both service life and in environmental factors." He continued, "In considering wind speeds, for example, probabilities of different wind speeds occurring based on an underlying distribution of historical occurrences are used to define a design wind speed. Other analysis approaches are incorporating risk management techniques into the tradeoff between design criteria that will make a structure more reliable and the economic costs to society if the structure fails." Furthermore, Dewar and Wachs (forthcoming) discuss a wide variety of conceptual decision making tools that could be considered when designing frameworks to understand how to incorporate climate uncertainty into transportation infrastructure decisions.

### *Approaches to Risk Analysis and Impact Assessment*

Among those studies that attempted to implement a risk analysis or impact assessment framework for a particular transportation system, a number of different approaches were taken. For instance, Associated British Ports demonstrates an approach to risk evaluation that relies on expert elicitation to make a judgment on risk levels for U.K. ports (ABP Marine Environmental Research Ltd., 2004). Risk was broken into four themes: (1) flooding; (2) insurance; (3) physical damage; and (4) disruption. Port managers were asked to evaluate the risk level of each impact by indicating whether they thought it was a: (1) very low risk; (2) low risk; (3) moderate risk; (4) high risk; or (5) very high risk. Using this methodology, the study concluded that storm surge events represent the biggest threat to U.K. ports.

For the U.K. rail network, Eddowess et al. (2003) developed a framework for prioritizing risks that integrates the probability that a particular climate effect would impact the rail industry ("risk likelihood") with the scale of the impact, if it did occur ("risk impact"). The "risk likelihood" essentially combined an assessment of the present-day vulnerability to specific climate factors with projections of how they might change under global climate change scenarios, while the "risk impact" took into account the severity of a given impact, the amount of infrastructure affected, and the ability to adapt to the change. Their study did not, however, explicitly specify thresholds for when a given level of adaptation was worth implementing.

Transit New Zealand developed a methodology for determining thresholds for taking action by using a two-stage process (Kinsella and McGuire, 2005). The first stage constituted a decision tree that examined the necessity of taking action in the near term. No action was deemed necessary if (1) it was determined that a given impact was unlikely to occur before 2030, (2) the impact would not occur within the design life of the facility (for facilities with lifetimes of less than 25 years), or (3) current standards would adequately address the climate impact. If present-day action was deemed necessary, the second stage analysis determined the feasibility of taking action by comparing the costs of doing nothing, retrofitting the infrastructure, or designing all new infrastructure with future climate changes in mind.

Finally, the Climate's Long-term Impacts on Metro Boston CLIMB report develops tools for scenario analysis tools and decision support for Boston decision makers to use in understanding climate impacts. Specifically, the researchers developed a dynamic analytical modeling tool to help policy and decision makers assess changes in climate and in socioeconomic and technological developments and to understand their associated interrelated impacts on Boston's infrastructure system as a whole. The model allows users to input climate drivers in order to assess performance impacts and potential adaptation strategies for infrastructure systems, including transportation (Kirshen et al., 2004).

## ■ 1.4 Conclusions Drawn from Current Literature on the State of Research

Assessing the literature on the impacts of climate change on transportation as a whole, it becomes apparent that there are a number of areas in which more research is needed on potential impacts of climate change on transportation. Many authors noted that research on the potential impacts of climate change on transportation systems is limited. Warren et al. (2004) note that though much work has been done on adaptation to climate change in general, relatively little concerns climate impacts on transportation systems – to date, transportation research has been focused on emission-reduction strategies. Other authors noted the need for more research on specific impacts or modes. For instance, in their study of seasonal weight limits on prairie highways, Clayton et al. (2005) noted that there was essentially no transportation and climate impacts literature on their topic to draw upon.

Work in this field has so far been focused on the initial stages of risk assessment and adaptation; i.e., building a basic understanding of the issues involved. In general, the literature review shows that some work has been done on collecting data, assessing impacts, and evaluating the significance of these risks. Less work has been done to develop methodologies for assessment or to systematically evaluate adaptation strategies.

Work to develop decision support tools to facilitate these processes has received little formal attention. The state of research in each analytic area is summarized below.

**Collecting data needed to assess transportation vulnerability to climate impacts.** Some credible work on data collection and analysis has been done for selected modes and facilities in specific regions. Researchers have been able to make use of the good data on transportation networks and transportation engineering practice that exists for most of the developed world.

Most studies used climate projections consistent with long-term IPCC global projections as the basis for their analyses. However, few studies considered a broader range of plausible climate futures that could occur, such as scenarios, including additional feedbacks or abrupt climate change. In addition, few studies addressed the implications of changes in temperature or precipitation extremes.

In addition, there are significant gaps in data collection and analysis for several modes and for transportation infrastructure in hot or tropical climates, such as are found in the southwestern and southeastern portions of the United States. Most of the available literature addresses temperate or Arctic climates.

**Developing knowledge about potential impacts.** Researchers considered a wide variety of potential impacts on transportation, and significant work has been done for selected modes and facilities. However, a number of important gaps were found in the current literature, most notably the lack of quantitative assessment and dearth of literature on operations, network, performance, and secondary impacts:

- **Quantitative assessment –** Most studies to date have been qualitative. More quantitative assessments of impacts, along with the development of quantitative analytical methodologies, will provide needed information for decision makers.

- **Operations impacts –** The implications of climate change impacts on operations (both normal and emergency) are not as well explored as they are for physical infrastructure. Most of the existing literature on operations is focused on a select few issues such as waterborne freight and winter maintenance.

