

Weather and Climate Impacts on Commercial Motor Vehicle Safety



U.S. Department of Transportation
Federal Motor Carrier Safety Administration

April 2011

FOREWORD

The purpose of this report is to provide the Federal Motor Carrier Safety Administration (FMCSA) with an analysis on how existing weather conditions may affect the safe operation of commercial motor vehicles (CMVs) on our Nation's highways. Further, it also looks at the general impacts projected by climate change studies and hypothesizes how possible changes in weather patterns and extreme storms could affect CMV operations in the future. This includes climate changes that increase the potential of weather-related CMV crashes and those that may impact trucking industry practices to require a response in FMCSA regulatory enforcement.

The work performed under this project included:

- Literature review and Internet search for documents and articles that describe how weather affects surface transportation modes in general and CMVs in particular.
- Literature review and Internet search for documents and articles on the impacts of climate variability and climate change, particularly those that address the possible impacts on transportation and projections of regional climate change.
- Data analysis of fatal crashes involving CMVs where the crash occurred in the presence of adverse weather or on wet or slippery pavement.
- Analysis of the potential impacts of climate change on the safety and operating environments for CMVs.
- Examination of possible response options by the FMCSA.

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The United States Government does not endorse products or manufacturers named herein. Trade or manufacturers' names appear herein only because they are considered essential to the objective of the document.

This Report does not constitute a standard, specification, or regulation.

Technical Report Documentation Page

1. Report No. FMCSA-RRA-11-013	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle WEATHER AND CLIMATE IMPACTS ON COMMERCIAL MOTOR VEHICLE SAFETY		5. Report Date April 2011	
		6. Performing Organization Code	
7. Author(s) Michael A. Rossetti, Michael Johnsen		8. Performing Organization Report No.	
9. Performing Organization Name and Address U.S. Department of Transportation Research and Innovative Technology Administration Volpe National Transportation Systems Center Cambridge, MA 02142		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Motor Carrier Safety Administration 1200 New Jersey Ave SE Washington, DC 20590		13. Type of Report Final Report	
		14. Sponsoring Agency Code FMCSA	
15. Supplementary Notes This report was sponsored by the Federal Motor Carrier Safety Administration. The Contracting Officer's Technical Representative was Michael Johnsen.			
16. Abstract The Federal Motor Carrier Safety Administration (FMCSA) has an interest in how adverse weather may influence trucking industry practices, and what climate change might mean for future FMCSA efforts to reduce weather-related crashes. Weather conditions influence commercial motor vehicle (CMV) operations and driver safety through wet pavement, impaired visibility, heavy precipitation, frozen precipitation, flooding, high winds, extremes of temperature, and other factors. Climate variability and climate change may also increase these exposures by affecting the distribution, frequency, or intensity of those weather events. Regional, State, and/or local impacts projected by climate change studies may have future implications for CMV safety. Should climate change result in more frequent or intense storms affecting CMVs, the historic decline in weather-related crashes may level off. This could pose challenges to FMCSA's primary mission, and the agency may need to explore different strategies for reducing weather-related crashes, such as education and training programs or technologies that could alert drivers of adverse weather conditions.			
17. Key Words climate, CMV, commercial motor vehicle, safety, crashes, weather		18. Distribution Statement No restrictions.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 86	22. Price

MODERN METRIC CONVERSION FACTORS

Table of APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
In	inches	25.4	millimeters	mm
Ft	feet	0.305	meters	m
Yd	yards	0.914	meters	m
Mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yards	0.836	square meters	m ²
Ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
MASS				
Oz	ounces	28.35	grams	g
Lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	mega grams (or "metric ton")	Mg (or "t")
TEMPERATURE				
°F	Fahrenheit	$5 \times (F-32) \div 9$ or $(F-32) \div 1.8$	Temperature is in exact degrees Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
Force and Pressure or Stress				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

Table of APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	mega grams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE				
°C	Celsius	$1.8C + 32$	Temperature is in exact degrees Fahrenheit	°F
ILLUMINATION				
lx	Lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
Force & Pressure or Stress				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003, Section 508-accessible version September 2009)

TABLE OF CONTENTS

ABBREVIATIONS, ACRONYMS, AND SYMBOLS	VII
EXECUTIVE SUMMARY	IX
1. INTRODUCTION.....	1
1.1 PURPOSE.....	1
1.2 NEED.....	1
1.3 SCOPE	1
1.4 DATA SOURCES AND METHODOLOGY.....	2
1.5 ORGANIZATION OF REPORT.....	3
2. WEATHER EVENTS AND CMV OPERATIONS	5
2.1 CHARACTERISTICS OF CMVS AND THEIR ASSOCIATION WITH ADVERSE WEATHER.....	5
2.2 RAINFALL, WET PAVEMENT, AND FLOODING	6
2.2.1 Coastal Inundation	6
2.3 SNOW AND ICING.....	7
2.3.1 Freezing Rain and Ice Storms.....	7
2.3.2 Snow Squalls.....	8
2.4 FOG AND IMPAIRED VISIBILITY.....	9
2.5 TEMPERATURE EXTREMES	10
2.5.1 Excessive Heat	10
2.6 HIGH WINDS, CROSSWINDS AND TORNADOES.....	11
2.7 THUNDERSTORMS AND HAIL	12
2.8 DROUGHTS.....	12
2.8.1 Great Lakes Transportation Networks.....	13
3. CMV ACTIVITY, CRASHES, AND THEIR ASSOCIATION WITH WEATHER AND CLIMATE.....	15
3.1 INDUSTRY OVERVIEW	15
3.1.1 Local Trucking.....	15
3.1.2 Long Distance Trucking	15
3.1.3 Specialized Freight Trucking.....	16
3.2 USE OF WEATHER INFORMATION BY CMV OPERATORS	16
3.2.1 Regulatory and Corporate Responses	16
3.3 U.S. CMV ACTIVITY	17

3.4	WEATHER AND CLIMATE AS FACTORS IN THE SUPPLY CHAIN	18
3.5	CMV CRASH DATA	19
3.5.1	NHTSA Crash Statistics	19
3.5.2	Large Truck Crash Causation Study Results	21
3.6	FATAL CMV CRASHES AND WEATHER EVENTS	21
3.7	TRENDS IN THE NCDC STORM EVENTS DATABASE, 1993-2006	29
3.7.1	Caveats Concerning the Storm Events Database	30
3.8	REGIONAL AND CORRIDOR SPECIFIC IMPACTS OF EXTREME WEATHER EVENTS	30
3.8.1	Weather-related CMV Crashes on Interstate Corridors.....	32
4.	CLIMATE CHANGE AND VARIABILITY	37
4.1	EVIDENCE OF CLIMATE CHANGE	37
4.2	RECENT STUDIES.....	42
4.2.1	Intergovernmental Panel on Climate Change (IPCC).....	42
4.2.2	Climate Change Science Program	43
4.2.3	National Research Council	46
4.3	CLIMATE CHANGE AND EXTREME WEATHER EVENTS.....	47
5.	CONCLUSIONS	53
5.1	THE EFFECTS OF WEATHER AND CLIMATE	53
5.2	TRENDS IN WEATHER-RELATED FATAL CRASHES.....	54
5.3	RECOMMENDATIONS	54
5.3.1	Role of New Technology	56
5.4	SUMMARY	56
APPENDIX A: CLIMATE CHANGE, HIGHWAYS, AND ADAPTATION OPTIONS— (TRB REPORT 290).....		59
GLOSSARY.....		63
ACKNOWLEDGEMENTS		67
REFERENCES.....		69
BIBLIOGRAPHY		73

LIST OF FIGURES

Figure 1. Average Number of Hours of Freezing Rain	8
Figure 2. Mean Water Levels of Great Lakes (Meters), 1900–2000	14
Figure 3. Commercial Motor Vehicle Registrations and VMT, 1975–2005	18
Figure 4. A Typical Supply Chain	19
Figure 5. Fatal Large Truck Crashes vs. Fatal, Weather-related Large Truck Crashes per 100 Million VMT, 1975–2005	22
Figure 6. CMV Fatal Crashes, Weather-related, by State, Gross, and Normalized, 2005–2006...	23
Figure 7. Fatal, Weather-related CMV Crashes by Type of Weather Event, 1975–2006, with 5- year Moving Averages	24
Figure 8. CMV Crashes in Rain and on Wet Pavement (2001–2006), Compared to the NCDC U.S. Climate Atlas.....	26
Figure 9. CMV Fatal Crashes in Snow, Sleet, or on Icy Pavement (2001–2006) Compared to the NCDC U.S. Climate Atlas.....	27
Figure 10. CMV Fatal Crashes in Conditions with Impaired Visibility (2001–2006) Compared to the NCDC U.S. Climate Atlas.....	28
Figure 11. Locations of Fatal Crashes involving Commercial Motor Vehicles, by Type of Weather Event, 2001–2006, Compared to NCDC Climatology Statistics.....	31
Figure 12. CMV Fatal Weather-related Crashes by Selected Interstate Highways, Weather, and Road Surface Condition, 2001–2006	33
Figure 13. Tornado Tracks and Overlays on Selected Interstate Highways, 1961–1990.....	35
Figure 14. NEXRAD Hail Signatures along Interstate 80, June 2006.....	36
Figure 15. Northern Hemisphere Surface Temperature and CO ₂ , 1000 AD–2000 AD	39
Figure 16. Tracks of Tropical Cyclones in the Central Gulf Coast, 1851–2006	44
Figure 17. Evidence of Extreme Events: Billion Dollar U.S. Weather Disasters, 1980–2007.....	48
Figure 18. The U.S. Climate Extremes Index, 1910–2008.....	49
Figure 19. Weather and Climate Events, Hypothetical Forecast Likelihood and Lead Times Required by CMVs.....	50

LIST OF TABLES

Table 1. Example of CMV Crash in Adverse Weather from the NCDC Storm Events Database ..9	
Table 2. Human Responses to Excessive Heat11	
Table 3. The Enhanced Fujita (EF) Tornado Intensity Scale.....12	
Table 4. Fatal Weather-Related Crashes Involving Commercial Motor Vehicles and All Motor Vehicles by Type of Weather Condition.....20	
Table 5. FARS Codes for Atmospheric Condition and Road Surface Condition.....21	
Table 6. Weather Events Included in the NCDC Storm Events Database.....29	
Table 7. Selected Climate Indices and their Potential Impacts on Transportation41	
Table 8. IPCC Fourth Assessment Report Projections of Climate Changes43	
Table 9. IPCC Projections for Climate Change and Impacts in North America43	
Table 10. Climate Scenarios and Potential Impacts on CMVs51	

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

CCSP	Climate Change Science Program
CMV	commercial motor vehicle
EF	Enhanced Fujita Tornado Intensity Scale
ENSO	El Niño-Southern Oscillation
FARS	Fatal Analysis Reporting System
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GIS	Geographic Information System
HazMat	hazardous material
IPCC	Intergovernmental Panel on Climate Change
LTCCS	Large Truck Crash Causation Study
LTL	less-than-truckload
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NEXRAD	Next Generation Radar
NHTSA	National Highway Traffic Safety Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWS	National Weather Service
SED	Storm Events Database
TL	truckload
TRB	Transportation Research Board
USDOT	U.S. Department of Transportation
VMT	vehicle miles of travel

[This page intentionally left blank.]

EXECUTIVE SUMMARY

PURPOSE

The purpose of this report is to provide the Federal Motor Carrier Safety Administration (FMCSA) with an analysis of how existing weather conditions may affect the safe operation of commercial motor vehicles (CMV) on our Nation's highways. Further, it also looks at the general impacts projected by climate change studies and hypothesizes how possible changes in weather patterns and extreme storms could affect future CMV operations. This includes changes that increase the potential of weather-related CMV crashes and those that may impact trucking industry practices to require a response in FMCSA regulatory enforcement.

PROCESS

This study represents a comprehensive initial examination of the potential impacts of weather and climate variability on CMV safety. The study process included the following steps:

- Literature review and Internet search for documents and articles that describe how weather affects surface transportation modes in general and CMVs in particular.
- Literature review and Internet search for documents and articles on the impacts of climate variability and climate change, particularly those that address the possible impacts on transportation and projections of regional climate change.
- Data analysis of fatal crashes involving CMVs where the crash occurred in the presence of adverse weather or on wet or slippery pavement.
- Analysis of the potential impacts of climate change on safety and operating environments for CMVs.
- Examination of possible response options by the FMCSA.

RATIONALE AND BACKGROUND

The primary mission of the FMCSA is to improve safety and reduce the number of crashes involving large trucks and buses on our Nation's highways. Although human error is by far the leading contributing factor in fatal crashes involving CMVs, adverse weather—and the possibility of its influence changing due to climatic conditions—is another factor that may affect CMV safety. The FMCSA has conducted many safety studies and developed regulatory measures to address CMV crashes. However, except for the Large Truck Crash Causation Study (LTCCS),⁽¹⁾ the agency has not heavily investigated the role of weather and climate factors in these crashes. Accordingly, the FMCSA has an interest in investigating trends and factors that influence weather-related CMV crashes, and determining whether taking action(s) within its jurisdictional realm (e.g., driver, vehicle, and carrier) may reduce crashes primarily caused by adverse weather. The FMCSA thus intends to position itself to address potential future risks posed by climate variability, climate change, and extreme weather events through an understanding of how weather and climate forces affect CMV safety.

This report focuses on the effects of weather and climate on CMV safety. It examines different types of weather events as risk factors in CMV crashes and operations, including the possible role of climate change in affecting the distribution, frequency, or intensity of those weather events. The report also looks at the regional impacts projected by climate change studies and discusses the implications of changing weather patterns for CMV safety.

STUDY FINDINGS

A growing body of scientific literature supports the idea that the Earth has generally warmed during much of the past 100 years. Over the past couple of decades, international groups—such as the Intergovernmental Panel on Climate Change (IPCC), and national entities, such as the Climate Change Science Program (CCSP) and Transportation Research Board (TRB)—have released studies that describe the details of these trends and their potential societal impacts, including those on the transportation sector.

Weather influences the safety of CMVs in different ways. Conditions such as wet pavement, impaired visibility, heavy precipitation, frozen precipitation, flooding, high winds, and extremes of temperature can act in various ways to increase risks to CMV drivers and their vehicles, as well as the infrastructure. The vulnerability of the national highway system, CMVs, and CMV drivers to weather conditions and climate change arises from potential exposure to both unforeseen and anticipated changes in weather or climate patterns and from potential increases in the intensity and frequency of extreme weather events.

Overall, fatal weather-related crash data from the Fatality Analysis Reporting System (FARS) show a declining trend from 1975 to 2009, with a leveling off since 1999. When normalized by vehicle miles of travel (VMT), the 30-year trend shows fewer weather-related, fatal CMV crashes. This trend provides encouragement for efforts to make highway travel less sensitive to adverse weather, although Geographic Information System (GIS) data show pockets of persistent clusters of weather-related crashes along certain corridors or within specific regions of the country. When overlaid onto a GIS map, fatal CMV crashes display some regional and local clustering by type of weather and location of highway. CMV weather-related crash clusters generally align with the U.S. Climate Atlas, a database available from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC).

In future years, climate variability and climate change may increase both the number of good weather days and the number of extreme weather days for CMV travel. Climate variability or climate change may result in economic benefits from milder temperatures, but may also produce economic losses from increases in the frequency and intensity of extreme events. Of growing concern, under projections of climate change, is that conditions that give rise to these types of weather events may also result in less safe driving conditions.

RECOMMENDATIONS

Based on the finding set forth in this report, it is recommended that FMCSA:

(1) Examine trends and factors in weather-related CMV crashes, particularly in those interstate corridors that are vulnerable both to adverse weather and to increasing exposure due to climate change.

(2) Review potential actions within its jurisdictional realm that could reduce weather-related crashes (e.g., the agency's strategy might include expanded driver training and education programs aimed at operating CMVs in inclement and occasionally extreme weather conditions).

(3) Consider expanded research into the role of human factors in responding to adverse weather conditions (e.g., research into the effects of long duration weather events on physical abilities, driver fatigue, and concentration).

(4) Determine how to facilitate the delivery and interpretation of weather information into the vehicles by studying potential integration of weather information into CMV telematics technologies, and develop applications that use radar technologies and decision support systems to aid CMV operators, dispatchers, and other interested parties.

(5) Review possible modifications or waivers to existing CMV rules pertaining to weather. FMCSA rules currently limit the number of hours of service permitted for CMV drivers, with some exceptions based on extenuating weather conditions. In addition, States sometimes grant temporary waivers (e.g., when drivers are hauling relief supplies into a flood-stricken area, such as during Hurricane Katrina). If these events become more common, FMCSA may need to develop further regulations, policies, training, and guidance for CMV drivers on weather-related disaster relief actions.

(6) Examine a select set of geographic highway-based coordinates for weather-related crashes by association with GIS layers of highway segments and intersections. This effort might involve a review of weather factors that reduce CMV safety (e.g., road wetness, impaired visibility, heavy precipitation, snowfall, crosswinds, etc.) and automate the extraction of relevant weather data that would provide the basis for the GIS-based analyses. The approach could include re-analysis of past crashes, looking at data from nearby weather stations, the application of archived Next Generation Radar (NEXRAD) Doppler radar data, satellite imagery, and other data. One product of the corridor analysis might be the FMCSA encouraging the development of a model to predict CMV crashes based on VMT under different weather conditions along the selected routes. The information derived from this effort could identify and classify weather-related risks associated with the selected corridors, and thus assist the FMCSA in improving CMV safety.

(7) Conduct additional research into isolating the effects of weather from other crash factors, exploring other ways to normalize existing data. This includes examining differences between weather-related crashes on toll roads and non-toll roads, and the effects of travel direction—movement with, from, or into weather. In order to improve the quality of data required for analyzing CMV weather-related crashes, the FMCSA could coordinate its weather reporting needs with National Highway Traffic Safety Administration (NHTSA) when there is an opportunity to modify the FARS.

(8) Study how existing vehicle deficiencies such as low tire pressure or worn brakes, are exacerbated by weather conditions (which may only be a contributing factor) that increase the potential for a crash.

(9) Educate drivers and motor carriers on the potential use of weather and climate data for planning, investment, and other policy measures.

(10) Move forward toward decision-making on climate approaches, both individually and with other agencies.

CONCLUSIONS

There are several possible benefits of obtaining improved CMV weather and climate information. These include improved safety; improved decision making for routing and scheduling; better performance for the vehicle, driver, and infrastructure; better information for forensic investigation and crash event reconstruction; enhanced research, training, and education; more accurate economic impact analysis; and more research into the role of human factors.

If climate change results in more frequent or intense storms affecting CMVs, the historic decline in weather-related crashes may level off (as may be already occurring) or start to increase, which would pose significant challenges to FMCSA's primary mission to reduce CMV crashes and fatalities. Because weather-related crashes may be difficult for FMCSA to influence, the agency may need to explore more aggressive or creative strategies to reduce weather-related crashes. The FMCSA can address these concerns and promote safety through a combination of rulemaking or regulatory activity, data analysis studies, education and training programs, and working with the carrier industry and manufacturers to build in processes and equipment to respond to changes in climate patterns and weather conditions.

1. INTRODUCTION

1.1 PURPOSE

The purpose of this report is to provide the U.S. Department of Transportation's (USDOT) Federal Motor Carrier Safety Administration (FMCSA) with an analysis of how existing weather conditions affect the safety and operating characteristics of commercial motor vehicles (CMVs) on our Nation's highways. In addition, it looks at the general impacts projected by climate change studies and hypothesizes how possible changes in weather patterns and extreme storms could affect future CMV operations. This includes changes that could increase the potential of weather-related CMV crashes and those that may impact trucking industry practices, which could require a response in FMCSA regulatory enforcement.

1.2 NEED

A primary mission of the FMCSA is to improve safety and reduce the number of crashes involving large trucks and buses. Although human error remains as the leading cause of CMV crashes, adverse weather, and the possibility of its influence increasing due to changing climatic conditions, are among other factors that may contribute to, and affect, CMV safety. The FMCSA has conducted many safety studies and developed regulatory measures to address such crashes. The Large Truck Crash Causation Study (LTCCS)⁽¹⁾ found that adverse weather conditions were present in approximately 13 percent of the crashes studied. Other research has also assessed CMV crashes associated with weather events.⁽²⁾

In supporting this study, the FMCSA sought to increase its understanding of trends and factors involved in weather-related CMV crashes, and examine whether action(s) within its jurisdictional realm (e.g., driver, vehicle, and carrier) could be taken to reduce weather-related crashes. The FMCSA desired to address potential future risks posed by climate variability, climate change, and extreme weather events through an understanding of how weather and climatic forces affect CMV safety.

1.3 SCOPE

This study looked at fatal crashes involving all types of CMVs. CMVs are defined as trucks with a gross vehicle weight rating of more than 10,000 pounds, as well as most types of passenger buses. Buses comprise less than 9 percent of all CMVs. As of 2006, U.S. motor vehicle registrations of all types totaled about 245 million.⁽³⁾ CMVs comprised 3.5 percent of these. The study period included CMV safety and operating data from 1975 to 2006 in the United States. It includes crash data, meteorological data, and climate data for the same period. The report also employs research findings of the Intergovernmental Panel on Climate Change (IPCC), the U.S. Climate Change Science Program (CCSP), the National Research Council (NRC), and other groups. The study framework concerns the impact of observed climatic patterns on CMV safety, and the averages and variability of long-term weather conditions. These patterns result from the interactions of oceanic, geologic, and solar influences, the atmospheric concentrations of various

gases and aerosols, and other factors. These patterns may, in turn, have significance for the future operating environments and safety of CMVs.

1.4 DATA SOURCES AND METHODOLOGY

This report examines long-term data on weather and CMV fatal crashes from the Fatality Analysis Reporting System (FARS) database managed by the USDOT National Highway Traffic Safety Administration (NHTSA). CMV crash data are available from 1975 to the present. It also maps these data in Geographic Information System (GIS) format and incorporates weather and climate data from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). This report examines the role of different types of weather events as risk factors in CMV crashes and performance. This examination includes the possible role of climate change in increasing the distribution, frequency, or severity of those weather events, their impacts on performance metrics for safety and delay, and any measures that may be required to realize improvement.

Fatal Analysis Reporting System—FARS contains data on a census of fatal traffic crashes. Operational since 1975, FARS collects information on more than 100 different coded data elements that characterize the crash, persons, vehicles, and drivers. Performing online queries on the FARS Encyclopedia Web site generated FARS data for 1994–2006.⁽⁴⁾ NHTSA/FARS staff provided data for the years 1975–1993, and 2007–2008). This study examined all fatal CMV crashes 1975–2006, with emphasis on those that were weather-related. The study also normalized FARS data by using vehicle miles of travel (VMT) data. Where available, the latitude/longitude coordinates of FARS data were plotted into GIS maps.

Recent Studies by Climate Committees—The report also reviewed some of the projections of climate change contained in publications of the IPCC, CCSP, and Transportation Research Board (TRB). These projections assist FMCSA to understand how CMV safety and operations may change under a set of assumptions that underlie future patterns of temperature, rainfall, and other parameters.

NCDC Data Products—Climatic data from the NCDC also helped shape part of the analysis. These data, based on 30-year averages, provide maps of climate information, such as mean daily precipitation, the mean number of days with snowfall greater than one inch, hail events, and many other statistics. The NCDC maintains the Storms Events Database, a searchable online reference that provides storm specific information by State, county, date, economic impact, and description.

1.5 ORGANIZATION OF REPORT

The present section outlines the project purpose, need, scope, data sources, and organization. Section 2 provides an overview of the interactions of weather and CMV operations that may be observed today. Section 3 discusses how weather events typically affect CMVs. Section 4 presents a profile of CMV activity in the U.S. and an analysis of fatal crashes from the period 1975 to 2005 including weather events and adverse road conditions associated with the crash. It also includes some observations on the impact of weather events on specific interstate corridors. Section 5 presents a summary of climate change and variability (including trends from the historical past and recent past), a review of recent literature from the IPCC and others, and a discussion of projected regional climate impacts. The report finishes with a summary and set of recommendations.

[This page intentionally left blank.]

2. WEATHER EVENTS AND CMV OPERATIONS

Weather is a major factor at all transportation spatial and temporal scales. It is central to discussions of issues, such as carrier, driver and vehicle safety, congestion, emergency response, environmental modeling, and the potential effects of climate change on CMV operations. In order to realize the importance of weather to the USDOT and the transportation community requires:

- The development of an intermodal perspective, through tools, such as the Federal Highway Administration (FHWA) Clarus Initiative, situation displays, and decision support systems.
- Partnerships and innovative arrangements with university transportation centers, private industry, and academia, as well as State and local governments.
- The leveraging of existing and emerging technologies.

