Regional Assessment of Weather Impacts on Freight

February 2016

U.S. Department of Transportation
Federal Highway Administration

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No.
FHWA-HOP-16-044

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Regional Assessment of Weather Impacts on Freight

5. Report Date
February 2016

6. Performing Organization Code
HOP

7. Author(s)
Daniel Krechmer, Noel Perry, Sarahjoy Gallaher, Marjorie McGuirk, Thomas Burnett, Katherine Blizzard

8. Performing Organization Report No.

9. Performing Organization Name And Address

Cambridge Systematics, Inc.
4800 Hampden Ln Suite 800
Bethesda, MD 20814

with

CASE Consultants International
Asheville, NC 28805

Noel Perry
Transport Fundamentals, LLC
Lebanon, PA 17042

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTFH61-12-D-00048-T-13005

12. Sponsoring Agency Name and Address

U.S. Department of Transportation
Federal Highway Administration
Office of Operations
1200 New Jersey Ave., SE
Washington, DC 20590

13. Type of Report and Period Covered
September 2014-February 2016

14. Sponsoring Agency Code
HOP

15. Supplementary Notes
Government Task Manager: Jimmy Chu

16. Abstract

This project follows up on a study completed for the Federal Highway Administration (FHWA) in 2012 that provided a national estimate of weather-related delay affecting the trucking industry. The initial estimate indicated that weather-related delay costs the industry $8 billion to $9 billion annually. The goal of this study is to conduct a more detailed assessment of the impacts of adverse weather on freight movement in 13 diverse geographic regions, including both urban and rural corridors. The analysis presented in this report indicates that, overall, weather events have a significant negative impact on traffic speeds—and, therefore, the freight industry—when analyzed at the regional level. In this report's study area, which focuses solely on a limited set of major highways, decreased traffic speeds due to weather events are estimated to cost the freight industry $3.8 million per year. The study found that ice, snow, fog, heavy rain, wind, and extreme temperature events were the most correlated with reduced traffic speeds, with the largest decreases occurring during the first hour of storms. Adverse weather was shown to have a greater correlation with decreased traffic speeds during peak hours.

17. Key Words
Freight Economics, Trucking, Weather, Travel Delays

18. Distribution Statement
No restrictions

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
72

22. Price
N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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 yard	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
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	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

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")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

EXECUTIVE SUMMARY

This project follows up on a study completed for the Federal Highway Administration (FHWA) in 2012 that provided a national estimate of weather-related delay affecting the trucking industry.[1] The initial estimate indicated that weather-related delay costs the industry $8 billion to $9 billion annually. The goal of this study is to conduct a more detailed assessment of the impacts of adverse weather on freight movement in 13 diverse geographic regions, including both urban and rural corridors. The objective is to provide greater temporal and geographic detail than the first phase study allowed, and to use the results to refine the previously developed weather adjustment factors. These factors can be applied in future work to refine the national estimate and can be used at the local or regional level to help develop traffic management strategies for adverse weather.

After thoroughly reviewing the sources of available data on weather and freight, the project selected the following 13 regions and roadway segments to assess the regional impacts of weather on freight. The project also took freight movement patterns, weather patterns, economic diversity, and regional population size—among other factors—into consideration in the selection process.

- **Atlanta, Georgia**: The I-285 Beltway.
- **Chicago, Illinois**: I-57 from I-94 to the north and the Kankakee/Iroquois county line to the south.
- **Columbus, Ohio**: I-70 from I-75 to the west and the Licking/Muskingum county line to the east.
- **Denver, Colorado**: I-70 from State Route (SR)-191 in Grand, Utah to the west and the Elbert/Lincoln county line to the east.
- **Lake Tahoe, California**: I-80 from I-5 to the west and the California/Nevada border to the east.
- **Lexington, Kentucky**: I-64 from I-265 to the west and the Bath/Rowan county line to the east.
- **Newark, New Jersey**: I-78 from I-476 to the east and I-95 to the west.
- **Oklahoma City, Oklahoma**: I-35 from I-44 to the north and U.S. 70 to the south.
- **Pittsburgh, Pennsylvania**: I-79 from I-80 to the north and the Pennsylvania/West Virginia border to the south.
- **Raleigh, North Carolina**: I-40 from the Davie/Forsyth county line to the east and the Johnston/Sampson county line to the west.
- **Rapid City, South Dakota**: I-90 from the Wyoming/South Dakota State line to the west and SR-45 (Kimball) to the east.
- **Salt Lake City, Utah**: I-80 from the Nevada/Utah border to the west and the Utah/Wyoming border to the east.
- **Seattle, Washington**: I-90 from I-5 to the west and I-82 to the east.