- **Network and performance impacts –** Relatively few studies (Kirshen et al., 2004; Suarez et al., 2005) focused on the network-level impacts of climate change. Most focused on the facility level (impacts to a type of facility, for instance, rather than system-level impacts on the whole network), and few measured performance impacts.

- **Secondary impacts –** Several secondary impacts mentioned in the literature but not discussed in-depth could provide useful avenues for further study. These include shifts in transportation demand due to climate-induced changes in economic activity and demographics; the impact of a warming climate on air quality (which influences transportation investment decisions); and other environmental impacts related to climate change that may intersect with transportation decision making in relation to ecosystem and habitat preservation, water quality and stormwater management, mitigation strategies, safety, and system and corridor planning.

**Assessing the significance of these risks.** Work in this area is largely qualitative. Though many researchers were able to communicate an assessment of which risks were significant enough to require further study, few produced quantitative assessments of cost or performance impacts. In particular, more work is needed regarding the economic implications of climate impacts on transportation facilities and systems. Relatively few studies addressed this quantitatively from an overall life-cycle benefits/costs framework.

**Developing a methodological approach for assessment.** Most studies used a similar basic approach (identify climate effects of concern, assess potential risks for specific modes/facility types, and identify potential adaptations). However, very few attempted to develop a generalized approach or consider the ramifications of translating their approach to other modes/regions.

**Identifying strategies for adaptation and planning.** Most studies dealt with adaptation from a facility engineering approach, rather than a strategic or systems performance level. Thus, it is largely specific design adaptations appropriate for particular types of facilities that were identified in the literature (for instance, insulating railbeds to prevent permafrost melt or raising roads to protect them against sea level rise).

Nonetheless, beginning elements of larger adaptation strategies were recognized in the literature. There is a general understanding of the differences between likely short- and long-term effects and acknowledgment that different approaches might be needed at different points in time (Meyer, forthcoming). In addition, some studies recognized that institutional change is necessary and recommended institutional processes for examining impacts and deciding on adaptations.

Significantly, almost no research has been done on how climate change can be incorporated into the long-range transportation planning process. Issues to address in future research include the mismatch between the timeframe of 20- and 30-year long-range plans and the 50- and 100-year projections of climate impacts; how to address the potential for nonlinear or abrupt changes in climate systems in a planning process; and how to make planning decisions that account for uncertainty in climate projections.

**Developing decision-support tools.** Very little work has been done to develop decision-support tools for transportation managers and planners. The field is sufficiently new that there has likely been little demand from transportation decision makers for such tools; rather they are only now beginning to learn about the potential impacts they might face in the future.

One of the most important gaps in this area is the lack of probabilistic approaches to address uncertainty. More sophisticated methodologies to incorporate uncertainty will need to be developed for transportation decision makers in order for them to incorporate climate change into transportation planning. Currently, uncertainty is rarely incorporated in a probabilistic sense in the literature on climate impacts on transportation (though the existence of uncertainty is acknowledged and expressed through the use of ranges in the climate factors and sometimes the use of scenarios). In addition, little attention is given to decision making practices under uncertainty, such as the development of adaptation strategies that are robust across multiple potential futures.

In summary, research on the potential impacts of climate change on transportation is an emerging field and one that has shown a remarkable upturn in interest and activity over the past few years. This has coincided with greater interest in the subject of adaptation in general, as recognition has grown that some degree of climate change is inevitable in the coming decades, even as steps are taken to reduce future emissions. Considerable work remains to be done in bringing this field to a greater level of maturity, including investigations of impacts not yet thoroughly examined and developing strategies, methodologies, and tools that decision makers at all levels can use to both assess the importance of climate impacts and identify ways to respond.

## ■ 1.5 Gulf Coast Study Selection, Objectives, and Organization

### 1.5.1 Study Selection

To advance research on the implications of climate change for transportation, the U.S. DOT Center for Climate Change solicited and reviewed a range of project concepts. A case study approach was selected as an initial research strategy that would both generate concrete, useful information for local and regional decision makers as well as help to develop a prototype for analysis in other regions and contribute to research methodologies for broader application.

In selecting the study, U.S. DOT considered the extent to which the research would:

- Increase the knowledge base regarding the risks and sensitivities of transportation infrastructure to climate variability and change, the significance of these risks, and the range of adaptation strategies that may be considered to ensure a robust and reliable transportation network;
- Provide relevant information and assistance to transportation planners, designers, and decision makers;
- Build research approaches and tools that would be transferable to other regions or sectoral analyses;
- Produce near-term, useful results;
- Address multiple aspects of the research themes recommended by the 2002 workshop;

- Build on existing research activities and available data; and
- Strengthen U.S. DOT partnerships with other Federal agencies, State and local transportation and planning organizations, research institutions, and stakeholders.

Based on these criteria, the U.S. DOT selected a study of the Gulf Coast as the first of a series of research activities that its Center for Transportation and Climate Change will pursue to address these research priorities.

There are several intended uses for the products of this study. First, the findings of the study will help inform local and regional transportation decision makers in the central U.S. Gulf Coast region. While focused on one region of the United States, it is expected that this study will provide a prototype for analysis in other regions. The study findings will contribute to research methodologies in this new area of investigation. For example, Phase I has identified priority databases and methodologies for the integration of data for analysis in a GIS format, developed formats for mapping products, and developed criteria for assessing and ranking infrastructure sensitivities to the potential impacts of climate variability and change. Each of these outputs will offer useful information and example methodologies for use in research activities in other locations, as well as in decision making processes for transportation and planning in other areas. This research also is intended to help scientists and science agencies better understand the transportation sector's information needs, leading to improved data and better decision support.