Weather plays a key role in the planning and operations of virtually all modes of transportation. Weather conditions significantly affect both the safety and economic well-being of individuals and the public and private sectors. Numerous social consequences also occur with these relationships. Intelligent use of weather information can reduce property damage, save lives, and prevent injuries and crashes. This information also can produce additional benefits such as savings in fuel consumption, better efficiency and throughput, more effective traffic management and evacuations, savings in maintenance activities, and better data for infrastructure investment decisions and fleet operations.

2.1 CHARACTERISTICS OF CMVS AND THEIR ASSOCIATION WITH ADVERSE WEATHER

CMVs are different from other vehicles with respect to weather and weather-related crashes. CMVs have greater mass and thus a greater release of kinetic energy during a crash. They require longer stopping distances compared to other motor vehicles. Adverse weather may also affect CMVs indirectly, such as passenger cars stopping in breakdown lanes and being struck by CMV drivers impaired by low visibility. Passenger cars also are sometimes driven dangerously around CMVs. This can result in reduced safety margins for CMVs, which have less maneuverability and greater stopping distances. Drivers of passenger cars who weave in and out of lanes or otherwise drive recklessly in the vicinity of CMVs also run the risk of colliding with CMVs if they become blinded by dense fog, heavy precipitation, or solar glare, or other weather conditions.

CMVs also have different trip characteristics than other types of motor vehicles, and these characteristics may expose them to different types of weather conditions. Both truckload (TL) and less-than-truckload (LTL) carriers have longer trip lengths than automobiles. Commercial motor vehicle trips are business related and therefore less discretionary than trips by private

automobiles. These longer and less-discretionary trips may expose CMVs and their drivers to a variety of mesoscale weather conditions.

In contrast, CMVs engaged in local trucking operations along with some LTL carriers, may stop frequently for pickups and deliveries as part of a given trip. Local storms, road icing, and fog may affect local operations, particularly on routes involving many stops. Similar to long-distance trucking, local operations may also be less discretionary than local automobile travel, therefore increasing the likelihood of exposure to any adverse weather affecting the local area.

Weather events that are hazardous to CMVs can range from wet pavement, rain, winter storms, icing, temperature extremes, floods, hurricanes, high winds, and severe thunderstorms to more routine events, such as solar glare or poor visibility.

2.2 RAINFALL, WET PAVEMENT, AND FLOODING

Rainfall and wet pavement are the most common types of adverse weather that affect CMVs; more than 60 percent of all weather-related fatalities occur in rainy conditions.⁽²⁾ Rainfall causes delays and increases risks of collisions with other vehicles and highway structures. It induces loss of control due to acceleration from wheel spinning and hydroplaning. The initial onset of rain may mix with preexisting road oils to produce slippery conditions. Rain reduces the coefficient of friction of the pavement, which in turn reduces traction. Wet roads can double stopping distances.

Rainfall also reduces visibility and may make it harder to see clearly, especially at night. Wet surfaces produce similar effects on vehicles and their drivers, even if skies are not currently causing rainfall. After rain stops, it may take 30 minutes or more before pavement begins to dry. Wet conditions may persist much longer under certain types of atmospheric and soil moisture conditions (e.g., melting snow banks, previous snow falling from other vehicles, and flooding episodes).

In addition to the obvious physical risk of CMVs caught in high waters or floods, widespread flooding in major rivers may result in wholesale rerouting of shipments. Problems posed by high waters from flash floods, river floods, persistent heavy rains, and hurricanes may produce significant concerns for CMV carriers and drivers. For example, brakes that become wet may weaken or apply unevenly. Floods may also render roads and bridges impassable or produce complete washouts that require closures and rerouting. When high waters force the rerouting of CMVs, the results are often longer trips, higher fuel consumption, and potential higher exposures to additional crash risks.

2.2.1 Coastal Inundation

Coastal flooding accompanied by wave battering caused by large storms is a threat to road infrastructure, as is the storm surge that accompanies landfalling hurricanes and intense extratropical cyclones. Amplification of effects like these may gradually occur if sea levels rise as projected by climate change models. The Gulf Coast Study⁽⁵⁾ tentatively projects that relative sea level in the Gulf of Mexico coastal area may increase at least one foot during the next 50-100 years. Research derived from paleoclimatic data released by the U.S. Global Change Research

Program that is more recent indicates this figure may be greatly underestimated. For the New Orleans area, assuming a two-foot rise in sea levels without additional protective structures, the Gulf Coast Study estimates that inundation of highways, such as I-10 and U.S. 90 could put almost 300 miles of those roads under water. With a four-foot rise, more than 800 miles of roads could experience submersion.⁽⁵⁾ While long-term sea-level rise affects transportation systems, even small amounts of increased water levels exacerbate storm surge levels, which in a hurricane event causes further damage to roadways once considered out of range for a storm surge.

2.3 SNOW AND ICING

Heavy snow causes delays, road closures, loss of traction, loss of visibility, and other driver control problems. Surface temperatures on bridges and ramps cool more rapidly than the surrounding roadbeds, producing hazardous local icing conditions and resultant potential crashes, fatalities, and property damage. Black ice and light frozen precipitation glaze roads as temperatures fall over a short period. Winter conditions also place additional stress on CMV components, such as the cooling system, defrosting and heating equipment, wipers and washers, tires and chains, windows and mirrors, handholds and deck plates, radiator shutters, and exhaust systems. Many States require large trucks to carry and use tire chains as snow conditions warrant.

2.3.1 Freezing Rain and Ice Storms

Freezing rain and ice storms occur mainly in the upper Midwest and inland areas of the northeast United States.⁽⁶⁾ Freezing rain leads to accumulated ice on roads and structures over an extended period. Freezing rain and ice storms may stem from a variety of large scale weather features, but their common denominator is the existence of a mid-level layer of warm air sandwiched between cold layers above and below across a region.⁽⁷⁾

In the eastern United States, a typical example of this situation called “cold air damming” occurs when an arctic air mass is in place on the lee side of the Appalachians and a storm center tracks to the west of the region, producing a nose of warm air at mid-levels of the atmosphere. Warm air moves up and over the mountains, but cannot dislodge the cold air trapped on the lee side. This may result in extensive ice build up on roadways, structures, and trees. Accordingly, risks to CMV operations include difficult traction and control, plus possible obstructions from fallen wires, utility poles, and trees. Figure 1 shows the average number of annual hours with freezing rain by region, and exemplifies the effect of cold air damming.⁽⁶⁾ A study indicates that warmer minimum temperatures in northern winters may increase the likelihood of conditions conducive to ice, rather than snow events,⁽⁸⁾ but as of yet no data support this hypothesis.

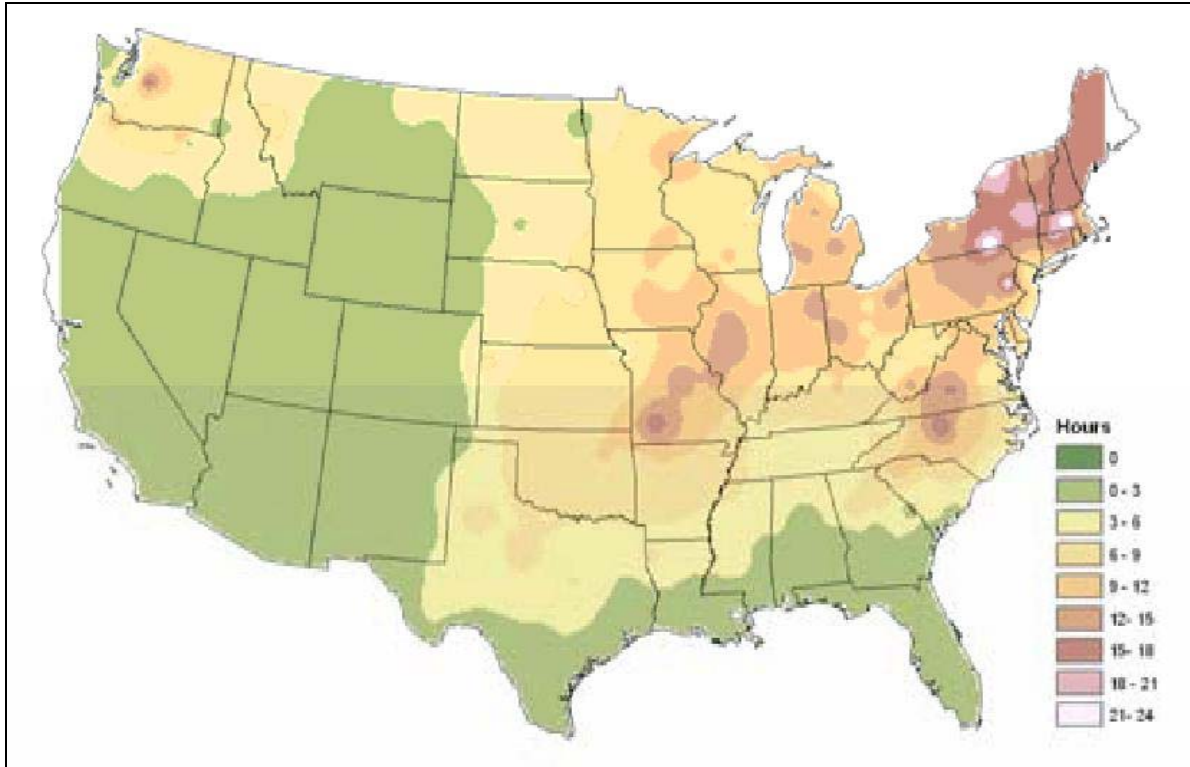


Figure 1. Average Number of Hours of Freezing Rain

2.3.2 Snow Squalls

Perhaps even more hazardous than blizzards or long duration heavy snow events, snow squalls that move quickly over highways are an important cause of crashes and fatalities for CMVs and other types of motor vehicles. Snow squalls result from low-level thermal instability, moist air, and a trigger mechanism. They often generate whiteout conditions, usually without warning. Squalls produce high intensity snowfall combined with strong winds. The sheer intensity of snow combined with its compression on road surfaces by vehicle tires may cause rapid glazing, loss of traction, and chain reaction crashes in conjunction with near-zero visibility.

Snow squalls that form in the lee areas of the Great Lakes are typically events of longer duration and larger area coverage than squalls that form in other terrain. Numerical models often cannot predict the specific locations where squalls may occur, but can identify the general types of conditions under which they are likely to form. Because snow squalls are often precursors to the arrival of arctic air masses, any glaze or compressed snow may become difficult to treat. Table 1 provides a description of how a 2004 snow squall event impaired CMVs traveling along an interstate highway.

Table 1. Example of CMV Crash in Adverse Weather from the NCDC Storm Events Database

Event Record Details	
Event	Winter Weather/Mix
Begin Date	06 Jan 2004, 11:15 a.m. EST
Begin Location	Not Known
End Date	06 Jan 2004, 11:30 a.m. EST
End Location	Not Known
Magnitude	0
Fatalities	6
Injuries	12
Property Damage	\$1.5 Million
Crop Damage	\$ 0.0
State	Pennsylvania
Forecast Zones Affected	Northern and Southern Centre County, Southern Clinton County
Description	An arctic cold front crossed central Pennsylvania during the mid morning hours of Tuesday, January 6, accompanied by a narrow band of intense snow squalls. These squalls caused the visibility to drop to near zero, and caused roadways to become snow covered and icy quickly. Two multivehicle accidents occurred around the time that these squalls affected the area. One accident occurred on Interstate 80, between Lock Haven and Bellefonte, and involved six fatalities and numerous injuries. Many tractor-trailers and other vehicles were involved in this accident. The second accident also occurred on Interstate 80, between Bellefonte and Milesburg. Three tractor-trailers were involved in this accident.

Source: NOAA/NCDC <<http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent-ShowEvent-552107>>

2.4 FOG AND IMPAIRED VISIBILITY

CMVs have significant vulnerability to fog and poor visibility. Impaired visibility may result from intense storms, coastal and ground fog, smog, dust, precipitation-induced road spray, and solar glare. Dense fog may form overnight in low-lying areas on highways, resulting in reduced speeds, sudden losses of control, and increased risks of collisions between vehicles and roadside structures. Freezing fog forms a coating of glaze and can seriously disrupt transportation and other types of commerce. Lowered visibility poses a safety risk to truckers and increases the risk of damage in the event of collision. Fog events have the potential for large, multivehicle accidents. Signs and signals may become more difficult to see, thus leading to human error. Reduced visibility also increases the potential for schedule delays.

CMVs are more vulnerable to low visibility than other vehicles. From 1995 to 2005, of all fatal CMV, weather-related crashes, about 12 percent occurred in fog conditions, including combinations of “rain and fog” and “sleet and fog.”⁽²⁾ The percentage of fatal CMV crashes that occur in fog is greater than the 2 percent of all fatal and non-fatal crashes for general motor vehicles that occur in fog. Fog and low visibility may increase the stopping distances required to avoid a crash. Once a crash occurs, the larger mass of a CMV and greater release of kinetic

energy produces a more severe impact. Accordingly, fog and other visibility impairments may result in more fatal crashes for CMVs than for motor vehicles as a whole.

2.5 TEMPERATURE EXTREMES

CMVs are vulnerable to both types of temperature extremes—bitter cold and excessive heat—as well as fluctuations between these two extremes. Prolonged episodes of heat and cold can degrade both the safety and performance characteristics of CMVs. Extremely cold temperatures experienced in northern locales may affect the operation of vehicle engines, tires, and mechanical and hydraulic systems. Hot weather may occur in any part of the country and lead to conditions, such as bleeding of road tars, which cause slippery surface conditions, or inducing stress on vehicles and drivers. Large variations between heat and cold, especially in winter, produce undesirable freeze-thaw cycles that lead to potholes and other types of deterioration to infrastructure.

2.5.1 Excessive Heat

Excessive heat, combined with steep grades on highways, have implications for CMV safety. It can cause engines to overheat, forcing vehicles off the road, or onto emergency lanes or runaway truck lanes. Some have speculated that a 2008 fatal crash involving a CMV on I-80 in Newcastle, CA, may have had these characteristics.⁽⁹⁾ Certain types of commodities are perishable and temperature-sensitive, requiring protection from the external conditions, including materials deemed hazardous (HazMat) by the Secretary of Transportation. HazMat includes some products that are temperature regulated, so excessive heat may cause problems. Certain types of livestock carried by trucks are very sensitive to excessive heat and cold. In addition, excessive heat requires greater fuel consumption during transportation in order to protect perishables and temperature-sensitive commodities from the effects of temperature extremes.

Climate change models project an increase in the number of very hot days and extended heat waves. From 1979 to 2003, excessive heat exposure caused 8,015 deaths in the U.S. During this period, more people in this country died from extreme heat than from hurricanes, lightning, tornadoes, floods, and earthquakes combined.⁽¹⁰⁾ Research also shows that extremes of heat and humidity place extra stress on CMV drivers, and can compromise safety.⁽¹¹⁾ Even if truck cabs are air-conditioned, data show that stepping outside at trip origination and destination points, or at intermediate stops, may have negative effects on CMV drivers' cognitive abilities, mental alertness, and physical endurance.⁽¹⁰⁾

Research has linked high temperatures to driver aggression, increased fatigue, decreased psychomotor and mental performance, loss of alertness, and reduced reaction time.⁽¹²⁾ From a medical standpoint, the Centers for Disease Control defines extreme heat as “temperatures that hover 10 degrees or more above the average high temperature of the region and last for several weeks.”⁽¹⁰⁾ If drivers also help load or unload shipments, oppressive heat may lead to medical emergencies, such as heat exhaustion or heat stroke (Table 2).⁽¹⁰⁾

Table 2. Human Responses to Excessive Heat

Condition	Description
Heat Stroke	Heat stroke occurs when the body is unable to regulate its temperature. Body temperature rises rapidly, the sweating mechanism fails, and the body is unable to cool down. Body temperature may rise to 106°F or higher within 10 to 15 minutes. Heat stroke can cause death or permanent disability if emergency treatment is not provided immediately.
Heat Exhaustion	Heat exhaustion is a milder form of heat-related illness that can develop after several days of exposure to high temperatures and inadequate or unbalanced replacement of fluids to the body. It is the body's response to an excessive loss of the water and salt contained in sweat. Those most prone to heat exhaustion are elderly people, people with high blood pressure, and people working or exercising in a hot environment.
Heat Cramps	Heat cramps usually affect people who sweat a lot during strenuous activity. This sweating depletes the body's salt and moisture. The low salt level in the muscles may be the cause of heat cramps. Heat cramps may also be a symptom of heat exhaustion.

Excessive heat also affects vehicle subsystems, such as brakes, electrical, cooling, hydraulics, wheels, and tires. Fuel consumption also increases. Heat is also the number one cause of battery failure. Extreme heat causes the water in the battery's electrolyte to evaporate. Further, heat causes a battery's positive plate grids to corrode more rapidly. These conditions are detrimental to the long-term life of a battery.⁽¹³⁾ Higher temperatures increase the perishability of certain types of cargo, such as livestock, refrigerated foods, pharmaceuticals, and other commodities.

Another researcher⁽¹⁴⁾ noted that excessive heat causes asphalt roads to soften. "Concrete roads have been known to explode, lifting three–four foot pieces of concrete. During the 1980 heat wave, hundreds of miles of highways buckled." Extreme heat degrades automobile cooling systems and diesel powered truck performance, and may lead to mechanical failures. Similarly, bridges designed for service within a certain temperature range may experience structural stress because of excessive heat or prolonged heat waves, particularly if these structures are aging or in a state of disrepair.

2.6 HIGH WINDS, CROSSWINDS AND TORNADOES

Winds greater than 25 mi/h can inhibit the maneuverability and stability of high-profile vehicles, including recreational vehicles, trucks, and buses.⁽¹⁵⁾ Strong winds can disrupt high profile trucks in exposed areas, such as interstate highways, mountain notches and open prairies. Lightly loaded semi-trailers are also particularly vulnerable. Such winds may take the form of crosswinds, headwinds, and tailwinds. High crosswinds induce control problems. Headwinds increase fuel consumption and may produce additional stress on engines and transmissions. The threat posed by high winds has received less attention than other types of weather events,⁽¹⁶⁾ and represents an area of opportunity to provide additional observations and databases for research and operations. Only six States now publish "best practices" for wind speeds and highway safety.

Although quite rare, tornadoes pose a significant threat to CMVs traveling along exposed sections of highways. For example, on February 5, 2008, tornadoes swept through the area around the town of Leighton in western Tennessee. One tornado (rated EF3) formed northeast of Huntersville near Interstate 40, blowing 13 tractor-trailers off the interstate. Table 3 displays the Enhanced Fujita (EF) intensity scale for tornadoes.

Table 3. The Enhanced Fujita (EF) Tornado Intensity Scale

EF Number	3 Second Gust (mi/h)
0	65–85
1	86–110
2	111–135
3	136–165
4	166–200
5	Greater than 200

A study of tornado winds on vehicle stability⁽¹⁷⁾ estimated the effects on stationary vehicles based on the six levels of the Fujita tornado intensity scale. Researchers found that winds less than 115 mi/h were not likely to upset stationary smaller vehicles in open terrain. Higher profile vehicles (semi-trailers and buses), however, may experience rollover at the EF1 level (i.e., winds above 95 mi/h). A simulation of heavy trucks in inclement weather⁽¹⁸⁾ analyzed various wind speeds, road surface, and loading conditions. The study showed how resonance of wind gusts plays a large role in determining the maximum wind speed in which a heavy truck can safely be driven.

2.7 THUNDERSTORMS AND HAIL

Hail is precipitation in the form of balls or irregular lumps of ice, always produced by convective clouds, nearly always cumulonimbus clouds. It primarily occurs in warm seasons and is of short duration. Although hail accompanies many severe thunderstorms, some studies^(5,19) project no significant increases in hailstorms under global warming scenarios. Other investigators⁽²⁰⁾ do project an increase in thunderstorm activity, but with considerable uncertainty about their overall severity. Under projections of global warming, more heat and moisture are available to fuel thunderstorms. On the other hand, reductions in wind shear at the middle and upper levels of the atmosphere—another trigger mechanism to catalyze thunderstorms—could help to offset the convective effects of greater warming.

2.8 DROUGHTS

Droughts affect transportation directly and indirectly. Prolonged periods of heat with little or no precipitation can lead to reduced soil moisture. Such conditions combined with strong winds may lower visibility from airborne dust and sand, and impair visibility for CMV drivers. These conditions may also degrade the efficiency of air intakes and filters on engines. Droughts also promote conditions that result in forest fires that may produce smoke dense enough to cause

delays and road closures. Very dry conditions may lower yields on agricultural commodities and thus influence the demand for trucking services.

Drought conditions may also harm CMVs operations through their effects on intermodal connections. Low water causes barges to run aground, resulting in delayed shipments of coal, chemicals, and agricultural goods produced by manufacturing plants in that region, causing diversion of shipments from one mode to another. The summer of 2005, for example, produced such conditions over part of the Midwest, lowering water levels on the Mississippi, Missouri, and Ohio Rivers.

2.8.1 Great Lakes Transportation Networks

Due to a combination of hotter conditions, increased evaporation, and reduced precipitation in that area, most IPCC scenarios project lower water levels in the Great Lakes. As ports along the Great Lakes experience these reductions, there will be an impact on the amount of vessel traffic and the maximum draft of vessels that the Great Lakes can accommodate in the future. To the extent that CMVs engage in intermodal transfers with ships calling on these ports, these scenarios could result in changes in local traffic and economic conditions derived from changes in shipping patterns. Shipments moving by large trucks often spend part of their journey aboard marine vessels. The Great Lakes have experienced many periods during the past 100 years when lake levels were much higher or lower than the long-term mean value (Figure 2).

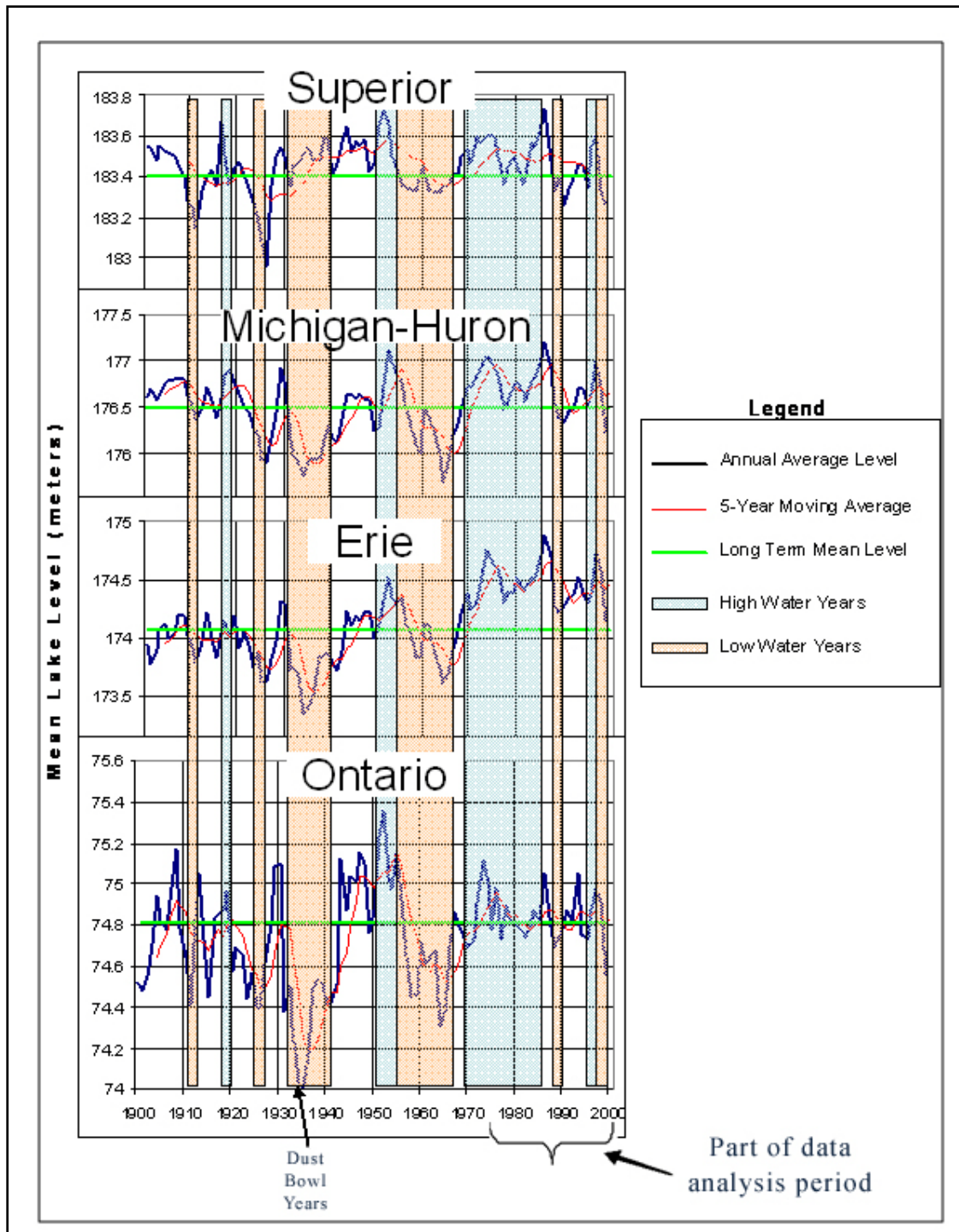


Figure 2. Mean Water Levels of Great Lakes (Meters), 1900–2000
 Source: NOAA/ Great Lakes Environmental Research Laboratory, 2008,
 analysis of data provided by NOAA (GLERL), personal communication, 26Mar08

3. CMV ACTIVITY, CRASHES, AND THEIR ASSOCIATION WITH WEATHER AND CLIMATE

Commercial motor vehicle transportation includes commercial and private fleet operators of various scales, from large fleets to independent owner-operators of a single vehicle, and transit and intercity buses. In general, it is a highly competitive industry, characterized by slim profit margins and rising costs due to expenses for fuel and insurance. Industry representatives often discuss a possible driver shortage. Depending on the type of service and time sensitivity of delivery, long distance trucks and buses may travel 500 to 1,000 miles or more per day, whereas local routes are in the range of 75 miles or less. Routes at both the local and long-distance levels may have different levels of exposure to adverse weather, so there may be weather-related distinctions depending on type of carrier. Because of the large spread in trip length for the different categories of vehicles, the relevant weather forecast zone of interest for fleet operators and drivers may be either the microscale or mesoscale.