---

[1] http://ntl.bts.gov/lib/48000/48200/48291/2019837E.pdf.

The project designed a methodology to associate weather events with freight activity using three categories of data: travel-time data, weather data, and freight data. For travel-time data, the project used the National Performance Management Research Data Set (NPMRDS) downloaded from HERE's online service, which provided data on average travel times for all vehicles, average travel times for passenger vehicles, and average travel times for freight vehicles along the National Highway System (NHS). The project used the National Oceanic and Atmospheric Administration's (NOAA) Storm Events Database (hereafter the "storm database") and the National Land Data Assimilation Systems (NLDAS) as its primary sources of data on weather events, including event type, State, county, date, time, and magnitude. Finally, for freight data, the project used FHWA's Freight Analysis Framework Version 3.5 (FAF3.5), which provided estimates of tonnage, value, and domestic ton-miles by region of origin and destination. In order to amass a significant sample size of weather events associated with highway travel and freight activity, the project associated weather events with roadway segment based on county. Since the weather events analyzed were predominately large storms, the likelihood that a weather event impacted roadways within the same county was relatively high. Still, this assumption introduced some uncertainty into the methodology, which is discussed further in the presentation of the results.

The results indicated that, overall, weather events have a significant negative impact on traffic speeds—and, therefore, the freight industry—when analyzed at the regional level. In this report's study areas alone, decreased traffic speeds due to weather events on the highways analyzed were estimated to cost the freight industry $3.8 million per year. These calculations were relative to the average cost of trucking, which includes both good and bad weather. These findings support the earlier estimates and—by examining 13 regions in the United States that vary in terms of their weather, population size, and economies—this report demonstrates how these national trends impact individual regions.

The regional analysis allowed for a more detailed investigation of how the impacts of weather on freight vary by weather event, highway type, time of day, and region size. The key takeaways from the regional analysis are listed below, followed by a discussion of important considerations and limitations of the analysis and directions for further research. All key takeaways are overall findings from the analysis of all 13 regional study areas.

- Weather events that fall into the categories of Ice and Snow, Fog, Flood, Wind, Rain, and Extreme Temperature were, together, associated with the vast majority of traffic speed decreases during weather events, as well as costs to the freight industry from weather-related delay.
- Ice and Snow events were associated with over half of all lost time due to decreased traffic speeds during weather events and are the most costly for the freight industry (costing over 25 dollars per segment hour and over 25 cents per truck per segment).
- Weather events exert the largest negative impacts on traffic speeds between hour 0 and hour 1. However, small decreases in speed are also seen in the hours leading up to a weather event, and moderate decreases in speed are still seen up to four hours after the event.

- Throughout the day, irregular flow highways (highways that experience morning and evening rush hours) suffer more than even flow highways in terms of loss of speed during weather events.
- Time of day matters—all highway types suffer more in terms of loss of speed during weather events that occur during morning and evening rush hour periods.
- Highways in smaller regions (where region size is based on population size and economic intensity) suffer less than highways in medium and large regions in terms of loss of speed during weather events.

While the analysis was able to detect these trends looking across the 13 regions, it is important to understand the limitations of the methodology and data used in order to best apply these insights. The association of traffic speeds with weather events based on county means that it is not certain that traffic speeds on a given roadway were always directly impacted by the associated weather event. The eight-hour timeframe applied to each weather event (four hours before and after hour 0) also limits the analysis as storms vary in length, but it was necessary to establish a common timeframe in order to have consistency in the analysis. Ideally, the analysis would track each storm individually for the time that it occurred, but the data processing requirements for such an approach were significant and not feasible within project resources. Nonetheless, given the sample size amassed using these assumptions, the research team was able to determine the significant trends listed above.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ASOS	Automated Surface Observing System
ATRI	American Transportation Research Institute
DOT	Department of Transportation
FAF	Freight Analysis Framework (FAF3.5 is Version 3.5)
FHWA	Federal Highway Administration
GIS	Geographical Information System
ITS	Intelligent Transportation Systems
MADIS	Meteorological Assimilation Data Ingest System
NCDC	National Climatic Data Center
NHS	National Highway System
NLDAS	National Land Data Assimilation System
NOAA	National Oceanic and Atmospheric Administration
NPMRDS	National Performance Management Research Data Set
NWS	National Weather Service
RWIS	Road Weather Information System
TMC	Transportation Management Code

CHAPTER 1: INTRODUCTION

BACKGROUND

This project follows up on a study completed for the Federal Highway Administration (FHWA) in 2012 that provided a national estimate of weather-related delay affecting the trucking industry.[2] The initial estimate indicated that weather-related delay costs the industry $8 billion to $9 billion annually. The goal of this study is to conduct a more detailed assessment of the impacts of adverse weather on freight movement in 13 diverse geographic regions, including both urban and rural corridors. The objective is to provide greater temporal and geographic detail than the first phase study allowed, and use the results to refine the previously developed weather adjustment factors, enabling an overall increased confidence in the 2012 nationwide study.