### 1.5.2 Gulf Coast Study Objectives and Three Phases

The Gulf Coast Study has been organized into three phases, as depicted in figure 1.1. This report presents the findings of Phase I. The objectives of the overall study are to:

- Develop knowledge about potential transportation infrastructure sensitivities to climate changes and variability through an in-depth synthesis and analysis of existing data and trends;
- Assess the potential significance of these sensitivities to transportation decision makers in the central U.S. Gulf Coast region;
- Identify potential strategies for adaptation that will reduce risks and enhance the resilience of transportation infrastructure and services; and
- Identify or develop decision support tools or procedures that enable transportation decision makers to integrate information about climate variability and change into existing transportation planning and design processes.

The two primary objectives of Phase I of the central Gulf Coast transportation impact assessment were to: (1) collect data needed to characterize the region – its physiography and hydrology, land use and land cover, past and projected climate, current population and trends, and transportation infrastructure; and (2) demonstrate an approach for assessing risks and vulnerability of transportation at regional and local scales. The results of this analysis are presented in this report. The methodologies developed during Phase I of the study can be applied to assess transportation risk and vulnerability at a community, county, or regional level.

Phase II of the study will entail an in-depth assessment of impacts and risks to selected areas and facilities (as identified in Phase I) and will contribute to the development of risk-assessment tools and techniques that can be used by transportation decision makers to analyze the vulnerability of other areas.

The objectives of Phase III are to identify the range of potential adaptation strategies available to Federal, regional, and local transportation managers to respond to the risks identified in Phases I and II; to identify the potential strengths and weaknesses of these responses; and to develop an assessment tool that may assist transportation managers in selecting adaptation strategies appropriate to their agency, community, or facility, and to the identified sensitivity to climate change.

[INSERT FIGURE 1.1 Gulf Coast Study Design]

### 1.5.3 Study Organization and Oversight

The Gulf Coast Study is 1 of 21 "synthesis and assessment" products planned and sponsored by the U.S. Climate Change Science Program (CCSP). The primary objective of the CCSP is to provide scientific information needed to inform public discussions and government and private sector decision making on key climate-related issues. This project is one of seven projects organized under CCSP Goal 4, which is "to understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes" (CCSP, 2003, p. 20).

Led by the U.S. DOT in collaboration with the U.S. Geological Survey (USGS), this study was conducted through a groundbreaking interdisciplinary approach that integrated natural science disciplines with expertise in risk assessment, transportation, and planning. The U.S. DOT and USGS convened a research team with expertise in multiple fields based on each agency's mission and core capabilities. The USGS coordinated the provision of scientific research support, coordinating expertise in climate change science and impacts assessment; meteorology; hydrology; storm surge analysis and modeling; risk analysis; and economics. Cooperators from Louisiana State University, the University of New Orleans, and Texas A&M University assisted in the data collection aspects of Phase I and in developing a framework for assessing risk and vulnerability. (The U.S. DOT assembled expertise in transportation planning, engineering, design, and operation.) Cambridge Systematics, Inc., (CS) a transportation consulting firm, supported the coordination and design of the study, assisted in organizing the data, and provided transportation experts with expertise in ports, rail, highways and transit, pipelines, aviation, emergency management, and transportation planning and investment. The CS Transportation Analysis Team included consultant support from Wilbur Smith Associates and the Texas Transportation Institute. The U.S. DOT's Bureau of Transportation Statistics (BTS) supported geospatial and other data collection and analysis related to transportation, working in coordination with USGS geospatial experts. Collectively, this group of scientists and transportation experts has served as the research team conducting Phase I of the study.

The Secretary of Transportation, following the guidelines of the Federal Advisory Committee Act (5 U.S.C. App. 2) or “FACA,” established a U.S. DOT Advisory Committee on Synthesis and Assessment Product 4.7: Impacts of Climate Variability and Change on Transportation Systems and Infrastructure – Gulf Coast Study, Phase I. The committee provides technical advice and recommendations in the development of this product for the CCSP. The committee provides balanced, consensual advice on the study design, research methodology, data sources and quality, and study findings. The committee functions as an advisory body to the two Federal agencies leading the research project.

This product adheres to Federal Information Quality Act (IQA) guidelines and Office of Management and Budget (OMB) peer review requirements. Background sources of information, included as illustrative material and to provide context, are clearly identified as such at the end of the list of sources in each chapter.

### 1.5.4 Characterizing Uncertainty

Some degree of uncertainty is inherent in any consideration of future climate change; further, the degree of certainty in climate projections varies for different aspects of future climate. Throughout this report, the research team has adopted a consistent lexicon first developed by the IPCC to indicate the degree of certainty that can be ascribed to a particular potential climate outcome. As presented in figure 1.2, the “Degree of Likelihood” ranges from “Impossible” to “Certain,” with different terminology used to describe different ranges of statistical certainty as supported by available scientific modeling and analysis. The analytic approach required to characterize uncertainty for each climate factor (e.g., temperature, precipitation, sea level rise, storm surge) is discussed in detail in the relevant section of this report.

[INSERT FIGURE 1.2 Uncertainty Lexicon]

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# Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006.