3.1 INDUSTRY OVERVIEW

With few exceptions, the public sector owns and operates most of the Nation's roads. By virtue of their roles in maintaining roads during all types of weather conditions, or curtailing or closing roads in the face of adverse weather, State and local authorities thus play a significant role in the response of CMV drivers to weather conditions. Weather-related restrictions on vehicle speeds or allowable cargo, along with outright closures of roads, help to improve safety by decreasing the risk that vehicles will collide, or become disabled due to poor weather conditions. Some States, such as California, even mandate the use of tire chains over certain routes in winter or during particularly severe storms. On the other hand, closures also impose substantial delays on road users, although CMV operators may shift routes to whatever alternates the State will allow.

3.1.1 Local Trucking

Local trucking firms characteristically provide trucking within a metropolitan area. Generally, the trips involve many stops over short distances, and include same-day return. These trucks operate on tight schedules that are highly sensitive to local weather and traffic conditions. Weather conditions may produce significant delays and make driving less safe, but the geographic scope acts to constrain many negative impacts. Although actual risk might vary according to geography, time, seasonality, and other factors, significant encounters with adverse weather are possible throughout local networks.

3.1.2 Long Distance Trucking

Long distance trucking includes truckload, less-than-truckload, and specialized carriers. Long-distance TL carriers provide full truck movement of freight from origin to destination. TL freight generally involves a full, single load not combined with other shipments. Although these shipments may involve great distances, with potentially large exposure to varying weather conditions, the TL driver's main concern is avoiding mesoscale weather primarily along highway routes. Further, since most weather systems move generally in a west to east direction, an eastbound TL trucker may have to endure similar weather conditions for a longer period, than a TL truck moving westbound against or through the same weather system.

In contrast, the character of long-distance LTL carriage is that of multiple shipments combined onto a single truck for multiple deliveries within a network, including local pickup, local sorting and terminal operations, line-haul, destination sorting and terminal operations, and local delivery. Because LTL requires multiple origin-destination pairs within a network, adverse weather may produce more difficult conditions than those for TL carriers.

3.1.3 Specialized Freight Trucking

Specialized freight truck carriers transport HazMat. Trucks, along with railroads, transport significant quantities of HazMat. About 325 billion ton-miles of hazardous materials move annually within the U.S. transportation systems, one-third of which goes by truck, mostly over short-distances. Accidental releases of certain HazMat may lead to a plume and dispersion of the material. Existing and forecast meteorological conditions strongly determine the degree of human exposure with the possibility of injuries and fatalities.

3.2 USE OF WEATHER INFORMATION BY CMV OPERATORS

CMV drivers obtain weather information from a variety of sources and mechanisms. The list includes company dispatchers, Road Weather Information Systems and traveler information Web sites, 511 cellular phone systems, AM/FM radio, satellite radio, Citizens' Band radio, NOAA Weather Radio, commercial television, and the Internet. Truck stops and weigh stations increasingly have Wireless Fidelity (WiFi) access and Internet kiosks from which drivers can get up-to-date weather information, in addition to reports from other drivers. In the future, wireless broadband technologies, such as the Worldwide Interoperability for Microwave Access (WiMax) may offer even greater access to weather and traffic information.

The National Weather Service (NWS) Web site (www.weather.gov) provides a variety of information from Weather Forecast Offices. This information includes: hourly reports from Automated Surface Observation Stations; zonal forecasts (by county or finer level of detail); area forecast discussions (often with probabilistic discussions of impending weather); special weather statements (provisional guidance and additional elaboration on weather impacts); active watches and warnings; hydrological (coastal and inland waters information); and climate data, radar and satellite reports, and other online information. These products contain valuable local, statewide, regional, and national information for CMV operators and drivers. Vast amounts of additional raw and packaged weather data are also available from various Web sites operated by NOAA. Nevertheless, some users may be reluctant or unwilling to make operational decisions without professional guidance, and many contract with private weather services for interpretation and forecasts.

3.2.1 Regulatory and Corporate Responses

Trucking companies do not routinely incorporate weather into overall truck network planning or scheduling in advance. Most fleet operators leave decisions to go, or not to go, up to the CMV drivers in the presence of adverse weather conditions, the chief exceptions being when public officials close a road, where chains are required, or when weather-specific rules apply. On the regulatory side, drivers themselves are also subject to the FMCSA's hours-of-service rules that allow an extra 2 hours to complete a run or reach their destination safely in the event of "adverse driving conditions."⁽²¹⁾

In the prairie region of south central Canada, seasonal weight restrictions apply to trucks. During the cold winter months, a “Winter Weight Premium” allows trucks to carry heavier loads over the hard frozen surface.⁽²²⁾ Weight restrictions apply to spring conditions when roadbeds thaw, soften, and become vulnerable to damage from trucks hauling heavy loads.

A St. Louis, MO-based trucking company maintains its own “Winter Weather Shutdown Policy.” From October through April, company officials review weather throughout the company’s operating area. If the company decides that weather conditions in a given area make it unsafe to drive, fleet operators send drivers a message ordering a shutdown of operations in that area. Most shutdowns are local. Once the trucking company declares a shutdown, it notifies customers of possible delays in shipment pickups or delivery.⁽²³⁾ The company defines adverse weather as snow, sleet, fog, other adverse weather conditions, a highway covered with snow or ice, or unusual road and traffic conditions—none of which were apparent on the basis of information known to the person dispatching the run at the time it was begun.

3.3 U.S. CMV ACTIVITY

There are now more than nine million CMVs registered in the U.S., most of which are large trucks. From 1975 to 2005, CMV registrations increased by 60 percent, while VMT grew by 163 percent (Figure 3). Combined with similar increases in automobile VMT, and little growth in highway capacity, congestion has become a serious problem on the Nation’s Interstate Highway system. From a weather perspective, CMVs and their operators face a variety of weather-related exposure risks.

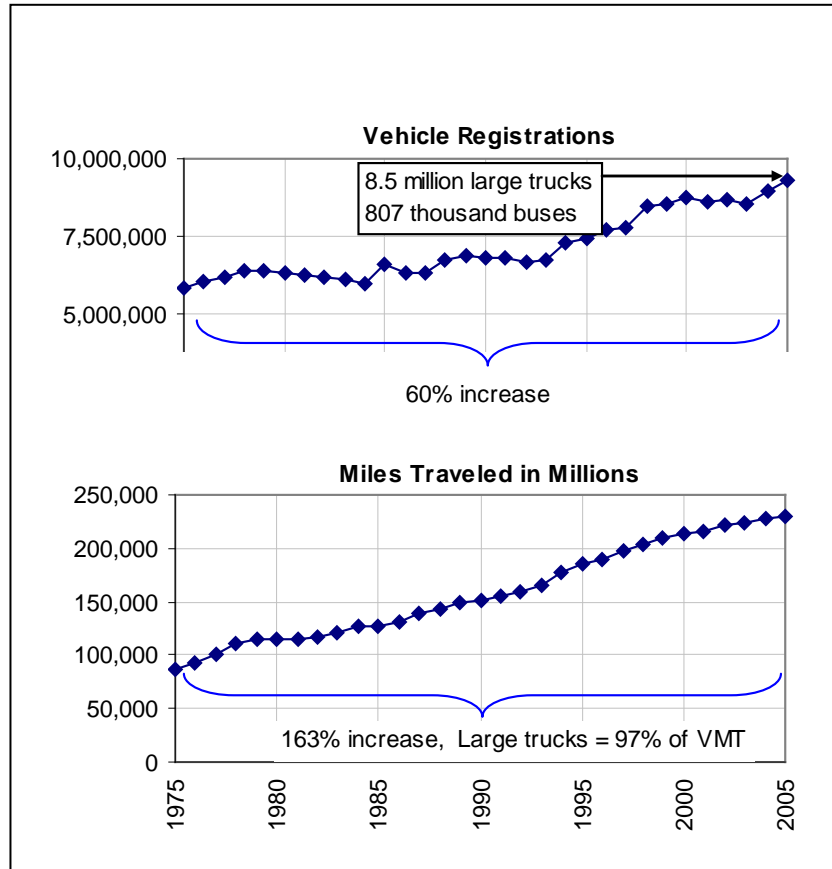


Figure 3. Commercial Motor Vehicle Registrations and VMT, 1975–2005

Source: FHWA, Highway Statistics 2005, Table VM-1; and FMCSA, Motor Carrier Management Information System (MCMIS).

This combination of congestion and weather exposure is of concern to the FMCSA as it pertains to how climate change could amplify some of those effects in its long-term planning horizon by increasing the frequency or intensity of severe weather. Commodities carried by CMVs are of great economic importance. Recent data indicate that trucking as a single mode, or as part of intermodal combinations, accounts for about 80 percent of the total value of \$13 trillion for all commodity shipments in the U.S., and 42 percent of all ton-miles. CMVs share an infrastructure that includes 47,000 miles of interstates, 115,000 miles of National Highway System roads, and 3.8 million miles of other roads.⁽²⁴⁾ The FHWA estimates that about 25 percent of non-recurrent delays on freeways are due to weather, and that weather-related delay adds \$3.4 billion to freight costs annually.⁽²⁵⁾

3.4 WEATHER AND CLIMATE AS FACTORS IN THE SUPPLY CHAIN

The transportation infrastructure relevant to CMVs includes all modes associated with the intermodal supply chain: highways, rail, air, and water. This includes all activities related to the transportation of goods, and reflects a weather-sensitive supply chain that extends from raw materials, to suppliers, manufacturers, wholesalers, retailers, and consumers (Figure 4). These effects may occur en route or at specific nodes. In addition, because of growing modal

interdependence, weather events may produce ripple effects and disrupt supply chains. Manufacturers and producers may have production delays due to employees unable to reach their jobs during bad weather, or because of delays in the shipment of intermediate goods needed for production. Carriers may lose speed, routing efficiency, and the ability to meet schedules for intermodal transfers. Consignees experience delays, or do not receive finished goods and supplies. Tight synchronization between production and delivery schedules to handle just-in-time delivery practices may create an environment increasingly vulnerable to the effects of weather and climate.

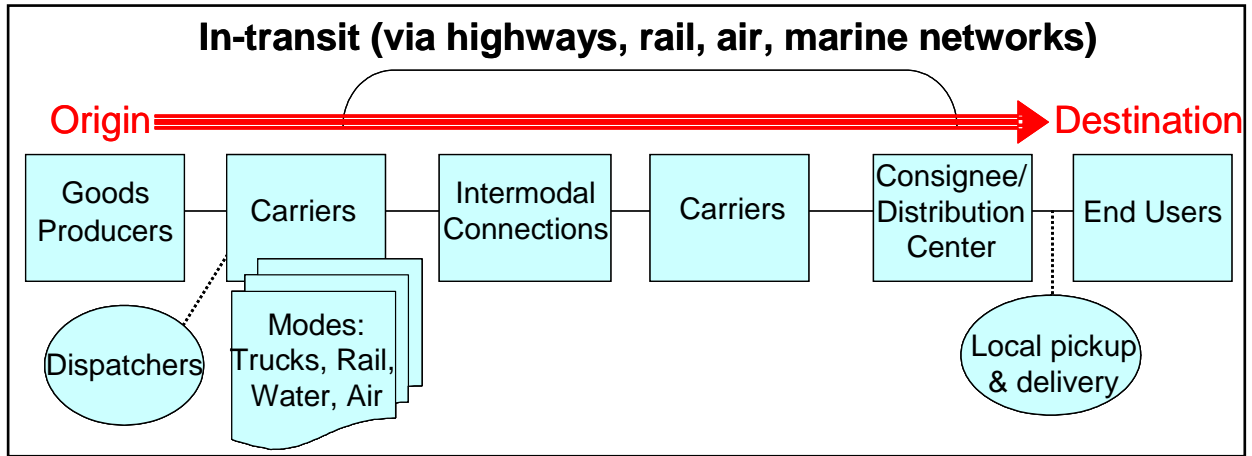


Figure 4. A Typical Supply Chain

3.5 CMV CRASH DATA

3.5.1 NHTSA Crash Statistics

Police investigators at CMV crash scenes collect accident data reported later to the NHTSA. NHTSA maintains a complete census of fatal crash data known as the FARS, which contains data on all police-reported fatal traffic crashes on U.S. public roads that resulted in death within 30 days of the crash.⁽⁴⁾

The NHTSA General Estimates System estimates non-fatal crashes based on a nationally representative sample of police accident reports. Research has shown that police accident reports include only about half of all non-fatal vehicle crashes,⁽²⁶⁾ although most involve only minor property damage and no significant injuries. FARS data suggests some overrepresentation of CMVs involved in fatal crashes. According to FHWA and NHTSA data, large trucks account for 3.4 percent of all vehicle registrations, 7.5 percent of VMT, and 11.1 percent of fatal crashes. Further, compared to all types of vehicles, the percent of fatal crashes involving CMVs is higher in rain, snow, or fog (Table 4).⁽²⁾

Table 4. Fatal Weather-Related Crashes Involving Commercial Motor Vehicles and All Motor Vehicles by Type of Weather Condition

Weather Conditions	Percentage of Crashes of Weather-Related Commercial Motor Vehicle Crashes	Percentage of Crashes of All Weather-Related Vehicle Crashes
Rain	60%	46%
Snow/Sleet	32%	12%
Fog	12%	8%

Source: Pisano, P., Goodwin, L., & Rossetti, M. 2008. U.S. Highway Crashes in Adverse Road Weather Conditions. Presented at the 24th Conference on Information and Processing Systems during the 88th annual meeting of the American Meteorological Society (New Orleans) Session 8.1.

FARS data and the underlying definition of what constitutes a crash and the role of weather in those crashes, have certain limitations (Table 5). For example, in the FARS field for weather (Atmospheric Condition), sleet and hail are grouped as one weather phenomena or crash record, which is incorrect from the standpoint of their meteorological origins. Further, FARS does not include any weather-related crashes associated with high winds, which is a significant omission in that database. Strong winds and crosswinds can disrupt CMV operations. High profile trucks are susceptible to potential vehicle instability, loss of control, and blowovers from crosswinds in exposed areas, such as bridges, interstate highways, and mountain passes. Expected peak wind gusts may also play a role in determining the maximum wind speed in which a heavy truck can be safely driven. In this study, the term “weather-related crashes” refers to all crashes coded with all combinations of atmospheric and road surface conditions that indicated either adverse weather or road surfaces that were wet, snowy, or icy. Accordingly, for a given crash record, if “atmospheric condition” is coded as “1,” but “road surface condition” is coded as 2, 3, or 4, a wet or icy pavement is inferred. Apart from coding error, in most cases this probably indicates the presence of antecedent surface moisture from prior precipitation, excessive soil moisture of ambient humidity, melting snow banks, or perhaps stream overflow. In any event, this is considered a weather-related crash. Wet road surfaces might also occur from events unrelated to weather, such as street washing, runoffs from fire hoses, or broken water pipes.

Table 5. FARS Codes for Atmospheric Condition and Road Surface Condition

Code	Atmospheric Condition	Road Surface Condition
1	No Adverse Atmospheric Conditions	Dry
2	Rain	Wet
3	Sleet (Hail)*	Snow or Slush
4	Snow	Ice
5	Fog	Sand, Dirt, Oil
6	Rain and Fog	n/a
7	Sleet and Fog	n/a
8	Other (Smog, Smoke, Blowing Sand, Dust)	Other
9	Unknown	Unknown

* Note: Although coded the same in FARS, sleet and hail are two different weather phenomena. Hail is a short duration, generally warm season phenomenon that accompanies severe thunderstorms, and can range in size from pea-size to baseball size. Sleet is a wintertime phenomenon that occurs when layers of warm and cold air aloft produce melting and refreezing of snowflakes that may accumulate several inches on the ground.

3.5.2 Large Truck Crash Causation Study Results

The Motor Carrier Safety Improvement Act of 1999 (MCSIA; Pub. L. 106—159, 113 Stat. 1764, Dec. 9, 1999) mandated a study to determine the causes and factors contributing to crashes involving CMVs. In the LTCCS,⁽¹⁾ the FMCSA and NHTSA examined a nationally representative sample of large truck fatal and injury crashes from 2001 to 2003 at 24 sites in 17 States. Investigators collected up to 1,000 data elements for each crash. Results from the LTCCS indicated adverse weather conditions were present in about 13 percent of the crashes. The main findings of the LTCCS indicate the majority of crashes are due to driver error. Some of the driver errors result from bad decisions in the presence of weather-related phenomena.

3.6 FATAL CMV CRASHES AND WEATHER EVENTS

Weather is only one of many factors that contribute to truck crashes. Other important factors include driver error, vehicle speed, alcohol consumption, vehicle characteristics, etc. In addition, average temperatures show a positive association with vehicle deaths, and precipitation a negative association.⁽²⁷⁾ Although only about 16 percent of all fatal CMV crashes are associated with adverse weather or wet pavement,⁽²⁾ that share can still have significant effects on vehicle performance and safety, as well as systemic effects that may impact other modes and economic sectors. It is part of FMCSA's mission to reduce or mitigate crashes, including the effects of weather-related crashes, to the extent that it is able to do so.

Normalized by VMT for large trucks, the trend of weather-related CMV crashes for large trucks shows a distinct downward trend, falling by about half during 1975–2006.⁽³⁾ The long-term trend may be indicative of the effects of many forces, such as benefits stemming from the NWS modernization program, advances in weather forecasting, vehicular improvements and technology, the introduction of intelligent transportation system features, changes in CMV traffic patterns, or changes in the frequency or distribution of weather events. Since about 2002, the decline has leveled off (Figure 5). This may indicate that there could be a minimum number of weather-related crashes that will occur over which the FMCSA and other agencies have little control, or that weather events that contribute to CMV crashes are becoming more frequent or severe, or are affecting a larger number of CMVs.

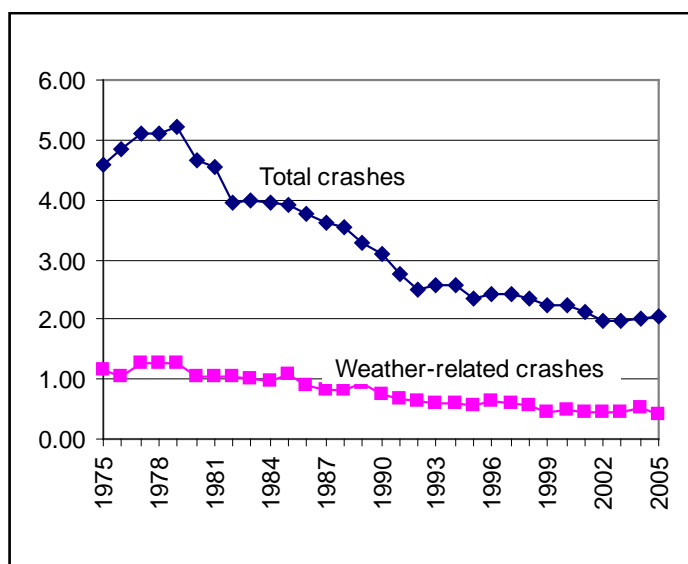


Figure 5. Fatal Large Truck Crashes vs. Fatal, Weather-related Large Truck Crashes per 100 Million VMT, 1975–2005

Over the 2005–2006 period, the total number of fatal CMV crashes associated with adverse weather predominated in States, such as Texas, Florida, Pennsylvania, and Ohio (Figure 6).¹ This upward trend in fatal CMV crashes is expected, since this data correspond with States with the highest levels of traffic volume. When normalized for VMT, however, a different picture emerges. Northern-tier States, which are winter impacted—the Dakotas, Montana, Wyoming, and Vermont—rank among the highest in terms of weather-related fatal crashes per 100 million VMT. The list also includes States such as West Virginia, Kentucky, Arkansas, and Alabama. These latter States may represent the impacts of flash flooding that sometimes occurs in mountainous and hilly terrain, or along the boundaries of major rivers and watersheds.

¹ Source data for Figures 5 and 6 are as follows: Calculations for fatal crash data for 1995–2006 were from data available at the NHTSA FARS data query site www-fars.nhtsa.dot.gov/QueryTool/QuerySection/SelectYear.aspx. For 1975–1994, fatal crash data were obtained from personal communications with Mr. Paul Lobo (NHTSA). VMT data are from FHWA.

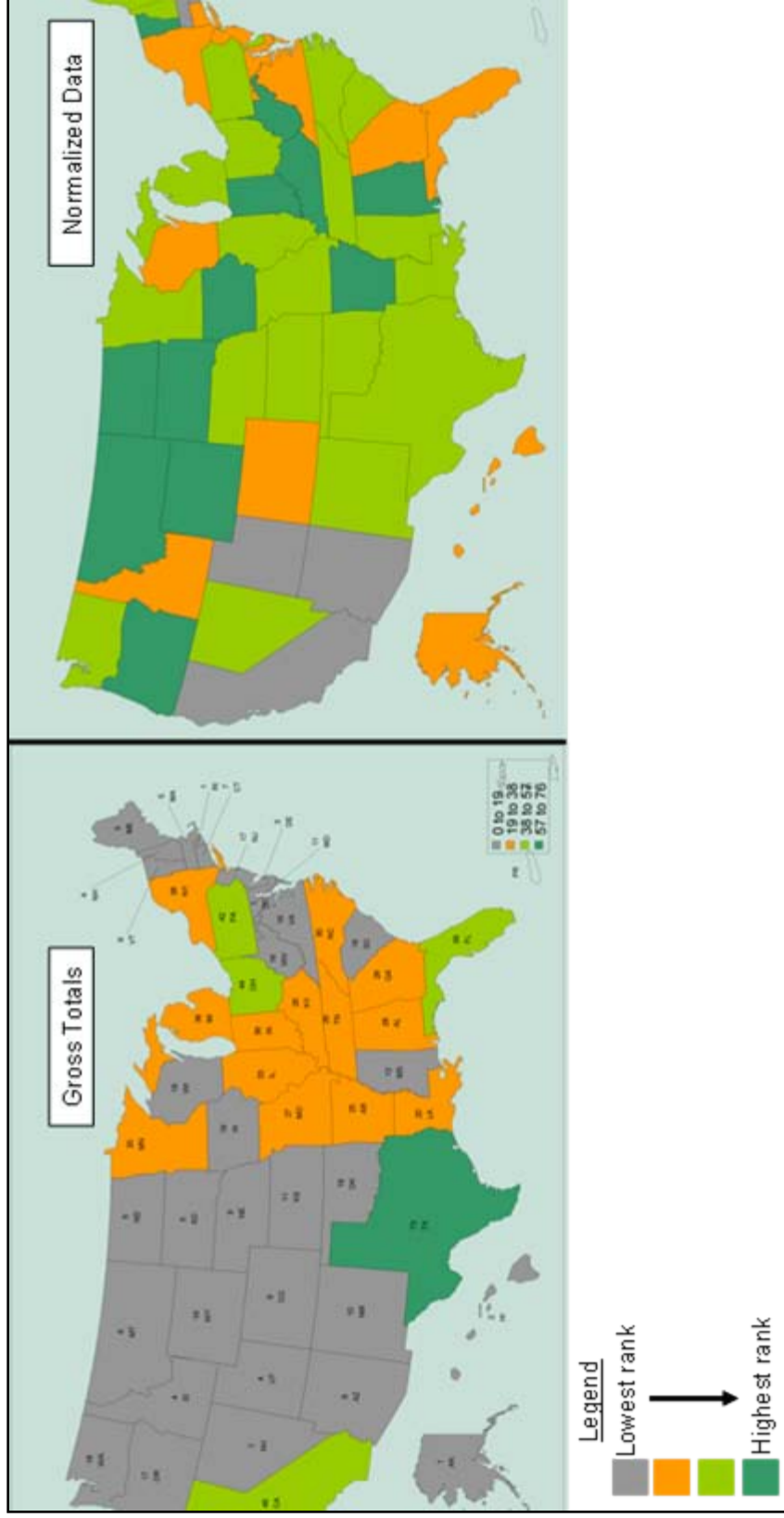


Figure 6. CMV Fatal Crashes, Weather-related, by State, Gross, and Normalized, 2005–2006

The six charts displayed in Figure 7 show the trend of specific types of weather elements associated with fatal CMV crashes. Rain, snow, fog, and wet pavement are the four main associations. The raw data indicate a slight decreasing trend over the period of 1975–2006 for rain, snow and fog, as well as for total weather-related crashes. The series for snow and fog show slightly more volatility. This may reflect short-term climate variability, such as exceptionally snowy winters in the eastern U.S.; 1996 is such an example.

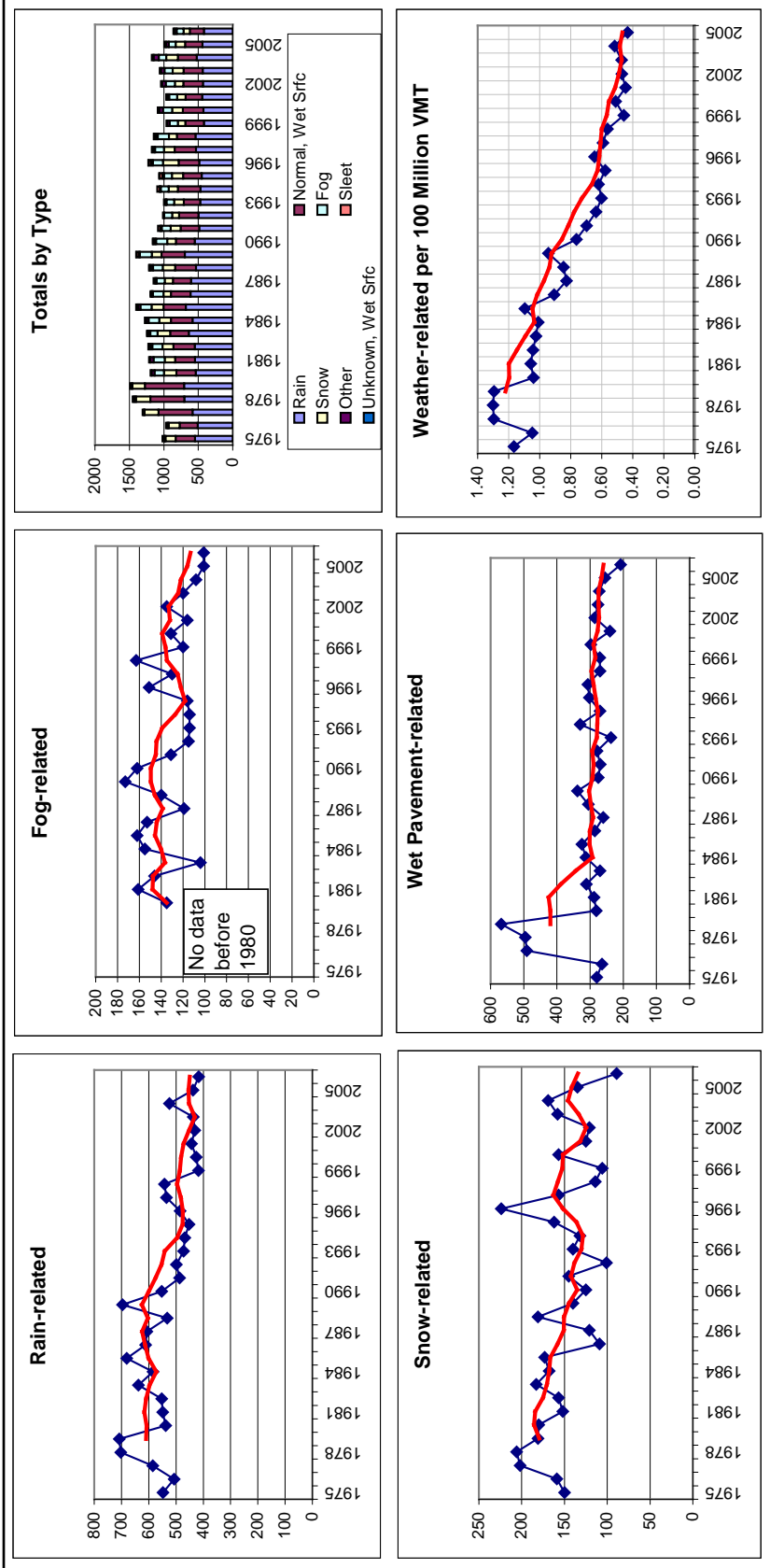


Figure 7. Fatal, Weather-related CMV Crashes by Type of Weather Event, 1975–2006, with 5-year Moving Averages

Figure 8, Figure 9, and Figure 10 isolate those CMV crashes relating, respectively, to rain and wet pavement, snow and icy pavement, and visibility hazards. It is somewhat easier to see the clustering effect by looking at these events by themselves. Figure 8 shows concentrations of crashes associated with rain and wet pavement through mid-Atlantic region, the Pacific Northwest, and parts of Florida. A side-by-side comparison with 30-year climatology data also indicates a relationship. As cited earlier, climate change studies project regional increases in the number of days with intense precipitation and in the overall amount of precipitation. Accordingly, regions with more vulnerability at present could show even greater sensitivity in the future.

Wet pavement crashes have shown little trend for many years. A 1980 study by the National Transportation Safety Board found that 13.5 percent of all fatal accidents occurred on wet pavement, while precipitation occurred only 3.0–3.5 percent of the time nationwide.⁽²⁸⁾

This indicates that fatal accidents on wet pavement occur 3.9 to 4.5 times more often than might be expected. The wet-pavement accident problem is probably a concern for all States.⁽²⁸⁾ Other studies have also noted the persistent problem of wet pavement exposure to drivers and the seeming lack of appreciation for its risks.

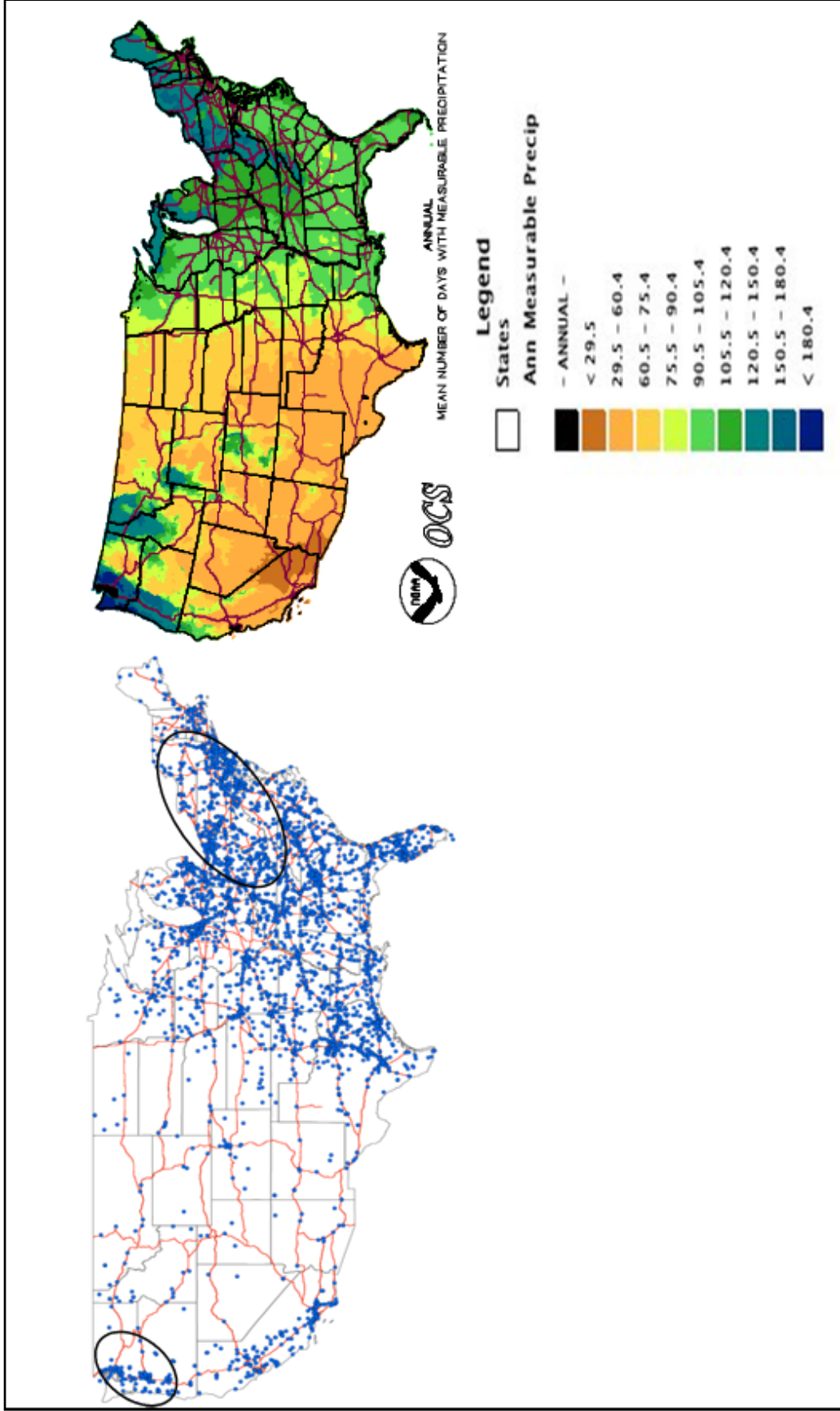


Figure 8. CMV Crashes in Rain and on Wet Pavement (2001-2006), Compared to the NCDC U.S. Climate Atlas
 Source: Fatal crash data for 2001-2006 (referenced by geographic coordinates) calculated from data available at the NHTSA FARS online data query site www-fars.nhtsa.dot.gov/QueryTool/QuerySection/SelectYear.aspx. Climatological data obtained from DOC/NCDC (2002)

Figure 9 isolates crashes where snow, sleet, and icy pavement appeared present in FARS data. Some clustering is apparent in locations, such as the lee of the Great Lakes (lake-effect snows), the Continental Divide in Wyoming, and along the Cascades in Oregon.

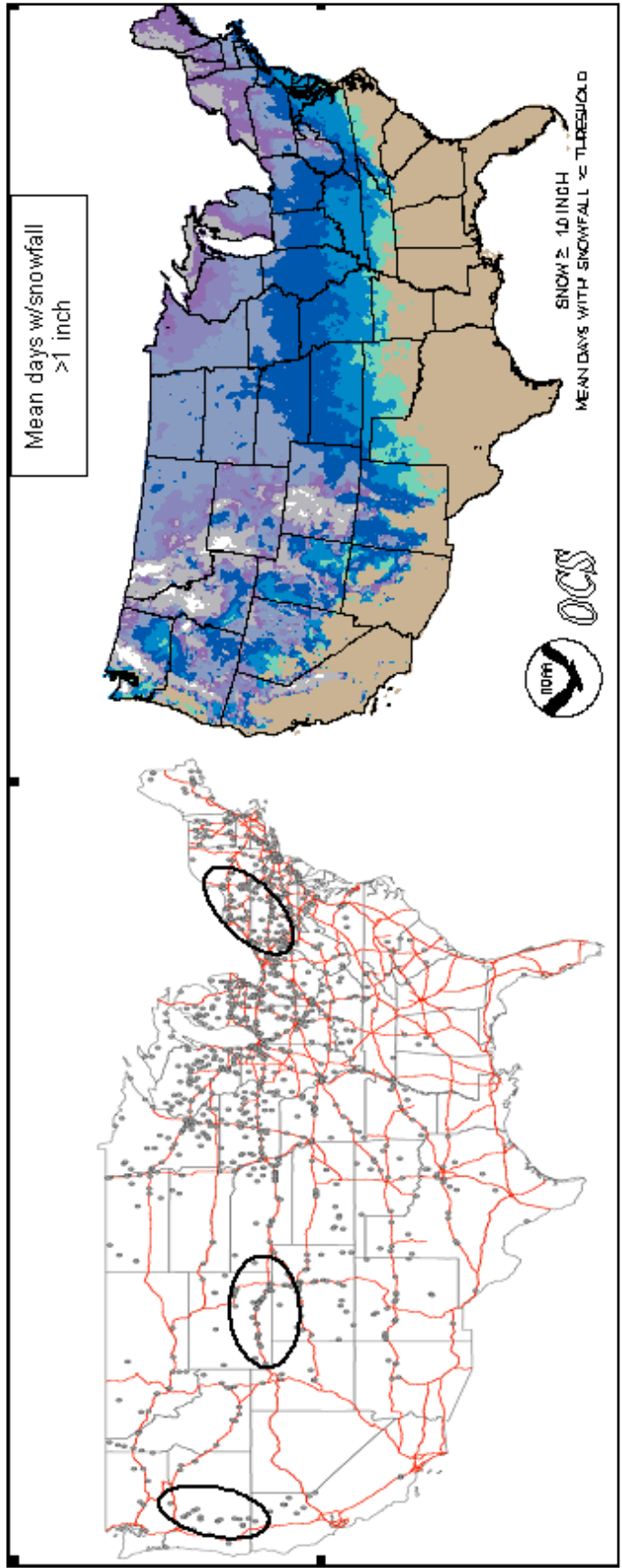


Figure 9. CMV Fatal Crashes in Snow, Sleet, or on Icy Pavement (2001–2006) Compared to the NCDC U.S. Climate Atlas

Source: Fatal crash data for 2001–2006 (referenced by geographic coordinates) calculated from data available at the NHTSA FARS online data query site www.fars.nhtsa.dot.gov/QueryTool/QuerySection/SelectYear.aspx. Climatological data obtained from DOC/NCDC (2002)

Figure 10 isolates crashes where fog and other type of impaired visibility may have played a role. Clustering of crashes occurs in the central and southern valley areas of California, the Pacific Northwest, the central Appalachian Mountains, and much of Florida. Fog, because of its unpredictability and often lack of homogeneity in affected areas, is among the most deadly of weather conditions.

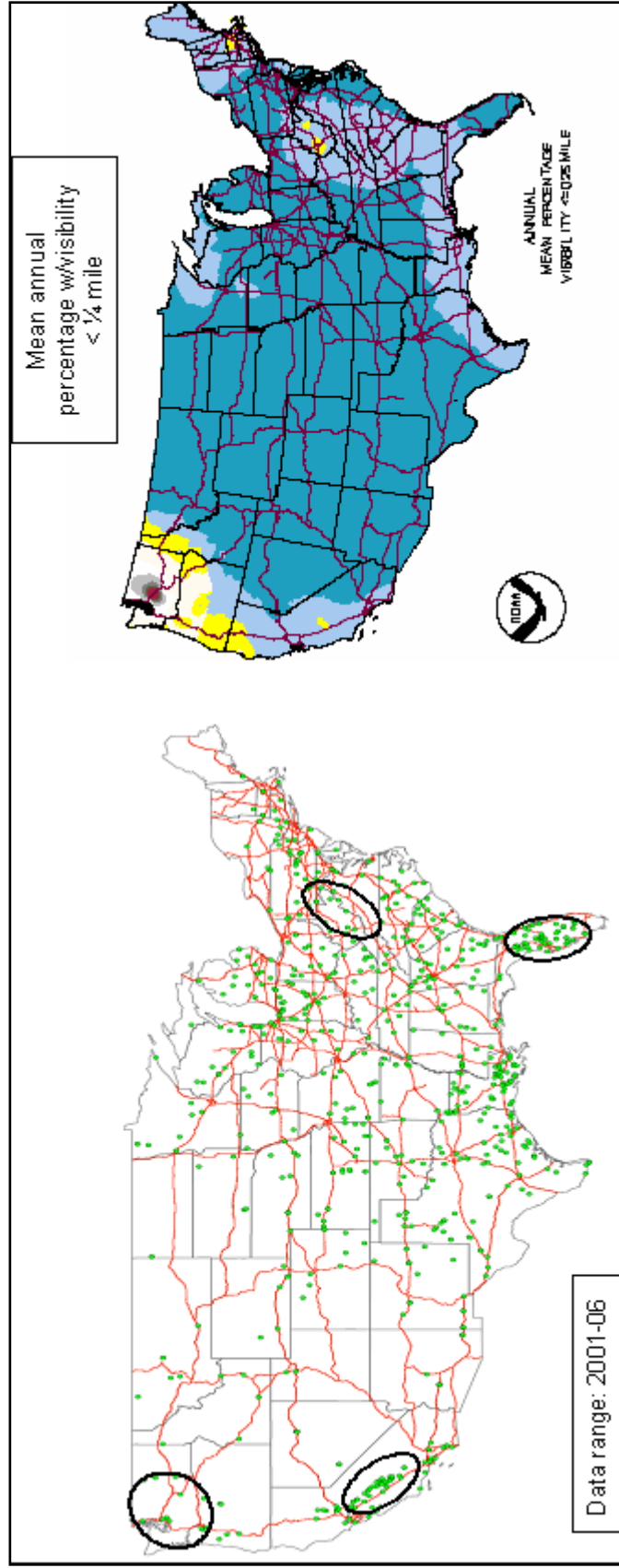


Figure 10. CMV Fatal Crashes in Conditions with Impaired Visibility (2001–2006) Compared to the NCDC U.S. Climate Atlas

Source: Fatal crash data for 2001-2006 (referenced by geographic coordinates) calculated from data available at the NHTSA FARS online data query site www-fars.nhtsa.dot.gov/QueryTool/QuerySection/SelectYear.aspx. Climatological data obtained from DOC/NCDC (2002)

3.7 TRENDS IN THE NCDC STORM EVENTS DATABASE, 1993-2006

Storm Data is an official publication of the NOAA NCDC that documents the occurrence of storms and other significant weather phenomena having sufficient intensity to cause loss of life, injuries, significant property damage, and/or disruption to commerce. It is also a partial record of other significant meteorological events. The latter include record maximum or minimum temperatures or precipitation that occurs in connection with another event. The Storm Events Database (SED) contains data from the following sources:

- All weather events from 1993–1995, as entered into *Storm Data* (except those events from June 1993–July 1993, which are missing, and those events with no latitude and longitude).
- All weather events from 1996 to the present, as entered into *Storm Data* (including latitude and longitude).
- Additional data from the NOAA Storm Prediction Center, including pre-1993 data for tornadoes, thunderstorm winds, and hail.

Many types of weather events are included in the SED (Table 6). NCDC receives SED information from the NWS, which, in turn, receives it from a variety of sources, such as county, State, and Federal emergency management officials, local law enforcement officials, NWS damage surveys, the insurance industry, and the general public.

Table 6. Weather Events Included in the NCDC Storm Events Database

Weather Event	Description
Winds	Severe thunderstorm winds, non-thunderstorm high winds
Floods	Flash floods, floods, river floods, small/stream or urban flooding
Winter Storms	Snowstorms, blizzards, ice storms (most deaths due to vehicle accidents are not directly related deaths, consequently, they are not counted)
Heat Wave	Periods of excessive heat and humidity
Cold Wave	Periods of extreme cold
Hail	Events when hail diameter was >3/4 inch
Tornadoes	All events from EF0 to EF5
Tropical Cyclones	All named storms
Fog	Events where visibility was <= ¼ mile

3.7.1 Caveats Concerning the Storm Events Database

The NCDC includes only “direct” deaths in the SED, in which the weather hazard is the major cause of death. Heat waves, heat, and humidity, however, are sometimes counted in the SED as secondary or contributing causes of death, and these are counted as “indirect” deaths. Likewise, nearly all deaths attributed to vehicle deaths on highways in winter storms are indirect deaths (e.g., the driver was driving too fast for the conditions, etc.). In other words, the snow or ice did not kill the individual; the death was the result of a vehicle accident. This restriction prevents an accurate count of weather-related crash deaths, since it results in undercounts and underrepresentation of true risks posed by driving in adverse weather.

3.8 REGIONAL AND CORRIDOR SPECIFIC IMPACTS OF EXTREME WEATHER EVENTS

Figure 11 presents the distribution of CMV fatal crash sites by latitude/longitude for the 2001–2006 period. Icons show the type of weather reported by police accident reports. The map shows the expected higher frequencies of snow- and sleet-related crashes in the northern and mountain States, fog in the Appalachian Mountain region, and rain in the southern-tier States. There is a more even distribution of wet pavement crashes (with fair weather reported) throughout the country. The observed patterns of weather-related crashes also conform well to the climatology norms published by the NCDC.