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| ***Temperature Increase*** | | | | |
| **Increased Summer Temperatures** | Highway asphalt rutting | | Proper design/construction, milling out ruts, more maintenance, overlay with more rut-resistant asphalt | (1) Wooler, Sarah. 2004.<br>(2) Andrey and Mills. 2003.<br>(3) Hass, et al. 2006.<br>(4) Black, William. 1990.<br>(5) Meyers, Michael. 2006.<br>(6) Barrett, et al. 2004.<br>(7) Marbek Resource Consultants Ltd. 2003.<br>(8) Kerr, Andrew, et al. 1999.<br>(9) Warren, et al. 2004.<br>(10) Entek U.K. Limited. 2000.<br>(11) Entek U.K. Limited. 2004.<br>(12) Lockwood, Steve. 2006.<br>(13) Kinsella, Y. and McGuire, E. 2005.<br>(14) Mills and Andrey. 2002.<br>(15) OFCM. 2002. |
| | Rail buckling | Potential for derailment and malfunction of track sensors and signal sensors, increased travel time due to speed restrictions, increased risk of hazardous material spill | Speed restrictions, reducing frequency of some services, better air conditioning for signals. Improve systems to warn and update dispatch centers, crews, and stations. Inspect and repair tracks, track sensors, and signals. Distribute advisories, warnings, and updates regarding the weather situation and track conditions. | (1) Wooler, Sarah. 2004.<br>(2) Eddowes, M.J., et al. 2003.<br>(3) Kerr, Andrew, et al. 1999.<br>(4) Warren, et al. 2004.<br>(5) Entek U.K. Limited. 2000.<br>(6) Land Use Consultants, et al. 2002.<br>(7) Smyth, et al. 2002.<br>(8) Kerr, Andy. 2001.<br>(9) Entek U.K. Limited. 2004.<br>(10) Rossetti. 2002.<br>(11) OFCM. 2002. |
| | More airport runway length and fuel needed because of less dense air | | New planes designed to takeoff more efficiently | (1) Wooler, Sarah. 2004.<br>(2) Andrey and Mills. 2003.<br>(3) Irwin and Johnson. 1990.<br>(4) Warren, et al. 2004.<br>(5) Entek U.K. Limited. 2000.<br>(6) Smyth, et al. 2002.<br>(7) Entek U.K. Limited. 2004. |
| | Heat/Lack of ventilation on underground urban transit systems | Personnel health/safety risk, heat exhaustion, engine/equipment heat stress. Overcrowding, failed, or delayed service will only compound the problem. Could cause passengers to avoid taking public transportation (mode shift). | Install better ventilation systems, climate monitoring systems, personnel safety and equipment monitoring systems. | (1) Wooler, Sarah. 2004.<br>(2) Greater London Authority. 2005.<br>(3) OFCM. 2002. |

## Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| ***Temperature Increase (continued)*** | | | | |
| | | Health and safety risks from heat stress to highway, transit, and pipeline system operators, maintenance personnel, and passengers; including increased risk of collisions/spills of hazardous cargo, control system integrity | Improve systems to advise operators, monitor personnel, and take prescribed and precautionary measures | (1) OFCM. 2002. |
| | Low water levels on inland waterways | Increased shipping costs; shift to other modes (rail, truck) | Changes to navigation, dredging of channels, flow augmentation | (1) Wooler, Sarah. 2004.<br>(2) Andrey and Mills. 2003.<br>(3) Olsen, et al. 2005.<br>(4) Black, William. 1990.<br>(5) Irwin and Johnson. 1990.<br>(6) U.S. Federal Highway Administration Office of Environment and Planning. 1998.<br>(7) U.S. Department of State. 2002.<br>(8) Institute for Water Resources, U.S. Army Corps of Engineers. 2004.<br>(9) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000.<br>(10) National Assessment Synthesis Team. 2000.<br>(11) Marbek Resource Consultants Ltd. 2003.<br>(12) D'Arcy, Pierre. 2004.<br>(13) Warren, et al. 2004.<br>(14) Entek U.K. Limited. 2000.<br>(15) Ministry of Housing, Spatial Planning, and the Environment, The Netherlands. 2001.<br>(16) Ruth, Matthais. 2006.<br>(17) Quinn. 2002. |
| | Thermal expansion of bridges | Frequent detours, traffic disruptions | Increased ongoing maintenance | (1) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005. |
| | Overheating of diesel engines | | Adaptation of cooling systems | (1) Entek U.K. Limited. 2000. |
| | Increased vegetation – leaf fall | Ineffective braking of rail cars, visual obstruction | Vegetation management, plant low-maintenance vegetation as buffer | (1) Wooler, Sarah. 2004.<br>(2) Eddowes, M.J., et al. 2003.<br>(3) Land Use Consultants, et al. 2002.<br>(4) Smyth, et al. 2002.<br>(5) Kerr, Andy. 2001.<br>(6) Entek U.K. Limited. 2004.<br>(7) Kinsella, Y. and McGuire, E. 2005. |
| | Changes to landscape/biodiversity | Highway agency owns many medians. Increased pest management. Impact on wetlands commitments | Different types of vegetation may have to be considered | (1) Wooler, Sarah. 2004.<br>(2) Kinsella, Y. and McGuire, E. 2005.<br>(3) Mortenson and Bank. 2002. |

# Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| ***Temperature Increase (continued)*** | | | | |
| **Increased Summer Temperature and Decreased Precipitation** | Less rain to dilute surface salt may cause steel reinforcing in concrete structures to corrode (Australia) | | Better protect reinforcing in saline environments | 1) Norwell, Gary. 2004. |
| **Increased Winter Temperatures** | Reduction in cold weather rail maintenance | Fewer broken rails, excessive wheel wear, and frozen switches | | (1) Andrey and Mills. 2002. |
| | Longer construction season | Drier and warmer days | | (1) Andrey and Mills. 2003.<br>(2) Kinsella, Y. and McGuire, E. 2005. |
| **Thawing Permafrost (United States, Canada, China)** | Road, rail, airport, pipeline embankments will fail and shallow pile foundations could settle | Potential for fewer construction problems in long run | Crushed rock cooling system, insulation/ground refrigeration systems, rehabilitation, relocation, mechanically stabilize embankments against ground movement, remove permafrost before construction | (1) Instanes et al.. 2005.<br>(2) Brown, Jeff. 2005.<br>(3) Cheng, Guadong. 2005.<br>(4) Hass, et al. 2006.<br>(5) Black, William. 1990.<br>(6) Irwin and Johnson. 1990.<br>(7) U.S. Arctic Research Commission Permafrost Task Force. 2003.<br>(8) Weller, Gunter, et al. 1999.<br>(9) Grondin et al. 2005.<br>(10) Wright, Fred. 2001.<br>(11) Warren, et al. 2004.<br>(12) Ruth, Matthais. 2006.<br>(13) Smith and Levasseur. 2002.<br>(14) Caldwell et al. 2002. |
| **Reduction of Freezing Season for Ice Roads (Arctic)** | Roads unusable during certain seasons | Shorter shipping season, higher maintenance costs, higher life-cycle costs, seasonal mode shift | Reconstruction of severely damaged infrastructure with less frost-susceptible foundation (geosynthetic barrier), retrofitting road side drains | (1) Instanes et al.. 2005.<br>(2) Lonergan, et al. 1993.<br>(3) Andrey and Mills. 2003.<br>(4) Hass, et al. 2006.<br>(5) Weller, Gunter, et al. 1999.<br>(6) Marbek Resource Consultants Ltd. 2003.<br>(7) Clayton et al. (and Montufar). 2005.<br>(8) Warren, et al. 2004.<br>(9) Lockwood, Steve. 2006. |

# Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| ***Precipitation Increase*** | | | | |
| **Increased Winter Precipitation – Rain/Snow** | Flooding of roads/airport runways/bikeways and walkways (frequency and magnitude will increase) | Infrastructure deterioration (quicker with acid rain), impacts on water quality, travel and schedule delays, loss of life and property, increased safety risks, increased risks of hazardous cargo accidents | Seek alternative routes, improve flood protection, risk assessment for new roads, emergency contingency planning, ensure bridge openings/culverts sufficient to deal with flooding, improve drainage, improved asphalt/concrete mixtures, perform adequate maintenance, and minimize repair backlogs | (1) Wooler, Sarah. 2004.<br>(2) Andrey and Mills. 2003.<br>(3) Irwin and Johnson. 1990.<br>(4) U.S. Department of State. 2002.<br>(5) Kirshen, Paul H. and Matthais, Ruth. 2004.<br>(6) Intergovernmental Panel on Climate Change. 2001.<br>(7) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000.<br>(8) Wilkenson, Robert. 2002.<br>(9) Meyers, Michael. 2006.<br>(10) Barrett, et al. 2004.<br>(11) Kerr, Andrew, et al. 1999.<br>(12) Warren, et al. 2004.<br>(13) Entek U.K. Limited. 2000.<br>(14) Land Use Consultants, et al. 2002.<br>(15) Smyth, et al. 2002.<br>(16) Kerr, Andy. 2001.<br>(17) Entek U.K. Limited. 2004.<br>(18) Norwell, Gary. 2004.<br>(19) Kinsella, Y. and McGuire, E. 2005.<br>(20) Rossiter, Lisa. 2004.<br>(21) Smith, Orson. 2006.<br>(22) OFCM. 2002. |
| | Flooding of rails | Service disruption, increased malfunctions of track or signal sensors, wash-outs and mud slides, increased risk of hazardous material spills | Engineering solutions, increase advisories, warnings and updates to dispatch centers, crews, and stations. Modify operations for current or forecast conditions. | (1) Wooler, Sarah. 2004.<br>(2) Irwin and Johnson. 1990.<br>(3) Eddowes, M.J., et al. 2003.<br>(4) Entek U.K. Limited. 2000.<br>(5) Smyth, et al. 2002.<br>(6) OFCM. 2002. |
| | Bridge scour | | Speed restrictions, closure to traffic, new materials, better maintenance | (1) Wooler, Sarah. 2004.<br>(2) Hass, et al. 2006.<br>(3) Kirshen, Paul H. and Matthais, Ruth. 2004.<br>(4) Meyers, Michael. 2006.<br>(5) Eddowes, M.J., et al. 2003.<br>(6) Smith, Orson. 2006.<br>(7) OFCM. 2002. |
| | Flooding of underground transit systems | Power outages (third rail blowouts), complete loss of service in affected areas, drowned passengers | Pumping systems | (1) Wooler, Sarah. 2004.<br>(2) Zimmerman, 2002a and 2002b.<br>(3) OFCM. 2002. |

## Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| ***Precipitation Increase(continued)*** | | | | |
| | Flooding of inland marine transportation waterways | Interruptions of river navigation and other inland waterway activities (ferries, boating, commerce, port operations, lock operations) | | (1) Intergovernmental Panel on Climate Change. 2001.<br>(2) Ning, Zhu H., et al. 2003.<br>(3) OFCM. 2002. |
| | Pipeline system flooding and damage from scouring away pipeline roadbed or unearthing buried pipelines | Disruption of fuel delivery, pipeline sensor failure, disruption of construction or maintenance cycles, leaks or other pipeline failures | | (1) OFCM. 2002. |
| **Increased Precipitation and Increased Summer Temperatures** | Highway, rail, and pipeline embankments at risk of subsidence/heave | Landslides | Fill cracks and carry out more maintenance | (1) Wooler, Sarah. 2004.<br>(2) Instanes et al.. 2005.<br>(3) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005.<br>(4) Wilkenson, Robert. 2002.<br>(5) Weller, Gunter, et al. 1999.<br>(6) Eddowes, M.J., et al. 2003.<br>(7) Konuk, Ibrahim. 2005.<br>(8) Marbek Resource Consultants Ltd. 2003.<br>(9) Kerr, Andrew, et al. 1999.<br>(10) Warren, et al. 2004.<br>(11) Entek U.K. Limited. 2000.<br>(12) Land Use Consultants, et al. 2002.<br>(13) Smyth, et al. 2002.<br>(14) Entek U.K. Limited. 2004.<br>(15) Kinsella, Y. and McGuire, E. 2005.<br>(16) Rossiter, Lisa. 2004.<br>(17) duVair et al. 2002.<br>(18) OFCM. 2002. |
| | Concrete deterioration | | | (1) Wooler, Sarah. 2004.<br>(2) U.S. Department of State. 2002.<br>(3) OFCM. 2002. |
| | More frequent and larger slush-flow avalanches (Arctic) | | Incorporate potential risk into planning process for new settlements, detection systems, temporary closures | (1) Instanes et al.. 2005.<br>(2) Marbek Resource Consultants Ltd. 2003.<br>(3) Warren, et al. 2004.<br>(4) Stethem, Chris, et al. 2003. |
| | Altered runoff patterns (Arctic) | Disruption of the ice-water balance | | (1) Instanes et al.. 2005. |

# Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| ***Glacial Melting/Thermal Expansion of Oceans*** | | | | |
| **Sea Level Rise** | Erosion of coastal highways | | Construction of sea walls | (1) Wooler, Sarah. 2004.<br>(2) Black, William. 1990.<br>(3) U.S. Federal Highway Administration Office of Environment and Planning. 1998.<br>(4) Marbek Resource Consultants Ltd. 2003.<br>(5) Norwell, Gary. 2004.<br>(6) Kinsella, Y. and McGuire, E. 2005.<br>(7) Ruth, Matthais. 2006.<br>(8) Hyman, William, et al. 1989.<br>(9) Titus, 2002.<br>(10) OFCM. 2002. |
| | Higher tides at ports/harbor facilities | Damage to docks and terminals | | (1) Wooler, Sarah. 2004.<br>(2) Black, William. 1990.<br>(3) U.S. Department of State. 2002.<br>(4) Kirshen, Paul H. and Matthais, Ruth. 2004.<br>(5) Smyth, et al. 2002.<br>(6) Ministry of Housing, Spatial Planning, and the Environment, The Netherlands. 2001.<br>(7) Caldwell et al. 2002.<br>(8) OFCM. 2002. |
| | Deeper water | Permit greater ship drafts | | (1) Andrey and Mills. 2003.<br>(2) Kerr, Andrew, et al. 1999.<br>(3) Titus. 2002. |
| | Low-level aviation infrastructure at risk | | Relocation or protection of facilities | (1) Andrey and Mills. 2003.<br>(2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.<br>(3) Warren, et al. 2004.<br>(4) Ruth, Matthais. 2006.<br>(5) Hyman, William, et al. 1989. |
| | Less bridge clearance | | | (1) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005.<br>(2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.<br>(3) Norwell, Gary. 2004.<br>(4) Hyman, William, et al. 1989.<br>(5) OFCM. 2002. |
| | | More search and rescue operations | Obtain more vessels with emergency towing capabilities, better weather forecasting, change seasonal classifications of waters around coast, change ship/boat design | (1) Wooler, Sarah. 2004.<br>(2) Marbek Resource Consultants Ltd. 2003.<br>(3) OFCM. 2002. |

## Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| *Storm Activity* | | | | |
| **Storm Surges** | Coastal road flooding | Increased VMT and VHT; increased number of road accidents, evacuation route delays, disruption of transit services, stranded motorists. | Seawalls, build more redundancy into system, support land use policies that discourage development on shoreline, design and material changes, pumping of underpasses, raise roads | (1) Choo, Kristin. 2005.<br>(2) U.S. Federal Highway Administration Office of Environment and Planning. 1998.<br>(3) Intergovernmental Panel on Climate Change. 2001.<br>(4) Suarez, Pablo et Al. 2005.<br>(5) Rosenzweig, Cynthia and Soleki, William. 2001.<br>(6) Wilkenson, Robert. 2002.<br>(7) National Assessment Synthesis Team. 2000.<br>(8) Meyers, Michael. 2006.<br>(9) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.<br>(10) Greater London Authority. 2005. |
| | Railway flooding | Safety risks to personnel and equipment (possible injury or death from accidents); rail and railway roadbed damage; disruption of rail traffic; rail sensor failure likely; increased risk of hazardous material spill. | Seawalls, raising rails | (1) Black, William. 1990.<br>(2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.<br>(3) Kerr, Andrew, et al. 1999.<br>(4) Greater London Authority. 2005.<br>(5) OFCM. 2002. |
| | Subway flooding | | Flood barriers | (1) Choo, Kristin. 2005.<br>(2) Black, William. 1990.<br>(3) Greater London Authority. 2005.<br>(4) Ruth, Matthais. 2006.<br>(5) Zimmerman, 2002. |
| | Port flooding/damage | Damage to ports facilities from vessels tied alongside. | Reduce “cope” level at ports to reduce likelihood of water flowing across docks; construct flood defense mechanisms | (1) ABP Marine Environmental Research Ltd 2004.<br>(2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.<br>(3) Entek U.K. Limited. 2000.<br>(4) Land Use Consultants, et al. 2002.<br>(5) OFCM. 2002. |
| **Increased Frequency/ Magnitude of Storms** | Damage to infrastructure on roads, railways, pipelines, seaports, airports | Closures or major disruptions of roads, railways, airports, transit systems, pipelines, marine systems and ports; emergency evacuations; travel delays | | (1) Instanes et al.. 2005.<br>(2) Smyth, et al. 2002.<br>(3) Ruth, Matthais. 2006.<br>(4) OFCM. 2002.<br>(5) Intergovernmental Panel on Climate Change. 2001. |