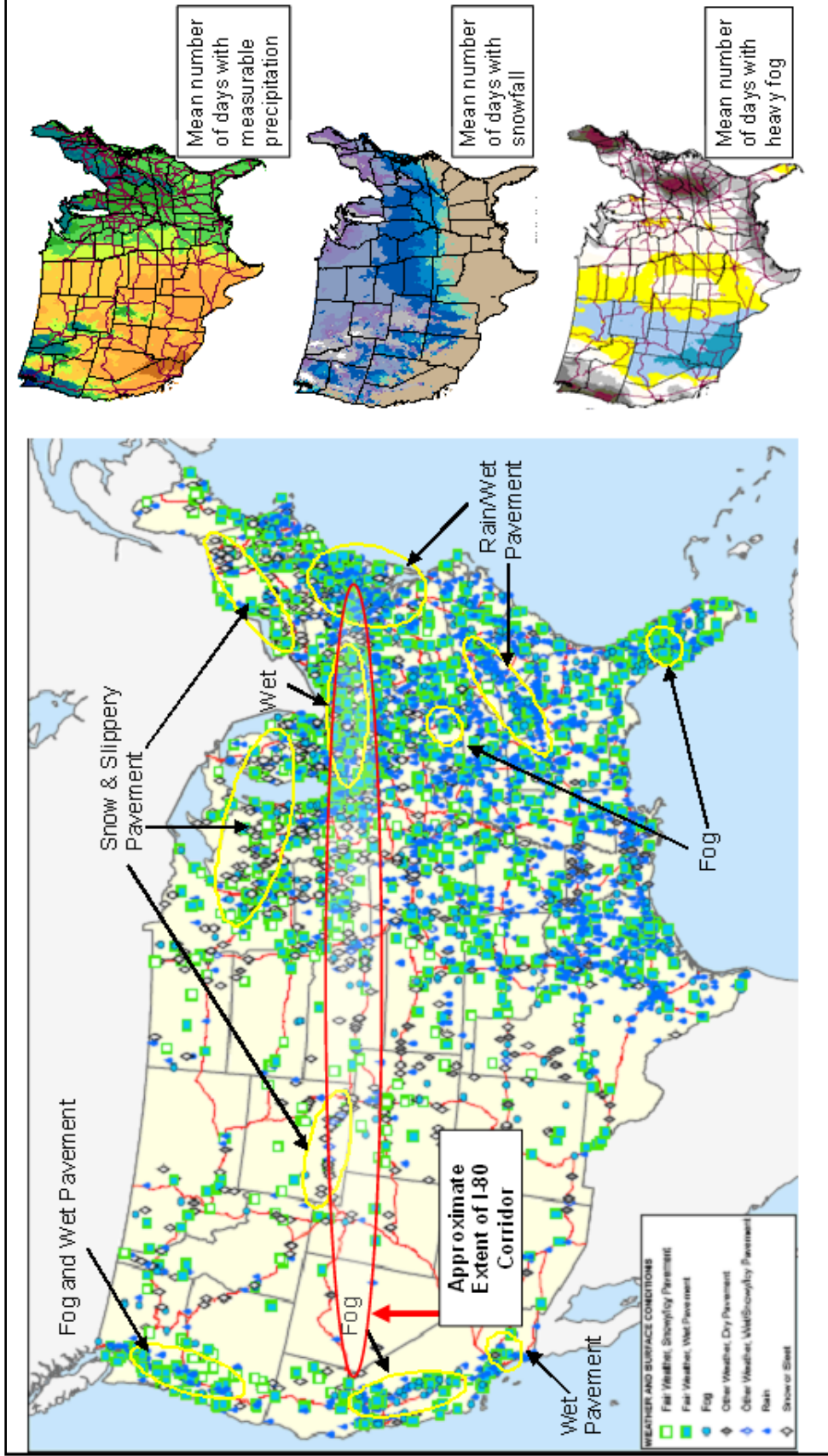


Figure 11. Locations of Fatal Crashes involving Commercial Motor Vehicles, by Type of Weather Event, 2001–2006, Compared to NCDC Climatology Statistics

3.8.1 Weather-related CMV Crashes on Interstate Corridors

Higher concentrations of fatal weather-related CMV crashes appear to exist in the major Interstate corridors of the East, Midwest, and in California. Figure 11 and Figure 12 display regional clusters of weather-related fatal crashes distributed by types of weather event and by road segments. The Interstate-80 corridor (highlighted by a red ellipse on Figure 11) provides a good reference for this type of analysis, and probably reflects a combination of high traffic volumes (the Battelle Institute indicated that total truck traffic volume approaches 10,000 trucks per day at some locations close to major cities along the corridor), and the road's exposure to adverse weather conditions throughout the year.⁽²⁹⁾ GIS data plots of FARS crashes indicate that other interstate corridors (I-10, I-90, I-35, I-75, and I-85) also had either clustering or a higher percentage of weather-related crashes (Figure 12).

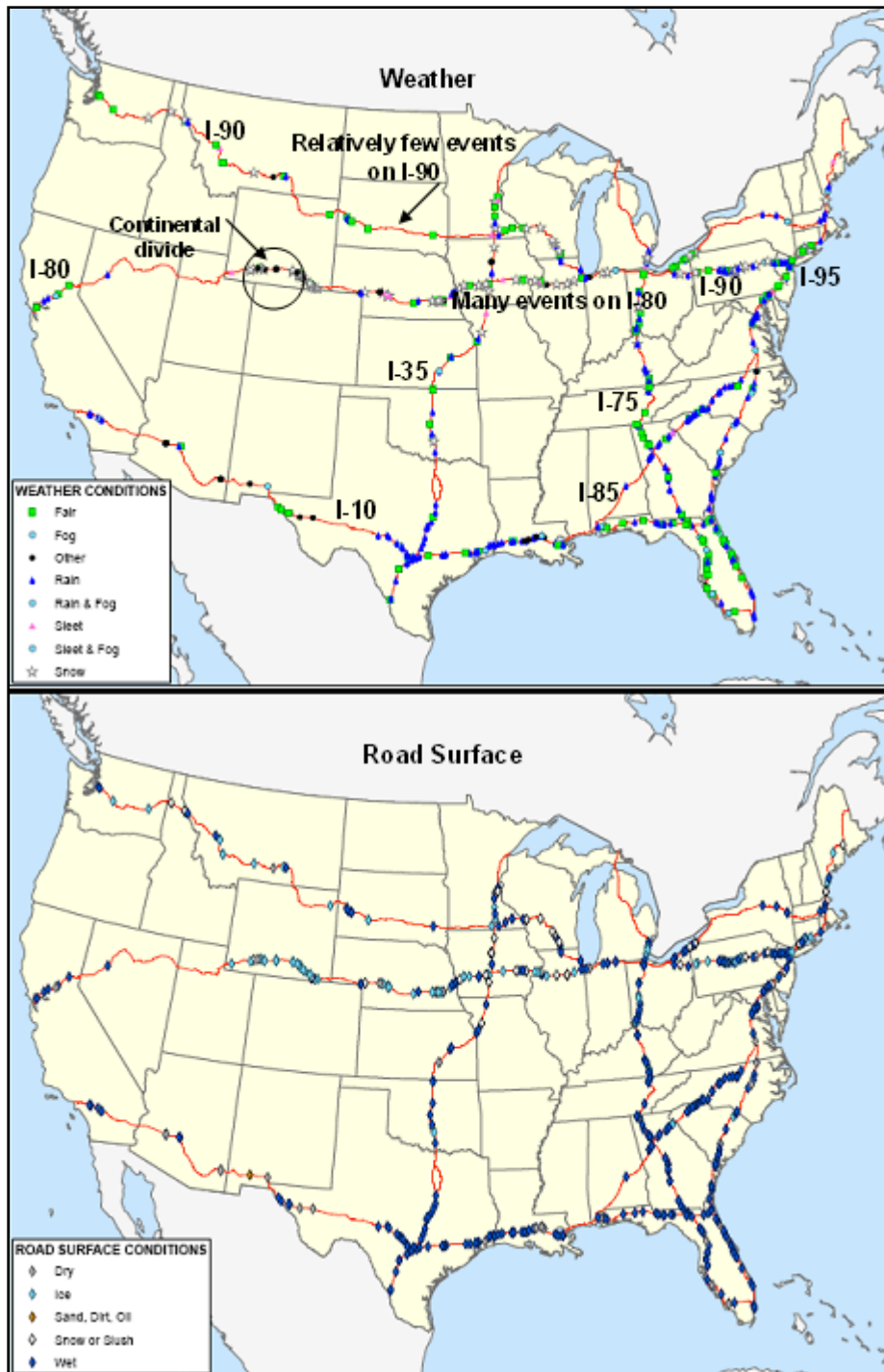


Figure 12. CMV Fatal Weather-related Crashes by Selected Interstate Highways, Weather, and Road Surface Condition, 2001–2006

Overall, I-80 extends from Eastern New Jersey to California and shows the greatest concentrations of weather related fatal crashes, including a diversity of winter and non-winter events, and wet pavement events. I-80 lies at the boundary of polar air masses to the north and warm, moist air masses from the south, thus producing more storminess. I-80 also crosses more diverse terrain, including mountain ranges, river valleys, open prairie, and desert. Topographic features often provide the necessary lift mechanism for a parcel of warm, moist surface air to interact with cooler air aloft and produce precipitation or stormy conditions. As discussed earlier, strong winds and tornadoes present dangers to CMV operators. Figure 13 shows 30-year tornado tracks across the U.S. Along I-80, a heavy clustering of tornadoes occurs in Nebraska, and activity is still apparent well to the east, as far away as Pennsylvania. I-40 is another prominent interstate corridor prone to tornadic activity, particularly where it traverses Oklahoma and Texas. Hail often accompanies severe thunderstorms, and presents a significant hazard to CMV operators due to its potential to impair visibility, reduce traction, and cause property damage. For reasons mentioned above, I-80 remains susceptible to hail (Figure 14), depicted through detection by Doppler radar (Next Generation Radar or NEXRAD) algorithms of hail signatures during the month of June 2007 along the entire length of I-80. The map shows heavy concentrations of hail signatures through central and western Pennsylvania, and all of Ohio and Indiana.

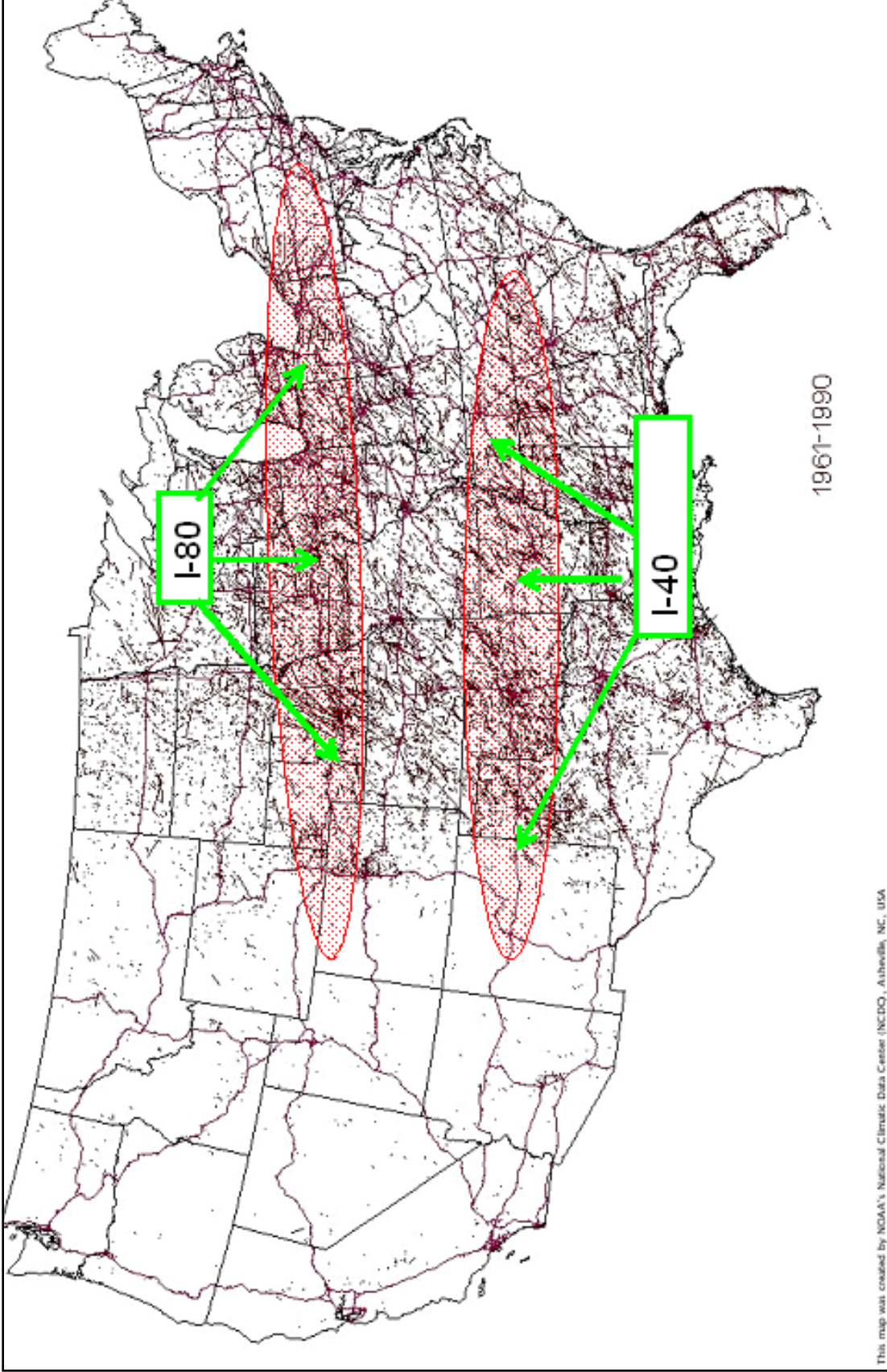


Figure 13. Tornado Tracks and Overlays on Selected Interstate Highways, 1961–1990

Source: <http://gis.ncdc.noaa.gov/website/fms-climatis/ustorn47/viewer.htm>.

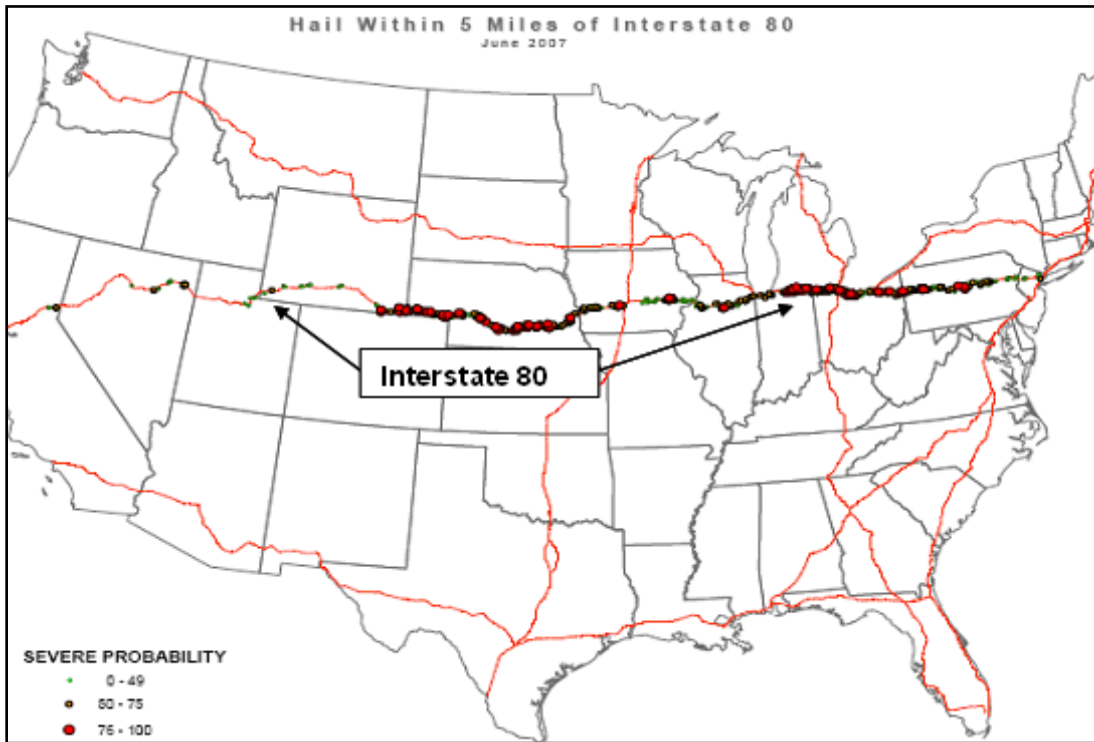


Figure 14. NEXRAD Hail Signatures along Interstate 80, June 2006

4. CLIMATE CHANGE AND VARIABILITY

4.1 EVIDENCE OF CLIMATE CHANGE

Two research bodies have produced reliable and extensive research on the issue of climate change: the Intergovernmental Panel on Climate Change (IPCC), which is the scientific body tasked by the United Nations to evaluate the risk of human-induced climate change; and the U.S. Climate Change Science Program (CCSP), which integrates Federal research on climate and global change, as sponsored by 13 Federal agencies and overseen by the Office of Science and Technology Policy, the Council on Environmental Quality, the National Economic Council, and the Office of Management and Budget. The issue of climate change has spurred research into almost every sector of society to examine adaptation to climate change impacts and ways of mitigating future climate change effects.

Most scientists now agree that climate change is largely a result of greenhouse gas emissions from human activities. The IPCC recently asserted that, “Most of the observed increase in global average temperatures since the mid-20th century is *very likely* [emphasis in report] due to the observed increase in anthropogenic greenhouse gas concentrations.”⁽³⁰⁾²

Some direct global evidence includes:

- Global temperatures have been increasing over the past century. The 100-year linear trend (1906–2005) is $0.13 \pm 0.03^\circ\text{F}$ per decade, while the corresponding 50-year linear trend of $0.23 \pm 0.05^\circ\text{F}$ per decade is nearly double that.⁽³¹⁾ Temperatures in the Arctic have increased more rapidly. Average Arctic temperatures have increased at about twice the global average rate in the past 100 years. Permafrost top layer temperatures have generally increased since the 1980s (about 5°F in the Arctic) while the maximum area covered by seasonal frozen ground has decreased since 1900 by about 7 percent in the Northern Hemisphere, with a decrease in spring of up to 15 percent.⁽³⁰⁾
- Over the past 50 years, extreme temperatures have been observed to change extensively in the form of hotter days and nights, and more frequent heat waves while cold days and nights, as well as frost, have become less frequent.⁽³³⁾
- Heavy precipitation events have increased in frequency over most land areas. This is due to an increase in average atmospheric water vapor content since at least the 1980s over land, ocean, and in the upper troposphere, largely consistent with air temperature increases.⁽³¹⁾
- Average temperatures of the oceans have increased since 1961 to depths of at least 10,000 feet, which causes sea levels to rise, as water expands when it warms. In addition, mountain glaciers, ice caps, and snow cover have declined on average, contributing to

² The IPCC uses standard terms to “define the likelihood of an outcome or result where this can be estimated probabilistically.” The term “very likely,” cited in italics above and elsewhere in this section, corresponds to a >90 percent probability of an occurrence or outcome, whereas the term “likely” corresponds to a >66 percent probability. These two terms are used in this section; a more expansive set of IPCC terminology regarding likelihood is used and defined in Section IV.E of the IPCC 4th Assessment Report.⁽³³⁾

further rise in sea level. Losses from the Greenland and Antarctica ice sheets have *very likely* [emphasis in report] contributed to sea level rise over 1993–2003.⁽³⁰⁾

- Global average sea level rose at an average rate of 0.07 ±0.02 inches per year over 1961–2003 with the rate accelerating in recent years (1992–2003) to about 0.12 ±0.03 inches per year. Total 20th-century rise is estimated at 0.56 ±0.16 feet.⁽³³⁾ However, these numbers are expected to dramatically increase, as land-based ice melt is not included in this calculation.⁽³⁴⁾

The IPCC concludes that, “At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns, and aspects of extreme weather including droughts, heavy precipitation, heat waves, and the intensity of tropical cyclones.”^(31, p. 7)

“Climate will have significant impacts on transportation, affecting the way U.S. transportation professionals plan, design, construct, operate and maintain infrastructure. Decisions made today will affect how well the system adapts to climate change far into the future.”—National Research Council, Transportation Research Board⁽³⁵⁾

As more details emerge about these trends and their potential impacts on society and possible adaptation strategies, there has been increasing realization that the overall effects, while global in nature, may have repercussions down to economic sectors, such as transportation and its individual modes. Specifically, there is concern that climate change and climate variability may potentially increase the frequency, duration, intensity, and location of certain types of weather events known to affect surface transportation modes, such as CMVs.

Although not the main focus of this report, it should be noted that transportation-based emissions from the combustion of fossil fuels have contributed about 14 percent to the buildup of atmospheric greenhouse gases over the past century. This is also called anthropogenic (caused by humans) change. Over the years, public debate about mitigation strategies—devising plans and technologies to reduce the level of greenhouse gases—increasingly encompasses discussions about adaptation measures (i.e., ways to prepare for and reduce the future impact of climate change on regional scales).

Fluctuations in local, regional, and national climate regimes occur at intervals ranging from periodic to irregular. Some of these processes, such as volcanic activity and the El Niño-Southern Oscillation (ENSO), are better understood than others, but most have some direct or indirect implications for transportation and CMVs. Some are naturally occurring conditions, while others are forcing mechanisms (e.g., a change in solar radiation or the atmospheric accumulations of greenhouse gases). Based on a combination of paleontological and historical records for the Northern Hemisphere, data archived by the National Academy of Sciences show the close relationship between temperature and atmospheric concentration of carbon dioxide over the past 1,000 years. Both have increased dramatically in the past decade or so (Figure 15). According to National Aeronautics and Space Administration (NASA) measurements,⁽³⁶⁾ the 8 warmest years on record have all occurred since 1998, and the 14 warmest years in the record have all occurred since 1990.

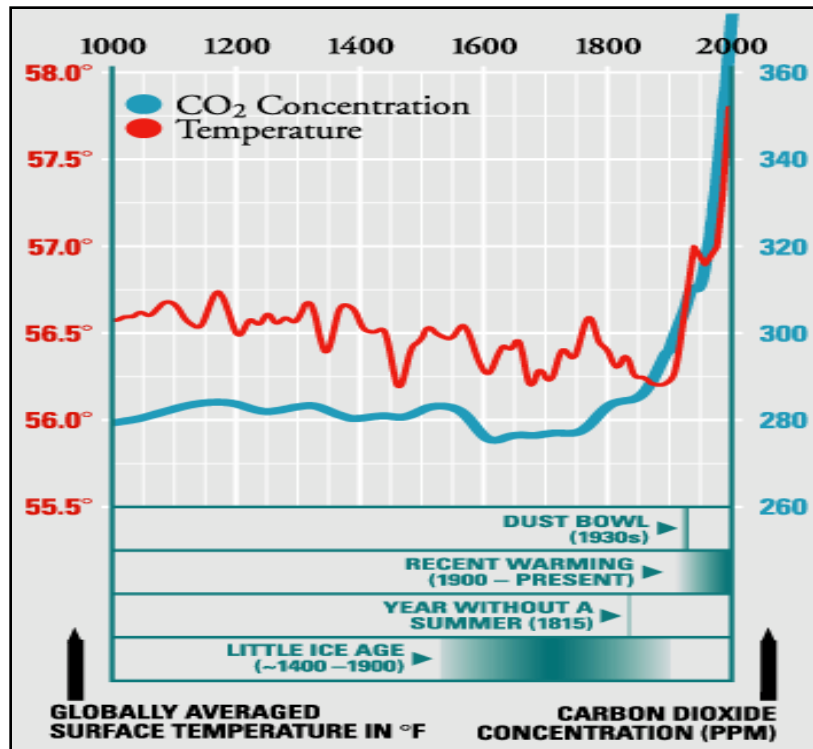


Figure 15. Northern Hemisphere Surface Temperature and CO₂, 1000 AD–2000 AD

Source: www.koshland-science-museum.org/exhibitgcc/historical03.jsp.

Climate models predict the future chemistry of the atmosphere, the response of the oceans, and the potential effects on broadly defined land areas. The IPCC and others have utilized 21 such models in performing their calculations and assessments of climate change. Models also predict potential large-scale atmospheric and hydrologic regimes within which day-to-day weather events occur. There are two general types of climate models:

- Seasonal to interannual (e.g., El Niño and other types of oscillations).
- Decadal to century (e.g., global warming studies/secular trends).

These models provide some lead information about general climatic conditions expected, and with some caution may be used to speculate about regional impacts or impacts on such sectors as transportation (Table 7).⁽³⁷⁾ These include:

- Changes in sea surface temperatures and major currents (from polar ice cap melt).
- Changes in ocean salinity levels (from melting ice).
- Changes in regional rainfall patterns that result in droughts or excessive precipitation.
- Warmer winters.
- Warmer nighttime.
- Increased cloudiness.

- Decreased snowfall.
- Increased storminess (overall higher amounts of heat energy can be converted into storminess or transferred to the oceans).
- Rising sea levels (when combined with more intense storms, this will allow battering waves to produce coastal erosion and destruction of infrastructure).

Table 7. Selected Climate Indices and their Potential Impacts on Transportation

Climate Influence	Description	Periodicity	Sample Effects on Climate	Sample Effects on Transportation
El Niño Southern Oscillation (ENSO)	Long-term changes in sea surface temperatures in the Pacific Ocean. Dominant southern jet stream results in warmer conditions, and heavy precipitation in the western U.S.	1–3 years.	<u>Warm phase</u> : flooding, storm tracks, violent weather, fewer Atlantic hurricanes. <u>Cold phase</u> : regional droughts, more Atlantic hurricanes.	Pacific coastal infrastructure exposed to stronger storms, heavy precipitation, high winds and waves. Heavy snows in Sierras and Rockies.
North Atlantic Oscillation	Long-term pressure changes over the Atlantic Ocean.	Broadband spectrum with no significant dominant periodicity.	<u>Positive phase</u> : milder, wetter, East Coast winters. <u>Negative phase</u> : colder, snowier winters in eastern States.	More frequent episodes of difficult travel conditions. Colder temperatures may result in price increases for fuels.
Arctic Oscillation	Changes in pressure patterns of polar vortex.	Broadband spectrum with no significant dominant periodicity.	<u>Positive phase</u> : milder U.S. winters. <u>Negative phase</u> : Colder winters.	More frequent winter travel conditions.
Pacific Decadal Oscillation	A cycle of long-term variability of sea surface temperatures in the North Pacific Ocean.	23–30 years.	<u>Warm phase</u> : warmer, drier winters in northern States; wetter and cooler in the South. <u>Cold phase</u> : colder, snowier condition in the eastern U.S., warmer in the West and Alaska.	Cold phase makes transportation more difficult in northern areas.
Pacific-North American Teleconnection	A strong trough and ridge pattern over the North Pacific Ocean and North America.	4 years.	Warmer conditions in western U.S, more polar outbreaks and storms in the East.	Similar to negative Arctic oscillation.
Global warming from greenhouse gases: carbon dioxide, black carbon, and methane	Combustion of fossil fuels results in higher levels of carbon dioxide, methane, black carbon, and particulates.	Secular trend.	Rising sea levels, warmer and wetter conditions, more frequent and intense storms.	Coastal infrastructure at risk (ports, airports, roads, rail).
Solar activity	Geomagnetic storms, solar radiation and radio blackouts.	Sunspot cycles every 11 years, and random events.	Periodic, long-term effects (e.g., “Little Ice Age”).	Affects navigation and communication grids.
Volcanic activity	Large volume ejection of particles into upper atmosphere.	n/a.	Reduced sunlight causes cooling.	Air traffic affected by volcanic ash, more winter-like conditions.

Because the same processes that change climate may affect short-term weather events, it may be possible to use seasonal or interannual oscillations, or long-term secular trends, to anticipate future changes in the distribution and profile of weather events. Intrinsic skill levels for weather forecasts have generally improved over the past 2 decades, thus input from climate knowledge

may help local forecasters at the margin, particularly in situations where short-term models disagree on things such as storm tracks and intensity, or the likelihood of severe convection.

Although the reliability of regional-scale climate and weather predictions is still low and the degree to which climate variability may increase remains uncertain, potentially serious changes have been identified. These changes include increases in some regions in the frequency and intensity of extreme weather events, such as high temperature waves, droughts, floods, sea levels, and storm tides. Over time, these forces could potentially jeopardize portions of the U.S. roadway system, the operating efficiency of vehicles, and the performance of drivers.

In this regard, the vulnerability of CMVs to climate change arises mainly from their susceptibility to sudden unforeseen changes in weather or climate patterns and from potential increases in the intensity and frequency of extreme weather events. Analysis of the potential effects of climate change and variability on CMVs must also distinguish between their potential effects on road infrastructure, operations, vehicles, and human factors. CMV infrastructure includes all physical capital infrastructure elements of freight. CMV operations and all recurring activities related to the movements of goods. Vehicles include the overall structures, components, and subcomponents of trucks and buses. Human factors include CMV drivers, passenger vehicle drivers and auxiliary personnel involved in shipments.

4.2 RECENT STUDIES

The IPCC, the CCSP, the NRC, and other groups have published studies that provide further information on the impacts of climate change and variability, and possible adaptation strategies by various economic sectors. Running throughout these reports are themes that suggest strong ties between human activity and global warming, the impact of that warming on climate systems and different classes of weather events, and the need to begin planning for adaptation and accommodation. At their present pace, these changes are likely to occur gradually enough to allow transportation and other sectors enough leeway to redesign infrastructure at risk, and to implement stricter mitigation strategies to control greenhouse gas emissions. The reports also state the smaller chance, however, that these changes could accelerate and force us to adapt within a shorter period.

4.2.1 Intergovernmental Panel on Climate Change (IPCC)

The IPCC was founded in 1988. It produced its First Assessment Report in 1990; its Fourth Assessment Report⁽³²⁾ was published in 2007. In its discussion of adaptation options for the transportation sector, the IPCC emphasizes options based on realignment and relocation strategies, including design standards and planning for roads, railroads, and other infrastructure to cope with warming and drainage (Table 8). The Fourth Assessment Report has stronger language than its earlier versions, with the IPCC now using such phrases as, “warming of the climate system is unequivocal.” Further, the Fourth Assessment Report delves into regional impacts of climate change, many of which may have implications for CMVs during the next several decades. Table 9 lists a sample of such projected impacts for North America.⁽³³⁾

Table 8. IPCC Fourth Assessment Report Projections of Climate Changes

Degree of Confidence Likely	Degree of Confidence Very Likely	Degree of Confidence Virtually Certain
Areas affected by drought increases.	Frequency of warm spells/heat waves increases over most land areas.	Over most land areas, warmer and fewer cold days and nights; warmer and more frequent hot days and nights.
Intense tropical cyclone activity increases.	Frequency of heavy precipitation events increases over most areas.	
Increased incidence of extreme high sea levels (excluding tsunamis).		

4.2.2 Climate Change Science Program

The CCSP, in conjunction with the USDOT’s Center for Climate Change and Environmental Forecasting, published a study in 2008 that is relevant to CMVs: *Impact of Climate Change and Variability on Transportation: Gulf Coast Study*.⁽⁵⁾ This report, one of 21 assessment studies conducted by the CCSP, provides a review of the literature on the impact of climate change on transportation. It also provides a detailed analysis of how climate-induced changes in sea levels, storm surge, land subsidence, more severe hurricanes, and precipitation patterns might interact to compromise the transportation infrastructure along the central coast of the Gulf of Mexico (Galveston, TX to Mobile, AL).

Table 9. IPCC Projections for Climate Change and Impacts in North America

North American Impacts
Warming in western mountains is projected to cause decreased snowpack, more winter flooding and reduced summer flows, exacerbating competition for over-allocated water resources.
In the early decades of the century, moderate climate change is projected to increase aggregate yields of rain-fed agriculture by 5% to 20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or which depend on highly utilized water resources.
Cities that currently experience heat waves are expected to be further challenged by an increased number, intensity and duration of heat waves during the course of the century, with potential for adverse health impacts.
Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution.

The central Gulf Coast is a unique area from an economic, transportation, and meteorological point of view. The region represents the crossroads and major nexus of transshipment of grains, petroleum, and other cargo not only cross-country east-west but also north-south between the inland Mississippi, Missouri, Tennessee, and Ohio River valleys and oceanic destinations. It includes a network of interstate highways, long-haul railroads, barge operations, oil and gas pipelines, airports, and intermodal terminals. The area also lies within a zone of characteristic tracks for tropical cyclones, with the region of southwest Louisiana especially vulnerable (see historical tracks in Figure 16). Commercial motor vehicles operate extensively within the central Gulf Coast.

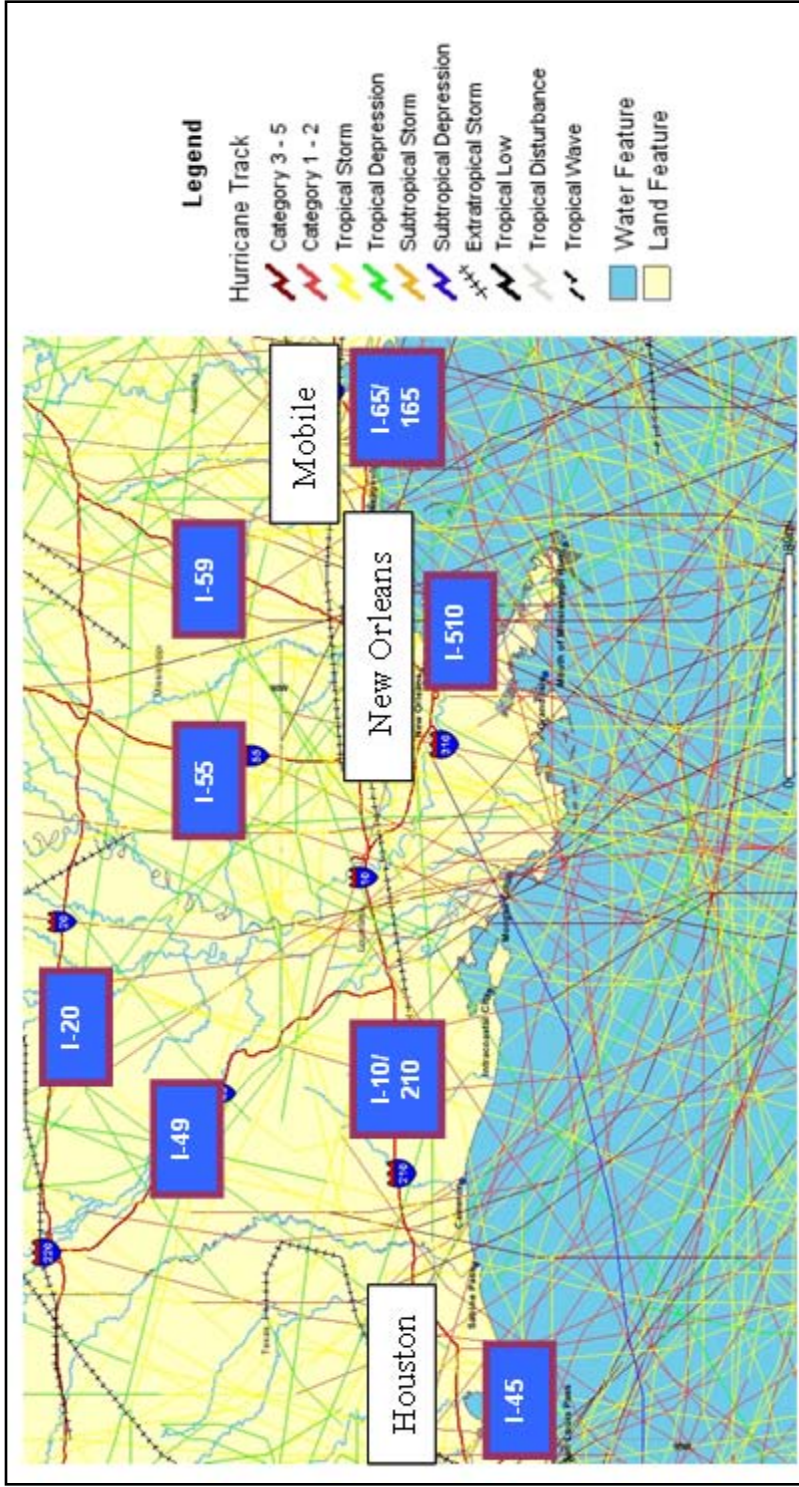


Figure 16. Tracks of Tropical Cyclones in the Central Gulf Coast, 1851–2006

Source: <http://maps.csc.noaa.gov/hurricanes/viewer.html>.

The Gulf Coast report is informative for assessing other areas of the country that have combinations of heavy transportation networks and vulnerable coastlines. This includes locations such as New York City, Long Beach, Norfolk, Seattle, and Boston. Although the compounding effect of land subsidence may not be as problematic as it is in the central Gulf Coast region, these other sites have greater susceptibility to large extratropical systems, and may also experience the disruptive effects of more frequent flooding incidents under climate change scenarios.

Rising sea levels projected under climate change present another threat. Even slight rises in sea levels may exacerbate storm effects and cause major coastal flooding, if such storms occur at times of astronomically high tides, are accompanied by a storm surge, large battering waves, or all three of these conditions. Further vulnerability exists on the Atlantic Coast from the prospect of more intense or more frequent hurricanes in conjunction with higher sea surface temperatures.⁽³⁸⁾ Within the Washington, DC–Boston metroplex, it has been almost 50 years since the last major hurricane and more than 70 years since the Great New England Hurricane of 1938. Since that time, the transportation infrastructure has grown substantially with increasing exposures of both property and populations to severe storms.

The CCSP published another major study in 2008, *Weather and Climate Extremes under Climate Change*.⁽³⁹⁾ As discussed later, scientists are concerned that a warming climate will provide additional fuel for the generation of extreme weather events, such as high-intensity rainfall in areas unaccustomed to such storms, an increase in the frequency and intensity of tropical cyclones, and heat waves and droughts of long duration. In regards to increased intensity of non-tropical systems, the evidence (while still inconclusive), suggests that a warming climate may also produce environmental conditions conducive to more frequent, severe thunderstorms,⁽²⁰⁾ which are at times accompanied by tornadic activity, large hail, and intense straight-line winds. The strongest types of thunderstorms and tornadoes also may occur more often.⁽⁴⁰⁾

“Extreme precipitation episodes (heavy downpours) have become more frequent and more intense in recent decades over most of North America and now account for a larger percentage of total precipitation. For example, intense precipitation (the heaviest 1 percent of daily precipitation totals) in the continental U.S. increased by 20 percent over the past century while total precipitation increased by 7 percent” -U.S. Climate Change Science Program, 2008⁽⁵⁾

The potential impact of climate change on U.S. winter storms is not yet known. In general, a warming climate is expected to produce a shorter winter season, a northward progression of snow cover, a thinner snow cover, a change in storm tracks further west and north, and more types of events featuring wintry mixes, including freezing rain. A 2006 study⁽⁸⁾ indicates that warmer minimum temperatures in northern winters may increase the likelihood of conditions conducive to ice, rather than snow events, but as of yet little or no data support this hypothesis.

Overall, fewer snowstorms are expected, but perhaps an increased frequency of high intensity snowstorms due to greater available heat energy. Examining NOAA/NCDC data on annual

snowfall compared to normal snowfall over the period from 1960 to 2009 shows a discernible trend towards less snow cover, a northward progression of snow cover, and less severe intrusions of arctic air masses into the continental U.S. During the most of the 1960s, extensive snow cover occurred into the Deep South. With few exceptions (e.g., 1977–1978 and 1995–1996) for each succeeding decade since then, the geographic extent has diminished.³

4.2.3 National Research Council

A 2008 study by the TRB of the potential impacts of climate change on transportation infrastructure found that society could expect a greater than 90 percent chance of increases in very hot days and heat waves.⁽³⁵⁾ This would have significant influences on the vulnerability of vehicles, drivers, and infrastructure to extremes of heat.

“Transportation practitioners need to be able to articulate the types of climate data and model projections that will be relevant. What information could lead a public or private transportation agency to change a transportation investment plan, road location, or facility design?” -U.S. Climate Change Science Program, 2008⁽⁵⁾

The TRB report focused primary attention on potential impact of climate change on the physical infrastructure of the transportation system, including roads, bridges, railroad track, airports, and related facilities. The report covers all transportation modes, but its sections on highways are pertinent to the potential impacts of climate change on CMVs, and subsequent adaptation options (see Appendix A). It categorizes potential climate changes into the following general areas:

- Increases in very hot days and heat waves.
- Increases in drought conditions for some regions.
- Decreases in very cold days.
- Later onset of seasonal freezes and earlier onset of seasonal thaws.
- Rises in sea level added to storm surge.
- Increases in intense precipitation events.
- Changes in regional precipitation and river flow patterns.
- More frequent strong hurricanes.

These conditions are capable of degrading and destroying transportation infrastructure, and may affect the manner in which transportation operations take place in various regions and corridors.

³ The NCDC maintains these data as part of its *U.S. Snow Monitoring: Historical Monthly & Seasonal Snowfall Maps*. Estimates in the text come from the author’s calculations of U.S. seasonal snowfall as percent of normal for the past 4 decades. See the NCDC Snow Monitoring site at <http://gis.ncdc.noaa.gov/snowfallmo/>.

4.3 CLIMATE CHANGE AND EXTREME WEATHER EVENTS

It is important to note that potential shifts in weather patterns are only one result of a change in the chemical composition of the atmosphere induced by higher concentrations of CO₂ and other greenhouse gases. This report only examines climate variability and climate change in the context of changes in weather that could affect CMV safety.

Since the mid-1970s, the mean surface temperature of the planet has risen, reaching levels last observed in the mid-1930s. Mean annual precipitation also increased markedly during this same period. Both of these trends—increased temperature and precipitation—are consistent with projections of global circulation models as reported by the IPCC and others. The IPCC and other researchers now indicate that the planet is getting warmer due to anthropogenic increases in greenhouse gases. Further, global warming is beginning to impact regional weather patterns and thus weather-sensitive sectors of the economy.⁽⁴¹⁾

Even after adjusting for the effects of inflation, some of the largest cost damages from weather-related disasters in U.S. history have occurred in the past few decades (Figure 17).

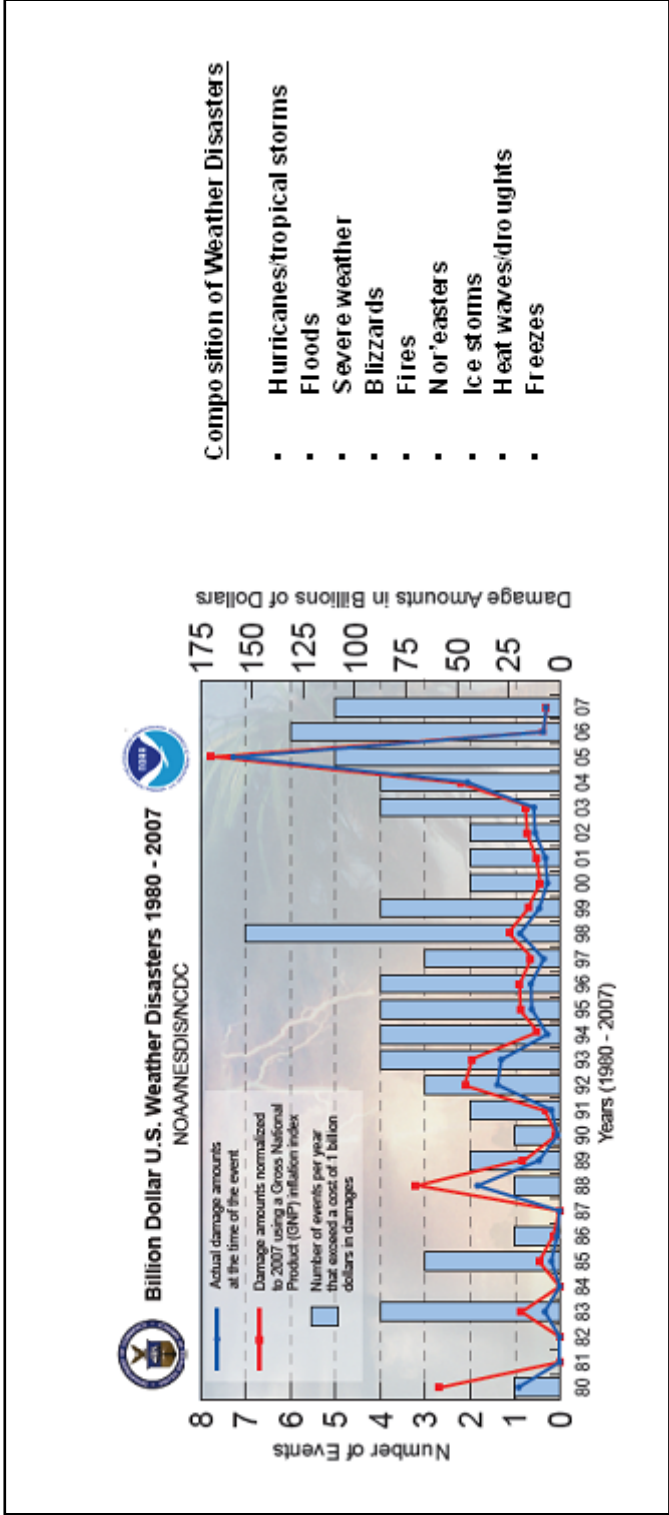


Figure 17. Evidence of Extreme Events: Billion Dollar U.S. Weather Disasters, 1980–2007
 Source: www.ncdc.noaa.gov/oa/reports/billionz.html.

The U.S. Climate Extremes Index (CEI) was established in 1996 to summarize and present a complex set of multivariate and multidimensional climate changes in the U.S. It was designed to answer such questions as: how has the climate changed over the past 50 or more years; in what ways has it changed; and by how much has it changed. The index, developed by the NCDC, derives from a statistical analysis of monthly mean temperatures, daily precipitation, the Monthly Palmer Drought Severity Index, and tropical cyclone activity. Each indicator is based on its reliability, length of record, availability, and its relevance to changes in climate extremes. The CEI indicates a trend toward an increased amount of extreme weather events from the period beginning in the mid-1970s to 2008 (Figure 18). This reversed a slight downtrend observed in the period from about 1910 to 1970. Some scientists have recently advanced evidence that extreme events, such as thunderstorms and hurricanes, will increase in frequency or intensity within the context of global warming scenarios.^(20,38)

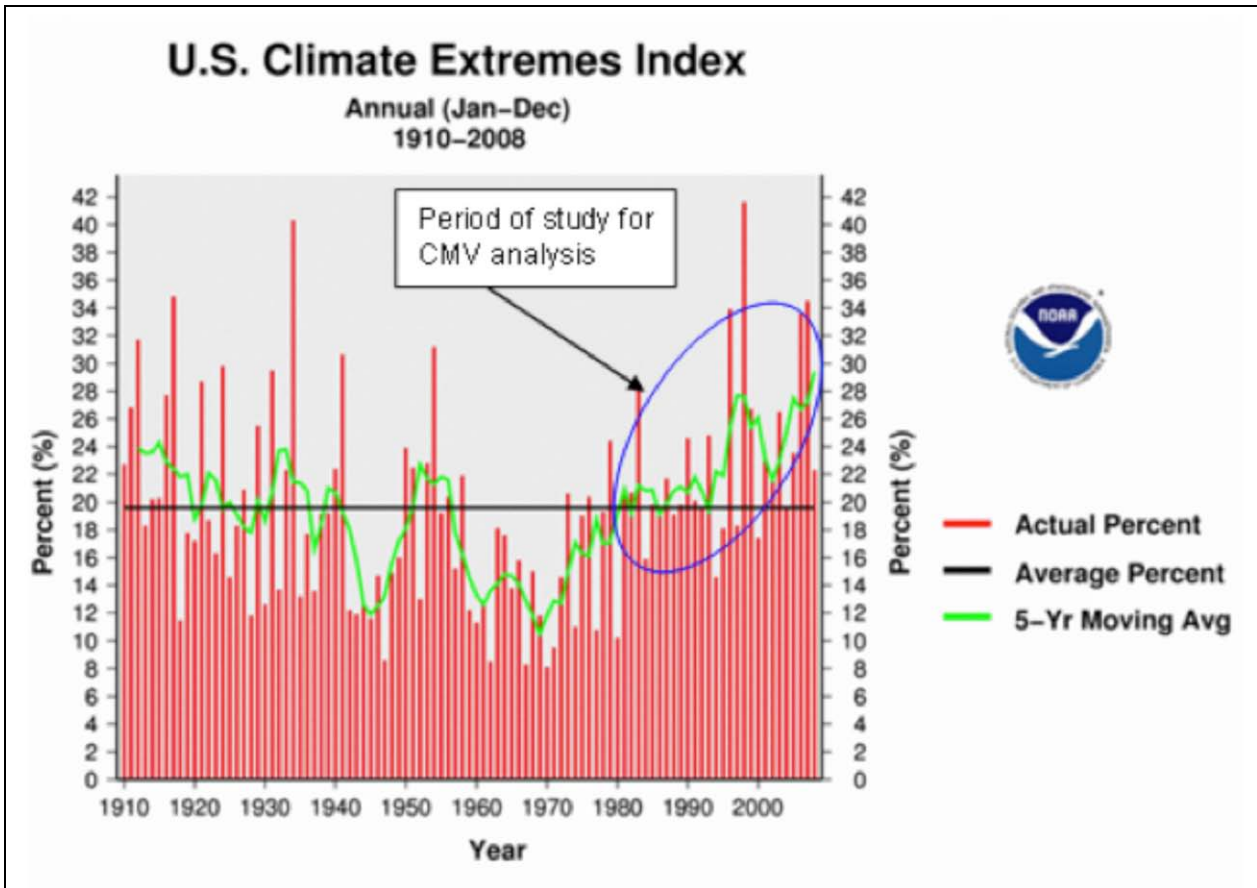


Figure 18. The U.S. Climate Extremes Index, 1910-2008
 Source: www.ncdc.noaa.gov/oa/climate/research/cei/cei.html.