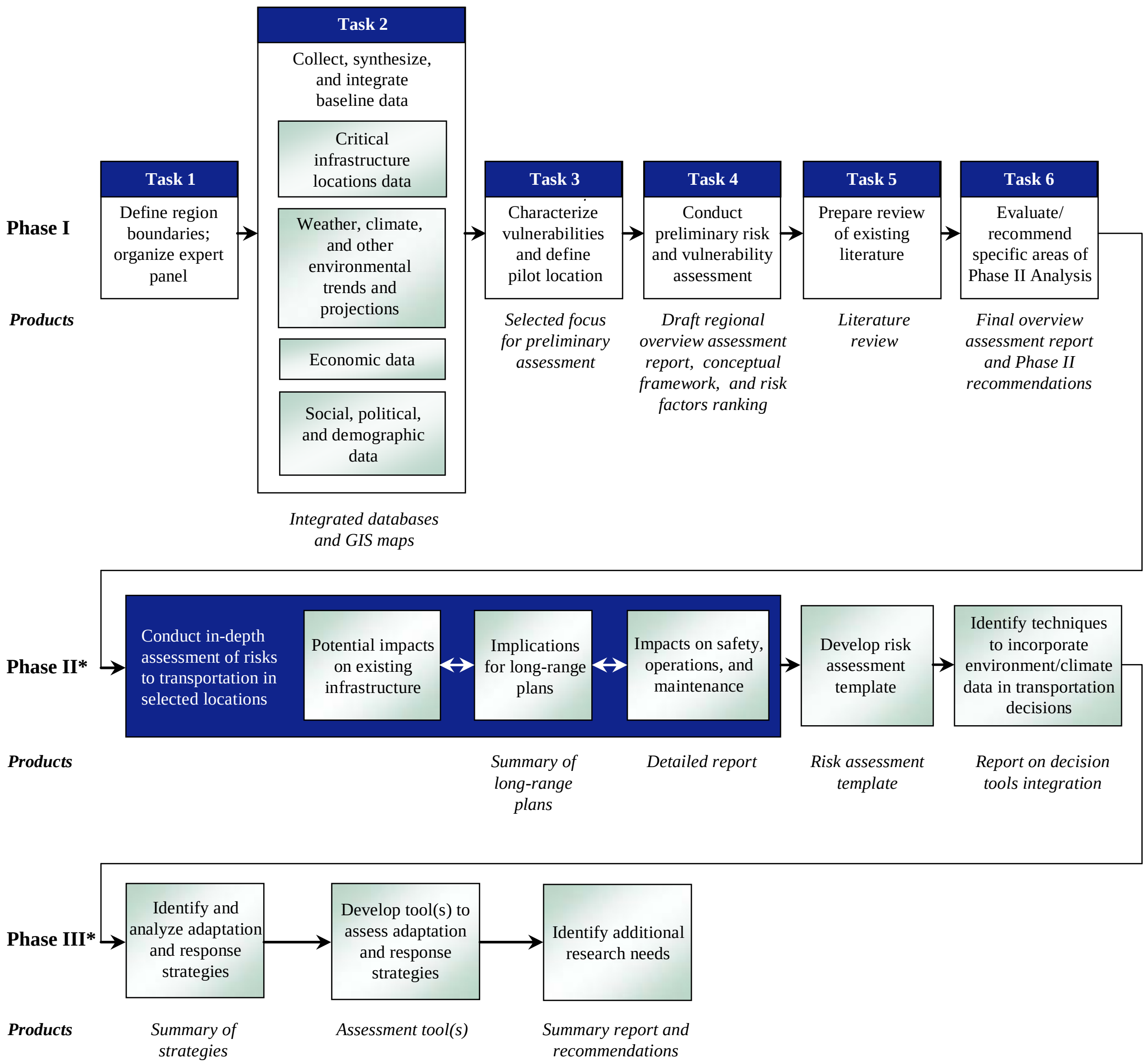
## Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| *Storm Activity (continued)* | | | | |
| **Increased Wind Speeds** | Bridges, signs, overhead cables, railroad signals, tall structures at risk | | Design structures for more turbulent wind conditions, build with better material, use "smart" technologies to detect abnormal events | (1) Wooler, Sarah. 2004.<br>(2) Meyers, Michael. 2006.<br>(3) Eddowes, M.J., et al. 2003.<br>(4) Kerr, Andrew, et al. 1999.<br>(5) Kerr, Andy. 2001.<br>(6) Kinsella, Y. and McGuire, E. 2005.<br>(7) OFCM. 2002. |
| | | Roadways: loss of visibility from drifting snow, loss of stability/maneuverability, lane obstruction (debris), treatment chemical dispersion, | | (1) OFCM. 2002. |
| | | Railways: Rail car blow over; schedule delays; increased risk of hazardous material spill | | (1) OFCM. 2002. |
| | | Ship handling becomes difficult | | (1) OFCM. 2002. |
| | | Impacts on airport ground operations: increased incidence of foreign objects present in aircraft movement areas, maintenance at high locations on large aircraft impeded/slowed, snow removal and de-icing operations affected | | (1) OFCM. 2002. |
| **Lightning/Electrical Disturbance** | Disruption to transportation electronic infrastructure, signaling, etc. | Risk to personnel from lightning, maintenance activity delays, rail and aircraft refueling operations delayed, track signal sensor malfunction resulting in possible train delays and stops, threats to barge tow equipment, communications and data distribution from pipeline sensors may fail | | (1) Wooler, Sarah. 2004.<br>(2) Eddowes, M.J., et al. 2003.<br>(3) OFCM. 2002. |
| **Fewer Winter Storms** | Less snow/ice for all modes | Improved mobility/safety, reduced maintenance costs, less pollution from salt, decrease in vehicle corrosion | | (1) Andrey and Mills. 2003.<br>(2) Black, William. 1990.<br>(3) Irwin and Johnson. 1990.<br>(4) Intergovernmental Panel on Climate Change. 2001.<br>(5) Barrett, et al. 2004.<br>(6) Marbek Resource Consultants Ltd. 2003.<br>(7) Kerr, Andrew, et al. 1999.<br>(8) Warren, et al. 2004.<br>(9) Entek U.K. Limited. 2000.<br>(10) Land Use Consultants, et al. 2002.<br>(11) Entek U.K. Limited. 2004.<br>(12) Wooler, Sarah. 2004.<br>(13) Kinsella, Y. and McGuire, E. 2005.<br>(14) Hyman, William, et al. 1989.<br>(15) Pisano et al. 2002. |

# Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)

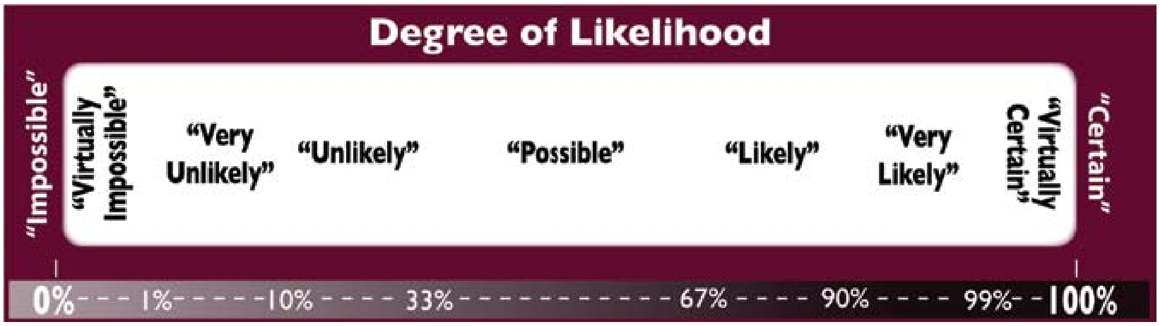
| Climate Impact | Potential Infrastructure Impact | Potential Operations Impact | Adaptation | Source |
|---|---|---|---|---|
| ***Ice Melting*** | | | | |
| **Reduced Ice Cover (Canada, Alaska, Great Lakes)** | Reduced ice loading on structures, such as bridges or piers | | | (1) Instanes et al.. 2005. |
| | New northern shipping routes | Shorten shipping distance and delivery time, security concerns, environmental risks, law-diplomacy issues, Inuit unease | Develop a "transit management regime" for area | (1) Instanes et al.. 2005.<br>(2) Johnston, Douglas. 2002.<br>(3) Brigham, Lawson and Ben Ellis, Eds. 2004.<br>(4) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001.<br>(5) National Assessment Synthesis Team. 2000.<br>(6) Marbek Resource Consultants Ltd. 2003.<br>(7) Warren, et al. 2004.<br>(8) Smith and Levasseur. 2002.<br>(9) Caldwell et al. 2002. |
| | | Lengthened season for float planes | | (1) Black, William. 1990.<br>(2) Irwin and Johnson. 1990. |
| | | Longer shipping season | | (1) Wooler, Sarah. 2004.<br>(2) Andrey and Mills. 2003.<br>(3) Black, William. 1990.<br>(4) Irwin and Johnson. 1990.<br>(5) U.S. Federal Highway Administration Office of Environment and Planning. 1998.<br>(6) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000.<br>(7) National Assessment Synthesis Team. 2000.<br>(8) Warren, et al. 2004.<br>(9) Ruth, Matthais. 2006.<br>(10) Caldwell et al. 2002. |
| | Multiyear ice, in low concentrations, will be hazard to ships and naval submarines | | New ship/submarine design or modifications | (1) Brigham, Lawson and Ben Ellis, Eds. 2004.<br>(2) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001. |
| **Earlier River Ice Breakup (United States, Canada)** | Ice-jam flooding risk | | | (1) Instanes et al.. 2005.<br>(2) Hass, et al. 2006.<br>(3) Smith and Levasseur. 2002. |

# Figure 1.1 Gulf Coast study design.




*Study design of Phases II and III will be refined based on findings of Phase I.

**Figure 1.2 Lexicon of terms used to describe the likelihood of climate outcomes.**




Source: Karl et al., 2006.