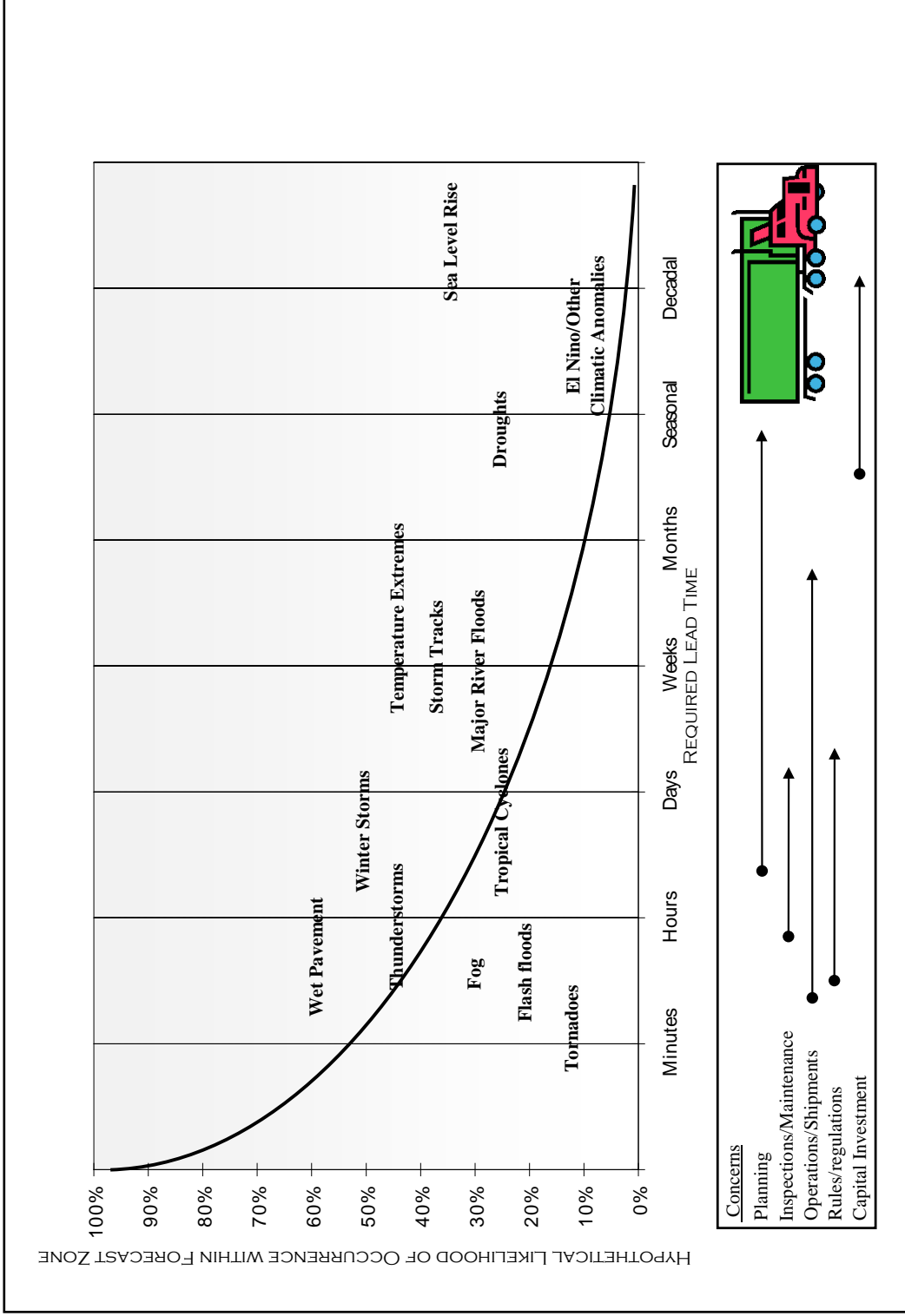


Figure 19. Weather and Climate Events, Hypothetical Forecast Likelihood and Lead Times Required by CMVs

Developed by Michael Rossetti and Mike Johnsen

Table 10. Climate Scenarios and Potential Impacts on CMVs

Region	Possible Climate Scenarios	Potential CMV Impacts
Northeast	<ul style="list-style-type: none"> • Higher winter temperatures, especially in coastal areas. • Shorter snow season/less extended cold in winter. • Modest increases in summer temperatures. • More variable precipitation for coastal areas. • Sea level rise and elevated storm surges. • Storms more intense. • More flood episodes. 	<ul style="list-style-type: none"> • Stresses on road and port infrastructures from thaw-freeze cycles and coastal flooding. • Extreme event storms, more situational delay. • Less vehicle stress from extreme cold and snow. • Less winter-related disruption. • Increased exposure safety risks from severe events.
Southeast	<ul style="list-style-type: none"> • Higher temperatures. • Reduced soil moisture. • Increased risk of fires. • Agricultural dislocations. • Sea level rise and coastal flooding. • More frequent/intense hurricanes. • Less extended cold in winter. 	<ul style="list-style-type: none"> • Heat stresses on vehicles, drivers, and cargo. • More episodes of reduced visibility/road closures from smoke. • Crop-specific changes in freight distribution patterns. • Stresses on roads and transportation infrastructure from coastal flooding/wave battering and extended heat waves. • Increased exposure and safety risks from severe events.
Midwest	<ul style="list-style-type: none"> • Warmer temperatures. • Shorter snow season. • Increases in heavy precipitation events/flash flooding. • Reduced soil moisture. • Increased risk of fires. • More risk of both high and low water levels on rivers. • Lower water levels and less ice on Great Lakes. • Agricultural shifts. 	<ul style="list-style-type: none"> • Intermodal disruptions and mode diversion from low water levels. • Heat stresses on infrastructure, vehicles, drivers and cargo. • Increased safety risks from extreme events. • Crop-specific changes in freight distribution patterns. • More episodes of reduced visibility/road closures from smoke and dust. • Less vehicle stress from extreme cold. • Increased exposure from severe events. • Intermodal disruptions from intermittent impacts on barge traffic.
Great Plains	<ul style="list-style-type: none"> • Higher temperatures throughout region, with largest increases in northern and western areas. • Shorter snow season. • Precipitation increases, except in less of Rockies. • Reduced soil moisture. • Increased risk of drought conditions. 	<ul style="list-style-type: none"> • Increased exposure and safety risk from severe events. • Less vehicle stress from extreme cold and snow. • More episodes of reduced visibility/road closures from smoke and dust. • Heat stresses on infrastructure, vehicles, drivers, and cargo. • Crop-specific changes in freight distribution patterns.

West	<ul style="list-style-type: none"> • Warmer summer temperatures. • Increases in extreme precipitation events. • More extreme wet and dry years. • Increased winter precipitation in California. • Greater potential for flooding due to runoffs. • Increases in average precipitation. • Higher risk of fires. 	<ul style="list-style-type: none"> • Increased exposure and safety risks from extreme events. • Stresses on road infrastructure from heat, flash flooding/erosion. • Extreme event storms, more situational delay. • More episodes of reduced visibility/road closures from smoke and dust. • Heat stresses on vehicles, drivers, and cargo. • Crop-specific changes in freight distribution patterns.
Pacific Northwest	<ul style="list-style-type: none"> • Shorter snow season/earlier snowmelt. • Sea level rise/coastal erosion. • Wetter winters/drier summers. • Increased risk of fires. • Increases in extreme precipitation events. 	<ul style="list-style-type: none"> • Stresses on road and port infrastructures from coastal flooding/wave battering/erosion. • Less vehicle stress from extreme cold and snow. • Increased exposure/safety risks from severe events. • More episodes of reduced visibility/road closures from smoke. • Intermodal disruptions in winter from high water levels on rivers.

Source: U.S. Global Climate Change Research Program, 2009⁽³¹⁾

5. CONCLUSIONS

This paper has examined different types of weather events as safety risk factors in CMV crashes, including the possible role of climate change in altering the distribution, frequency, or severity of those weather events. A growing body of scientific literature supports the idea that the Earth has generally warmed during much of the past 100 years. International groups, such as the IPCC, national entities, the CCSP, and TRB, have all published studies that describe the details of these trends and their potential societal impacts, including those on the transportation sector.

CMVs are different from other vehicles with respect to weather and weather-related crashes. They have greater mass and thus a greater release of kinetic energy during a crash. They require longer stopping distances compared to other motor vehicles. CMVs also have different trip characteristics than other types of motor vehicles, and these characteristics may expose them to different types of weather conditions while operating on our Nation's highways.

5.1 THE EFFECTS OF WEATHER AND CLIMATE

Weather influences the safety of CMVs in different ways. Adverse weather and consequent conditions, such as wet pavement, impaired visibility, heavy precipitation, frozen precipitation, flooding, high winds, and extremes of temperature act in various ways to increase risks to CMV drivers and their vehicles, as well as to the infrastructure. Heavy trucks and buses also require greater stopping distances on wet pavement. Road spray further impairs visibility. The national highway system, CMVs, and CMV operators also face potential exposure to changes in weather or climate patterns and from potential changes in the intensity and frequency of extreme weather events.

Rainfall and wet pavements are the most common type of adverse weather-related issues that affect CMVs. More than 60 percent of all weather-related fatalities occur in rainy conditions. Heavy snow causes delays, road closures, loss of traction, loss of visibility, and other driver-control problems. Snow squalls that move quickly over highways are an important cause of crashes and fatalities for CMVs and other types of motor vehicles. About 12 percent of fatal weather-related crashes occur in fog conditions. Fog and low visibility may increase the stopping distances required to avoid a crash.

Winds greater than 25 mi/h can inhibit the maneuverability and stability of CMVs, particularly in exposed areas, such as interstate highways. Wind hazards may occur from crosswinds, headwinds, and tailwinds. CMVs are vulnerable to temperature extremes; prolonged episodes of heat and cold can degrade both the safety and performance characteristics of CMVs.

Drought conditions may also harm CMVs operations through intermodal connections. Low water causes barges to run aground, resulting in delayed or diverted shipments. Strong storms may cause coastal flooding and damage to road infrastructure; these effects may gradually worsen if sea levels rise as projected by climate change studies.

Climate change may produce more episodes of excessive heat, intense precipitation and flooded roadways, which could impose added stresses on drivers and vehicles. Certain regions may

experience an increase in the number of days when the ambient atmosphere is more saturated, thus leading to an increase in the number of days with fog and impaired visibility. Transportation networks along coastal zones could intermittently experience the effects of rising sea levels, particularly during times of astronomically high tides, storm surges, major coastal flooding, and wave battering from large extratropical storms and hurricanes. In future years, climate variability and climate change may increase both the number of good-weather days and the number of extreme-weather days for CMV travel. Climate variability or climate change may result in economic benefits from milder temperatures, but may also produce economic losses from increases in the frequency and intensity of extreme events.

5.2 TRENDS IN WEATHER-RELATED FATAL CRASHES

Overall, fatal weather-related crash data from the FARS show a declining trend from 1975 to the present, with a recent leveling off. When normalized by VMT, this 30-year trend shows fewer weather-related, fatal CMV crashes. This trend provides encouragement for efforts to make highway travel less sensitive to adverse weather. The long-term trend may be indicative of the effects of many forces, such as benefits stemming from the NWS modernization program, advances in weather forecasting, vehicular improvements and technology, the introduction of intelligent transportation system technologies, changes in CMV traffic patterns, or possibly changes in the frequency or distribution of weather events. Since about 2002, the decline has leveled off. If data reporting is consistent, this may indicate that there could be a minimum number of weather-related crashes that will occur over which the FMCSA and other agencies have little control or that weather events that contribute to CMV crashes are becoming more frequent or severe, or are affecting a larger number of CMVs.

Normalized for VMT, northern-tier States exposed to winter conditions, such as the Dakotas, Montana, Wyoming, and Vermont, rank among the highest in terms of weather-related fatal crashes per 100 million VMT. The list also includes States such as West Virginia, Kentucky, Arkansas, and Alabama. Clustering of crashes is associated with rain and wet pavement through the mid-Atlantic region, the Pacific Northwest, and parts of Florida. For winter conditions, some clustering is apparent in locations, such as the lee of the Great Lakes (lake effect snows), the Continental Divide in Wyoming, and along the Cascade Mountain Range in Oregon. Clustering also occurs with respect to fog and other types of impaired visibility, with concentrations in the central and southern valley areas of California, the Pacific Northwest, the central Appalachian Mountains, and much of Florida. On a broader scale, higher concentrations of fatal weather-related CMV crashes appear to exist in the major interstate corridors of the East, the Midwest, and California. For example, Interstate 80 shows concentrations of weather-related fatal crashes, including a diversity of winter and non-winter events, and wet pavement events.

5.3 RECOMMENDATIONS

Based on the finding set forth in this report, it is recommended that FMCSA:

- (1) Examine trends and factors in weather-related CMV crashes, particularly in those Interstate corridors that are vulnerable both to adverse weather and to increasing exposure due to climate change.

(2) Review potential actions within its jurisdictional realm that could reduce weather-related crashes (e.g., the agency's strategy might include expanded driver training and education programs aimed at operating CMVs in inclement and occasionally extreme weather conditions).

(3) Consider expanded research into the role of human factors in responding to adverse weather conditions (e.g., research into the effects of long duration weather events on physical abilities, driver fatigue, and concentration).

(4) Determine how to facilitate the delivery and interpretation of weather information into the vehicles by studying potential integration of weather information into CMV telematics technologies, and develop applications that utilize radar technologies and decision support systems to aid CMV operators, dispatchers, and other interested parties.

(5) Review possible modifications or waivers to existing CMV rules pertaining to weather. FMCSA rules currently limit the number of hours of service permitted for CMV drivers; exceptions are based on extenuating weather conditions. In addition, States sometimes grant temporary waivers (e.g., when drivers are hauling relief supplies into a flood-stricken area, such as during Hurricane Katrina). If these events become more common, FMCSA may need to develop further regulations, policies, training, and guidance for CMV drivers on weather-related disaster relief actions.

(6) Examine a select set of geographic highway-based coordinates for weather-related crashes by association with GIS layers of highway segments and intersections. This effort might involve a review of weather factors that reduce CMV safety (e.g., road wetness, impaired visibility, heavy precipitation, snowfall, crosswinds, etc.) and automate the extraction of relevant weather data that would provide the basis for the GIS-based analyses. The approach could include reanalysis of past crashes, looking at data from nearby weather stations, the application of archived Next Generation Radar (NEXRAD) Doppler radar data, satellite imagery, and other data. One product of the corridor analysis might be the FMCSA encouraging the development of a model to predict CMV crashes based on VMT under different weather conditions along the selected routes. The information derived from this effort could identify and classify weather-related risks associated with the selected corridors, and thus assist the FMCSA in improving CMV safety.

(7) Conduct additional research into isolating the effects of weather from other crash factors, exploring other ways to normalize existing data. This includes examining differences between weather-related crashes on toll roads and non-toll roads, and the effects of travel direction—movement with, from, or into weather. In order to improve the quality of data required for analyzing CMV weather-related crashes, the FMCSA could coordinate its weather reporting needs with National Highway Traffic Safety Administration (NHTSA) when there is an opportunity to modify the FARS.

(8) Study how existing vehicle deficiencies such as low tire pressure or worn brakes, are exacerbated by weather conditions (which may only be a contributing factor) that increase the potential for a crash.

(9) Educate drivers and motor carriers on the potential use of weather and climate data for planning, investment, and other policy measures.

(10) Move forward toward decision-making on climate approaches, both individually and with other agencies.

5.3.1 Role of New Technology

For CMV applications, the concept of telematics refers to onboard computing through wireless communications, land location, and communications technology for a range of applications. These features include navigation, vehicle and driver monitoring, automated routing, roadside assistance, and traveler information. Telematics technology also allows drivers to both receive and send real-time, and get weather forecast information for points along a route.

Major automakers are equipping new prototype vehicles with wireless-based services controlled by voice commands, which could enable motorists to access the Internet, receive or send email, download digital audio and video files, or obtain “smart” transportation information. * A vehicle’s telematics control unit usually works with the vehicle’s electronic/engine control module to transmit information about vehicle subsystems. Many large trucks also have event data recorders that work in conjunction with the electronic/engine control module. The modules record and store data about vehicle trips and provide information for analysis of vehicle safety, performance, and reconstruction of crashes. The telematics control unit interfaces with wireless and satellite networks to send and receive information from service providers about the vehicle, driver, and environment.

The growing use of and features of telematics equipment is part of the USDOT Vehicle IntelliDriveSM initiative (formerly known as the Infrastructure Integration [VII] initiative). This initiative represents an integrated communications infrastructure that supports both vehicle-to-vehicle and vehicle-to-infrastructure communications. It incorporates vehicle data, such as ambient temperature, dew point, wiper state, rain sensor, lights (fog and headlights), accelerometer, anti-lock braking system, traction control, stability control, sun sensor, and driver assist systems. It addresses major goals related to transportation safety, mobility, and commerce, and is a new method of delivering and receiving microscale weather information using dedicated short-range communications frequencies. Extending IntelliDriveSM to include CMVs, would enable drivers and weather providers to send and receive real-time vehicle data and utilize it to better quantify the weather risks associated with specific types of routing and scheduling. These data include both functional information about the vehicle and driver performance and weather information from onboard telemetry readings about local atmospheric and pavement conditions.⁽⁴³⁾

5.4 SUMMARY

There are several possible benefits of improved CMV weather and climate information. These include improved safety; improved decision making for routing and scheduling; better performance for the vehicle, driver and infrastructure; better information for forensic investigation and crash event reconstruction; enhanced research, training, and education; more accurate economic impact analysis; and more research into the role of human factors, including driver health and wellness. Climate variability and climate change, changes in transportation

* http://searchnetworking.techtarget.com/sDefinition/0,,sid7_gci517744,00.html.

management and vehicle technology, and changes in infrastructure may bring about changes in future operating environments. CMV carriers, dispatchers, and drivers will have access to enhanced weather information that will provide benefits to their vehicles, general traffic conditions, road surfaces, and driver responses to various weather phenomena. Improved dissemination technology, better training, and protocols that improve the skill of drivers in adverse weather and wet pavement will help to realize the value of this information and the benefits it produces.

**APPENDIX A:
CLIMATE CHANGE, HIGHWAYS, AND ADAPTATION OPTIONS—(TRB REPORT 290)**

Potential Climate Change	Impacts on Highways			Adaptation Options	
	Operations and Interruptions	Infrastructure	Changes in Operations	Changes in Infrastructure Design/New Materials	Other
Increases in very hot days and heat waves (>90% chance of occurrence).	<ul style="list-style-type: none"> • Limitations on periods of construction activity due to health and safety concerns; restrictions typically begin at 29.5°C (85°F); heat exhaustion possible at 40.5°C (105°F). • Vehicle overheating and tire deterioration. 	<ul style="list-style-type: none"> • Impacts on pavement and concrete construction practices. • Thermal expansion on bridge expansion joints and paved surfaces. • Impacts on landscaping in highway and street rights-of-way. • Concerns regarding pavement integrity, e.g., softening, traffic-related rutting, migration of liquid asphalt; sustained air temperature over 32°C (90°F) is a significant threshold. 	<ul style="list-style-type: none"> • Shifting construction schedules to cooler parts of the day. 	<ul style="list-style-type: none"> • Development of new, heat-resistant paving materials. • Greater use of heat tolerant street and highway landscaping. 	
Decreases in very cold days.	<ul style="list-style-type: none"> • Regional changes in snow and ice removal costs and environmental impacts from salt and chemical use (reduction overall, but increases in some regions). • Fewer cold-related restrictions for maintenance workers. 	<ul style="list-style-type: none"> • Decreased utility of unimproved roads that rely on frozen ground for passage. 	<ul style="list-style-type: none"> • Reduction in snow and ice removal. • Extension of construction and maintenance season. • Shortening of season for use of ice roads. 		

Potential		Impacts on Highways		Adaptation Options	
Later onset of seasonal freeze and earlier onset of seasonal thaw.	<ul style="list-style-type: none"> Changes in seasonal weight restrictions. Changes in seasonal fuel requirements. Improved mobility and safety associated with a reduction in winter weather. Longer construction season. 	<ul style="list-style-type: none"> Reduced pavement deterioration resulting from less exposure to freezing, snow, and ice, but possibility of more freeze-thaw conditions in some locations. 	<ul style="list-style-type: none"> Relaxation of seasonal weight restrictions. Shortening of season for use of ice roads. 		
Sea level rise, added to storm surge (>99% chance of occurrence).	<ul style="list-style-type: none"> More frequent interruptions in travel on coastal and low-lying roadways and rail service due to storm surges. More severe storm surges, requiring evacuation. 	<ul style="list-style-type: none"> Inundation of roads in coastal areas. More frequent or severe flooding of underground tunnels and low-lying infrastructure. Erosion of road base and bridge supports. Bridge scour. Reduced clearance under bridges. Loss of coastal wetlands and barrier shoreline. Land subsidence. 		<ul style="list-style-type: none"> Elevation of streets and bridges* Addition of drainage canals near coastal roads. Elevation and protection of bridge and tunnel entrances. Additional pumping capacity for tunnels. 	<ul style="list-style-type: none"> Relocation of sections of roads inland. Protection of high value coastal real estate with levees, seawalls, and dikes. Strengthening and heightening of existing levees, seawalls, and dikes. Restriction of most vulnerable coastal areas from further development. Increase in flood insurance rates to help restrict development. Return of some coastal areas to nature.

Potential	Impacts on Highways			Adaptation Options
<p>Increases in intense precipitation events (>90% chance of occurrence).</p>	<ul style="list-style-type: none"> Increases in weather related delays. Increases in traffic disruptions. Increased flooding of evacuation routes. Disruption of construction activities. Changes in rain, snowfall, and seasonal flooding that impact safety and maintenance operations. 	<ul style="list-style-type: none"> Increases in flooding of roadways and tunnels. Overloading of drainage systems, causing backups and street flooding. Increases in road scouring, road washout, and landslides and mudslides that damage roadways. Impacts on soil moisture levels, affecting structural integrity of roads, bridges, and tunnels. Adverse impacts of standing water on road bases Increases in scouring of pipeline roadbeds and damages to pipelines. 	<ul style="list-style-type: none"> Expansion of systems for monitoring scour of bridge piers and abutments. Increase in monitoring of land slopes and drainage systems. Increases in real-time monitoring of flood levels. Integrating emergency evacuation procedures into operations. 	<ul style="list-style-type: none"> Protection of critical evacuation routes. Upgrading of road drainage systems. Protection of bridge piers and abutments with riprap. Increases in culvert capacity. Increases in pumping capacity for tunnels. Addition of slope retention structures and retaining facilities for landslides. Increases in the standard for drainage capacity for new transportation infrastructure and major rehabilitation projects (e.g., assuming a 500-year rather than a 100-year storm).
<p>Increases in drought conditions for some regions.</p>	<ul style="list-style-type: none"> Increased susceptibility to wildfires, causing road closures due to fire threat or reduced visibility. 	<ul style="list-style-type: none"> Increased susceptibility to wildfires that threaten transportation infrastructure directly. Increased susceptibility to mudslides in areas deforested by wildfires. 	<ul style="list-style-type: none"> Vegetation management. 	
<p>Changes in seasonal precipitation and river flow patterns.</p>	<ul style="list-style-type: none"> Benefits for safety and reduced interruptions if frozen precipitation shifts to rainfall, depending on terrain. 	<ul style="list-style-type: none"> Increased risk of floods from runoff, landslides, slope failures, and damage to roads if precipitation changes from snow to rain in winter and spring thaws. 		

Potential	Impacts on Highways		Adaptation Options
<ul style="list-style-type: none"> • More frequent strong hurricanes (Category 4–5). 	<ul style="list-style-type: none"> • More debris on roads interrupting travel and shipping. • More frequent and potentially more extensive emergency evacuations. 	<ul style="list-style-type: none"> • Greater probability of infrastructure failures. • Increased threat to stability of bridge decks. • Increased damage to signs, lighting fixtures and supports. • Decreased expected lifetime of highways exposed to storm surge. 	<ul style="list-style-type: none"> • Emergency evacuation procedures that become more routine. • Improvements in ability to forecast landfall and trajectory of hurricanes. • Improvements in monitoring of road conditions and issuance of real-time messages to motorists. • Improvements in modeling of emergency evacuation.
			<ul style="list-style-type: none"> • Changes in bridge design to tie decks more securely to substructure and strengthen foundations. • Increases in drainage capacity for new transportation infrastructure or major rehabilitation projects. • Removal of traffic bottlenecks on critical evacuation routes and building of more system redundancy. • Adoption of modular construction techniques where infrastructure is in danger of failure. • Development of modular traffic features and road sign systems for easier replacement. <ul style="list-style-type: none"> • Strengthening and heightening of levees. • Restriction of further development in vulnerable coastal locations. • Increase in flood insurance rates to help restrict development. • Return of some coastal areas to nature.

Source (NRC 2008)

GLOSSARY

These terms are available from the NOAA/ National Weather Service, National Centers for Environmental Prediction / Climate Prediction Center, and may be found online at: <http://amsglossary.allenpress.com/glossary>.

Anomaly—The deviation of a measurable unit, (e.g., temperature or precipitation) in a given region over a specified period from the long-term average, often the thirty year mean, for the same region.

Anthropogenic—Caused by humans.

Arctic Oscillation—A pattern in which atmospheric pressure at polar and middle latitudes fluctuates between negative and positive phases. The negative phase brings higher-than-normal pressure over the polar region and lower-than-normal pressure at about 45 degrees north latitude. The negative phase allows cold air to plunge into the midwestern States. The positive phase brings the opposite conditions, steering ocean storms farther north and bringing wetter weather to Alaska, and drier conditions to areas such as California.

Atmospheric Circulation Model—A mathematical model for quantitatively describing, simulating, and analyzing the structure of the circulation in the atmosphere and the underlying causes.

Chlorofluorocarbons—Manufactured substances used as coolants and computer-chip cleaners. When these products break down they destroy stratospheric ozone, creating the Antarctic Ozone Hole in the Southern Hemisphere spring (Northern Hemisphere fall). While no longer in use, their long lifetime will lead to a very slow removal from the atmosphere.

Climate—The average of weather over at least a 30-year period. Note that the climate taken over different periods of time (30 years, 1,000 years) may be different.

Climate Change—A non-random change in climate that is measured over several decades or longer. The change may be due to natural or human-induced causes.

Climate Model—Mathematical model for quantitatively describing, simulating, and analyzing the interactions between the atmosphere and underlying surface (e.g., ocean, land, and ice).

Climate System—The system consisting of the atmosphere (gases), hydrosphere (water), lithosphere (solid rocky part of the Earth), and biosphere (living) that determine the Earth's climate.

Climatology—(1) The description and scientific study of climate. (2) A quantitative description of climate showing the characteristic values of climate variables over a region.

Convection—Transfer of heat by fluid motion between two areas with different temperatures—In meteorology, the rising and descending air motion caused by heat. Atmospheric convection is usually turbulent and is the dominant vertical transport process over tropical oceans and during sunny days over continents.

Cyclone—A type of atmospheric disturbance centered around a low-pressure center that often results in stormy weather. In practice, the terms cyclone, and low, are used interchangeably and are frequently referred to as storms.

Doppler Radar—Radar that measures speed and direction of a moving object, such as water or ice particles, birds, and insects.

El Niño—A periodic warming of ocean surface waters in the eastern tropical Pacific along with a shift in convection in the western Pacific further east than the climatological average. These conditions affect weather patterns around the world. El Niño episodes occur roughly every 4 to 5 years and can last up to 12 to 18 months.

Ensemble Forecast—Multiple predictions from an ensemble of slightly different initial conditions or various versions of models. The objective is to improve the accuracy of the forecast through averaging the various forecasts, which eliminates non-predictable components, and to provide reliable information on forecast uncertainties from the diversity amongst ensemble members. Forecasters use this tool to measure the likelihood of a forecast.

El Niño-Southern Oscillation (ENSO)—This cycle includes La Niña and El Niño phases as well as neutral phases of the coupled atmosphere/ocean system though sometimes it is still used as originally defined. The Southern Oscillation is quantified by the Southern Oscillation Index.

General Circulation Models—These computer simulations reproduce the Earth's weather patterns and can be used to predict change in the weather and climate.

Global Warming—Certain natural and human-produced gases prevent the sun's energy from escaping back to space leading to an overall rise in the temperature of the Earth's atmosphere.

Greenhouse Effect—The atmosphere allows solar radiation to reach the earth relatively easily. The atmosphere absorbs the infrared radiation emitted by the Earth's surface and radiates it back to the Earth in much the same way a greenhouse traps heat as the sun's rays pass through the glass, and the heat generated does not pass back through the glass. The "greenhouse effect" causes the surface of the Earth to be much warmer than it would be without the atmosphere 60°F.

Greenhouse Gas—Certain gases, such as water vapor, carbon dioxide, and methane, that more effectively trap heat affecting the Earth's surface temperature.

Intraseasonal Oscillations—Variability on a timescale less than a season. One example is the Madden-Julian Oscillation.

Jet Stream—Strong winds concentrated within a narrow zone in the atmosphere in the upper troposphere, about 30,000 feet aloft that generally move in an easterly direction and that drive weather systems around the globe. In North America, jet streams are more pronounced in winter.

Kelvin Waves—Fluctuations in wind speed at the ocean surface at the Equator result in eastward propagating waves, known as Kelvin Waves. Kelvin Waves cause variations in the depth of the oceanic thermocline, the boundary between warm waters in the upper ocean and cold waters in the deep ocean. They play an important role in monitoring and predicting El Niño episodes.

La Niña—A phase of ENSO, is a periodic cooling of surface ocean waters in the eastern tropical Pacific along with a shift in convection in the western Pacific further west than the climatological average. These conditions affect weather patterns around the world. The preliminary Climate Prediction Center definition of La Niña is a phenomenon in the equatorial Pacific Ocean characterized by a negative sea surface temperature departure from normal.

Long Wave (or Planetary Wave)—In meteorology, a long wave in atmospheric circulation in the major belt of westerlies has different characteristics than rapidly moving storms nearer the Earth's surface.

Madden-Julian Oscillation—Tropical rainfall exhibits strong variability on time scales shorter than the seasonal El Niño-Southern Oscillation. These fluctuations in tropical rainfall often go through an entire cycle in 30–60 days, and are referred to as the Madden-Julian Oscillation or intraseasonal oscillations, naturally occurring components of the coupled ocean-atmosphere system. They strongly affect the wintertime jet streams and atmospheric circulation features over the North Pacific and western North America, and thus have an important impact on storminess and temperatures over the United States.

Mesoscale—Refers to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers. Such phenomena include thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes.

Microscale—Refers to atmospheric phenomena having horizontal scales from 40 meters to 4 kilometers.

Nor'easter—Strong extratropical cyclones that develop off the U.S. East Coast, mainly during winter months, and characterized by high winds from the northeast, heavy precipitation, and often coastal flooding.

Normal—To understand whether precipitation and temperature is above or below normal for seasons and longer timescales, normal is defined as the average weather over 30 years. These averages are recalculated every 10 years.

North Atlantic Oscillation (NAO)—A large-scale fluctuation in atmospheric pressure between the subtropical high-pressure system located near the Azores in the Atlantic Ocean and the sub-polar low-pressure system near Iceland and is quantified in the NAO Index. The surface pressure drives surface winds and wintertime storms from west to east across the North Atlantic affecting climate from New England to Western Europe as far eastward as central Siberia and eastern Mediterranean and southward to West Africa. The NAO index measures the anomalies in sea-level pressure between the Icelandic low-pressure system and the Azores high-pressure system.

Numerical Forecasting—A computer forecast or prediction based on equations governing the motions and the forces affecting motion of fluids. The equations are based, or initialized, on specified weather or climate conditions at a certain place and time.

Oscillations—A shift in position of various high and low-pressure systems that in climate terms is usually defined as an index (i.e., a single numerically derived number that represents the

distribution of temperature and pressure over a wide ocean area, such as the El Niño-Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal Oscillation).

Ozone—A molecule consisting of three oxygen atoms that is formed by a reaction of oxygen and ultraviolet radiation. In the stratosphere, ozone has beneficial properties where it forms an ozone shield that prevents dangerous radiation from reaching the Earth's surface. Closer to the planet's surface, ozone is considered an air pollutant that adversely affects humans, plants, and animals, as well as a greenhouse gas.

Ozone Hole—A severe depletion of stratospheric ozone over Antarctica that occurs each spring. The possibility exists that a hole could form over the Arctic as well. The depletion is caused by a chemical reaction involving ozone and chlorine, primarily from human-produced sources, cloud particles, and low temperatures.

Pacific Decadal Oscillation—A recently described pattern of climate variation similar to ENSO though on a timescale of decades and not seasons. It is characterized by sea surface temperature anomalies of one type in the north-central Pacific and sea surface temperature anomalies of an entirely different nature to the north and east near the Aleutians and the Gulf of Alaska. It primarily affects weather patterns and sea surface temperatures in the Pacific Northwest, Alaska, and northern Pacific Islands. Its cause and predictability are unknown.

Palmer Drought Severity Index—An index that compares the actual amount of precipitation received in an area during a specified period with the normal or average amount expected during that same period. It was developed to measure lack of moisture over a relatively long period of time and is based on the supply and demand concept of a water balance equation. Included in the equation are amount of evaporation, soil recharge, and runoff, as well as temperature and precipitation data.

Teleconnection—A strong statistical relationship between weather in different parts of the globe. For example, there appears to be a teleconnection between the tropics and North America during El Niño.

ACKNOWLEDGEMENTS

The authors would like to thank several individuals who made this report possible. Mr. Quon Kwan of the FMCSA provided helpful comments on earlier drafts of the report. Mr. Simon Prensky and Mr. Thomas Seliga of the Volpe Center also provided many helpful suggestions during the course of the study. Ms. Marjorie McGuirk, Mr. Steve Ansari and Ms. Tamara Houston of the National Climatic Data Center helped in providing access to various climate data, and Mr. Paul Lobo of NHTSA, as well as the NHTSA/FARS staff for their help in providing crash data.

[This page intentionally left blank.]

REFERENCES

1. Federal Motor Carrier Safety Administration. 2005. *Report to Congress on the Large Truck Crash Causation Study*. Washington, DC: USDOT. FMCSA. Accessed online Nov. 3, 2009: http://ai.fmcsa.dot.gov/lccs/data/documents/reportcongress_11_05.pdf.
2. Pisano, P., Goodwin, L., & Rossetti, M. 2008. U.S. Highway Crashes in Adverse Road Weather Conditions. Presented at the 24th Conference on Information and Processing Systems during the 88th annual meeting of the American Meteorological Society (New Orleans) Session 8.1.
3. FHWA. 2007. *Highway Statistics* (series). Washington, DC: USDOT, FHWA. Accessed online Nov. 3, 2009: <http://www.fhwa.dot.gov/policy/ohpi/hss/hsspubs.cfm>.
4. National Highway Traffic Safety Administration (NHTSA). 2007 (and earlier years). *Fatality Analysis Reporting System (FARS database)*. Washington, DC: USDOT, NHTSA. Accessed online Nov. 3, 2009: <http://www-fars.nhtsa.dot.gov/Main/index.aspx>.
5. U.S. Climate Change Science Program. 2008: *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Savonis, M. J., V.R. Burkett, and J.R. Potter (eds.)]. Washington, DC: USDOT. Accessed online Nov. 3, 2009: <http://www.climatechange.gov/Library/sap/sap4-7/final-report/sap4-7-final-all.pdf>.
6. McGuirk, M. 2007. *Climate - Transportation Applications*. Presentation to the NOAA Office of the Federal Coordinator for Meteorology, Weather Information for Surface Transportation. NOAA/NCDC, Asheville NC.
7. Changnon, S. 2004. *Climate Atlas: Freezing Rain and Ice Storms*. Changnon Climatologist, Mahomet IL.
8. Peterson, T.C, McGuirk, M., Houston, T.G., Horvitz, A.H., & Wehner, M.F. 2006. *Climate Variability and Change with Implications for Transportation*. Commissioned by the National Research Council/National Academy of Sciences. Washington, DC: NAS Press. Accessed online Nov. 3, 2009: <http://onlinepubs.trb.org/onlinepubs/sr/sr290Many.pdf>.
9. Big rig truck driver sentenced in roadside death. 2009, August 12. *Auburn (California) Journal*. Accessed online Nov. 3, 2009: http://auburnjournal.com/detail/127042.html?content_source=&category_id=&search_filter=I-80&user_id=&event_mode=&event_ts_from=&event_ts_to=&list_type=&order_by=&order_sort=&content_class=1&sub_type=stories&town_id.
10. Centers for Disease Control and Prevention. 2006. *Extreme Heat: A Prevention Guide to Promote Your Personal Health and Safety*. Atlanta, GA. Accessed online Nov. 3, 2009: http://www.bt.cdc.gov/disasters/extremeheat/heat_guide.asp.
11. Stern, E., & Zehavi, Y. 1990. Road Safety and Hot Weather: A Study in Applied Transport Geography. *Transactions of the Institute of British Geographers, New Series*, Vol. 15, No. 1, 102–111.

12. Rowland, B.D., Davey, J.D., Freeman, J.E., & Wishart, D.E. 2007. Road Transport Sensitivities to Weather and Climate Change in Australia. Conference paper from the 30th Australasian Transport Research Forum (Melbourne, Australia). Accessed online Nov. 3, 2009: <http://eprints.qut.edu.au/9945/>.
13. Exide Technologies. *Frequently Asked Questions about Automotive Batteries*. Accessed online Nov. 3, 2009: http://links.exide.com/faq/faq_auto.html.
14. Adams, C.R. 1997. Impacts of Temperature Extremes. In Pielke, R. Jr. (ed.), *Workshop on the Social and Economic Impacts of Weather* (Boulder, CO). Accessed online Nov. 3, 2009: <http://sciencepolicy.colorado.edu/socasp/weather1/>.
15. Office of the Federal Coordinator For Meteorological Services and Supporting Research. 2002. *Weather Information for Surface Transportation: National Needs Assessment Report* (Report No. FCM-R18-2002). Silver Spring, MD: U.S. Department of Commerce/National Oceanic and Atmospheric Administration. Accessed online Nov. 3, 2009: http://www.ofcm.gov/wist_report/pdf/entire_wist.pdf.
16. Young, R., Liesman, J., Lucke, D., & Schieck, S. 2005. *Wyoming Freight Movement and Wind Vulnerability*. Laramie, WY: University of Wyoming. Accessed online Nov. 3, 2009: <http://www.mountain-plains.org/pubs/pdf/MPC05-170.pdf>.
17. Schmidlin, T.W., Hammer, B.O., King, P.S., & Miller, L.S. 2003. *Wind Speeds Required to Upset Vehicles*. Paper presented at the Symposium on the F-Scale and Severe-Weather Damage Assessment during 83rd annual meeting of the American Meteorological Society (Long Beach, CA). Accessed online on Nov. 3, 2009: <http://ams.confex.com/ams/pdfpapers/50675.pdf>.
18. Summerfield, S., Kosior, J. 2001. Simulation of heavy trucks in inclement weather. Winnipeg: University of Manitoba Transport Institute. Accessed online on Nov. 3, 2009: http://umanitoba.ca/faculties/management/ti/media/Simulation_Heavy_Trucks_Inclement_Weather_2001.pdf.
19. Niall, S., & Walsh, K. 2005. The impact of climate change on hailstorms in southeastern Australia. *International Journal of Climatology*, 25:14, 1933-1952.
20. Trapp, R.J. Diffsenbaugh, N.S., Brooks, H.E., Baldwin, M.E., Robinson, E.D., & Pal, J.S. 2007. Changes in Severe Thunderstorm Environment Frequency During the 21st Century Caused by Anthropogenically Enhanced Global Radiative Forcing. In: *Proceedings of the National Academy of Sciences*, 104(50):19719–19723. Accessed online on Nov. 3, 2009: <http://www.pnas.org/content/104/50/19719.abstract?maxtoshow=&HITS=10&hits=10&RESULTFORMAT=&fulltext=extreme+weather&searchid=1&FIRSTINDEX=0&resourcetype=HWCIT>.
21. Code of Federal Regulations (CFR), Title 49, Subchapter B, Part 395.1
22. Clayton, A., Montufar, J., Regehr, J., Isaacs, C., & McGregor, R. 2005. *Aspects of the Potential Impact of Climate Change on Seasonal Weight Limits and Trucking in the Prairie Region*. Manitoba, CA: University of Manitoba. Accessed online on Nov. 3, 2009: http://adaptation.nrcan.gc.ca/projdb/pdf/135a_e.pdf.

23. Vise, A. 2004. Innovators: Awake at the Wheel. *Commercial Carrier Journal*, July. Accessed online on Nov. 3, 2009: http://www.randallpub.com/ccj/ccjinnovators/2004finalists_june.html
24. U.S. Department of Transportation (DOT), Research and Innovative Technology Administration (RITA), Bureau of Transportation Statistics (BTS). 2006. *Freight in America: A New National Picture*. Washington, DC: USDOT, RITA. Accessed online on Nov. 3, 2009: http://www.bts.gov/publications/freight_in_america/.
25. Maccubbin, R. 2002. Analysis of weather incident effects on commercial vehicle mobility in large U.S. cities. Presentation to the Federal Highway Administration, Mitretek Systems, Falls Church, VA.
26. Braver, E.R., Solomon, M.G., & Preusser, D.F. 2002. Toll Road Crashes of Commercial and Passenger Motor Vehicles. *Accident Analysis and Prevention*, 34(3):293-303. Accessed online on Nov. 3, 2009: <http://cat.inist.fr/?aModele=afficheN&cpsidt=13512715>.
27. Loeb, P.D., & Clarke, W.A. 2007. The Determinants of Truck Accidents. *Transportation Research Part E: Logistics and Transportation Review*, 43(4):442-452. Accessed online on Nov. 3, 2009: [doi:10.1016/j.tre.2005.11.002](https://doi.org/10.1016/j.tre.2005.11.002).
28. National Transportation Safety Board. 1980. *Fatal Highway Accidents on Wet Pavement – the Magnitude, Location and Characteristics. Special Study* (Report No. NTSB-HSS-80-1, National Technical Information Service No. PB80-163744). Washington, DC. Abstract accessed online on Nov. 3, 2009: <http://www.nts.gov/publictn/1980/HSS8001.htm>.
29. Battelle Institute. 2006. *The Strategic Multimodal Analysis: Task 3: Chicago–New York City Corridor Analysis*. Washington, DC: Federal Highway Administration. Accessed online on Nov. 3, 2009: <http://www.fhwa.dot.gov/policy/otps/sma/>.
30. Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Synthesis Report, Summary for Policymakers*. An Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press. Accessed online Nov. 3, 2009: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf.
31. U.S. Global Climate Change Research Program. 2009. *Global Climate Change Impacts in the United States*. Karl, T.R., Melillo, J.M., & Peterson, T.C. (eds.). New York: Cambridge University Press. Accessed online on Nov. 3, 2009: <http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts>.
32. Intergovernmental Panel on Climate Change. 2007a. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. & Hanson, C.E. (eds.). Cambridge, UK: Cambridge University Press. Accessed online on Nov. 3, 2009: <http://www.ipcc-wg2.gov/publications/AR4/index.html>.

33. Intergovernmental Panel on Climate Change. 2007b. Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.). Cambridge, UK and New York: Cambridge University Press. Accessed online on Nov. 3, 2009: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf>
34. CCSP, 2008: *Abrupt Climate Change*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Clark, P.U., A.J. Weaver (coordinating lead authors), E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen (chapter lead authors)]. Reston, VA: U.S. Geological Survey. Accessed online Dec. 1, 2009: <http://www.globalchange.gov/publications/reports/scientific-assessments/saps/sap3-4>
35. National Research Council, Transportation Research Board. 2008. *Potential Impacts of Climate Change on U.S. Transportation*. Transportation Research Board Special Report 290. National Academy Press, Washington, DC. Accessed online Nov. 3, 2009: http://www.nap.edu/catalog.php?record_id=12179
36. McCarthy, L. 2008. *2007 Was Tied as Earth's Second-Warmest Year*. Washington, DC: Goddard Institute for Space Studies, NASA. Accessed online Nov. 3, 2009: http://www.nasa.gov/topics/earth/features/earth_temp.html.
37. Rossetti, M.A. 2002. Potential Impacts of Climate Change on Railroads. In *The Potential Impacts of Climate Change on Transportation, Summary and Discussion Papers*. Federal Research Partnership Workshop(The Brookings Institution, Washington, DC):209–221.
38. Mann, M.E., & Emanuel, K. 2006. Atlantic Hurricane Trends Linked to Climate Change. *EOS: Transactions of the American Geophysical Union*. 87(24):233–244. Accessed online on Nov. 3, 2009: <http://www.agu.org/pubs/crossref/2006/2006EO240001.shtml>
39. U.S Climate Change Science Program. 2008. *Weather and Climate Extremes under Climate Change*. Synthesis and Assessment Product 3.3. Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Karl, T.R., Meehl, G.A., Miller, C.D., Hassol, S.J., Waple, A.M. & Murray, W.L. (eds.). Washington, DC. Accessed online on Nov. 3, 2009:<http://www.climatechange.gov/Library/sap/sap3-3/final-report/>
40. Del Genio, A. D., Yao, M.S., & Jonas, J. 2007. Will Moist Convection be Stronger in a Warmer Climate? *Geophysical Research Letters*, 34(16). Accessed online on Nov. 3, 2009: <http://www.agu.org/pubs/crossref/2007/2007GL030525.shtml>
41. American Meteorological Society (AMS). 2007. Climate Change—An Information Statement of the American Meteorological Society. *Bulletin of the American Meteorological Society*, 88(3):418–421.
42. Changnon, S. 1999. Impacts of 1997–98 El Nino Generated Weather in the U.S. *Bulletin of the American Meteorological Society*, 80(9):1819–1827.
43. Research and Innovative Technology Administration (RITA). *IntelliDriveSM*. Washington, DC: USDOT, RITA. Accessed online on Nov. 3, 2009: <http://www.its.dot.gov/intellidrive/index.htm>.

BIBLIOGRAPHY

- Changnon, S. 2005. Economic Impacts of Climate Change Conditions in the United States: Past, Present, and Future. *Climatic Change*, 68:1-9.
- Changnon, S. 2007. Catastrophic Winter Storms: An Escalating Problem. *Climatic Change*, 84:131-139
- de Freitas, C. 1975. Estimation of the Disruptive Effects of Snowfalls in Urban Areas, *Journal of Applied Meteorology*, 14(September):1166-1173.
- Easterling, D. et al. 2007. *A Comparison of Model Produced Climate Extremes with Observed and Projected Trends for the 20th and 21st Centuries*. Presented at the 2007 Annual Meetings of the American Meteorological Society.
- Goodwin, L. et al. 2008. *U.S. Highway Crashes in Adverse Weather*. Presented at the 2008 Annual Meetings of the American Meteorological Society.
- Kirshen, P. et al. 2008. Interdependencies of Urban Climate Change Impacts and Adaptation Strategies: A Case Study of Metropolitan Boston USA. *Climatic Change*, 86:105-122.
- National Safety Council (NSC). 2007. *Manual on Classification of Motor Vehicle Traffic Accidents, 7th Edition*. ANSI Standard D16.1-2007. Itasca, IL: National Safety Council.
- Ross, T. and N. Lott. 2003. *A Climatology of 1980-2003 Extreme Weather and Climate Events*. Technical Report 2003-01, Asheville, NC: NOAA/National Climatic Data Center.
- Rossetti, M.A and M. Johnsen. 2008. *Impacts of Weather and Climate on Commercial Motor Vehicles*. Presented at the Annual Meeting of the American Meteorological Society. Session 4B.4 (New Orleans, January 21).
- Seliga, T. 1997. *The NEXRAD Radar System: A New Tool for Highway Traffic Management*. Seattle, WA: University of Washington.
- Staplin, L, et al. 2004. *Commercial Truck and Bus Safety, Synthesis 5, Training of Commercial Motor Vehicle Drivers*. Transportation Research Board. Washington, DC: NAS Press.
- Statement of Dr. Thomas C. Peterson, Climate Services Division, National Climatic Data Center, National Environmental Satellite and Dissemination Service, National Oceanic and Atmospheric Administration. 2008. In U.S. Senate. *Hearing on: Climate Change and Transportation Infrastructure*. 24 June. Washington, DC.
- Suarez, P. et al. 2005. Impacts of Flooding and Climate Change on Urban Transportation: A Systemwide Performance Assessment of the Boston Metro Area. *Transportation Research D* (10), 231-244.
- U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory. 2008. Analysis of data provided, personal communication, March 26.
- U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center. 2002. *Climate Atlas of the United States*. Ver.2. Asheville, NC: NOAA, NCDC.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. 2007. National Weather Service Instruction 10-1605. *Storm Data Preparation*. Washington, DC: U.S. Department of Commerce.

U.S. Global Change Research Program. 2000. *Climate Change Impacts in the United States: The Potential Consequences of Climate Variability and Change. Overview*, National Assessment Synthesis Team. Cambridge UK: Cambridge University Press.