Commercial motor vehicles are the nation's dominant mode of freight transportation. Estimates of the transportation component of the nation's freight are upwards of $600 billion of total gross domestic product. It is estimated that 70 percent of this total value and 60 percent of its total weight move by truck. Weather-related delays can add significantly to shipping costs, resulting in negative impacts on the overall economy.

Adverse weather is one of the major causes of delay on the roadway system. The FHWA Road Weather Management Program Web site[3] reports that as much as 23 percent of the Nation's roadway delays may be the result of adverse weather. Other studies show a lower, but still very significant, percentage of adverse weather-related delays; yet others identify a wide variation in adverse weather impact on speed, volume, and delay, as shown below in table 1 also from the FHWA Road Weather Management Web site. Table 2 summarizes the results of research funded by FHWA.

Table 1. Freeway traffic flow reductions due to weather.

	Freeway Traffic Flow Reductions			
Weather Conditions	**Average Speed**	**Free-Flow Speed**	**Volume**	**Capacity**
Light Rain/Snow	3% to 13%	2% to 13%	5% to 10%	4% to 11%
Heavy Rain	3% to 16%	6% to 17%	14%	10% to 30%
Heavy Snow	5% to 40%	5% to 64%	30% to 44%	12% to 27%
Low Visibility	10% to 12%	–	–	12%

Source: http://ops.fhwa.dot.gov/weather/q1_roadimpact.htm.

---

[2] http://ntl.bts.gov/lib/48000/48200/48291/2019837E.pdf.

[3] http://ops.fhwa.dot.gov/weather/.

Table 2. Empirical studies on weather and traffic.

Traffic Parameter	Weather Condition	Weather Condition Parameter	Range of Impact
Free-Flow Speed	Light Rain	<0.01 cm/h	-2% to -3.6%
	Rain	~1.6 cm/h	-6% to -9%
	Light Snow	<0.01 cm/h	-5% to -16%
	Snow	~0.3 cm/h	-5% to -19%
Speed at Capacity	Light Rain	~0.3 cm/h	-8% to -10%
	Rain	~1.6 cm/h	-8% to -14%
	Light Snow	<0.01 cm/h	-5% to -16%
	Snow	~0.3 cm/h	-5% to -19%
Capacity	Light Rain	<0.01 cm/h	-10% to -11%
	Rain	~1.6 cm/h	-10% to -11%
	Light Snow	<0.01 cm/h	-12% to -20%

Source: Presentation "Federal Program for Weather-Responsive Traffic Management," presented by Roemer Alfelor, Ph.D., FHWA, at Northwest Transportation Conference, Oregon State University, March 2014.

An important focus of this project is to better identify weather condition parameters specific to commercial vehicles, and to possibly expand the range of weather condition indices beyond those identified above.

PURPOSE OF STUDY

The results of the first-phase study were presented at a number of conferences and meetings since 2012. The responses to these presentations were enthusiastic, especially from State Departments of Transportation (DOT) and transportation logistics companies. These responses highlighted the importance of this analysis in promoting the need for investment in weather-related maintenance and traffic management activities, improved surface weather condition data, improved weather forecasting, and the dissemination of readily available real-time data oriented toward the freight industry. Some of these investments are in the realm of the public sector, while others will be made by the private sector. While safety remains a central motivation in promoting weather-related transportation programs, there is a clear economic imperative as well. Efficient movement of goods is becoming more critical to all segments of the economy. For example, just-in-time manufacturing and real-time inventory control both require and *depend* on deliveries within ever more precise time windows. A better understanding of weather impacts on travel speeds can help provide the freight industry and its customers with more accurate predictive information on travel times and support the implementation of weather-responsive traffic management strategies. Providing fact-based data to a freight industry that now depends on a more instant world could potentially allow companies to mitigate their costs by incorporating freight-shipping models to account for adverse weather patterns. They could choose to ship products early, later, or stop midway through an adverse weather event. Understanding the economic impacts helps to make the case for winter maintenance budgets and for development and deployment of new technologies that will enable those funds to be spent more cost effectively.

Finally, with this understanding of the real cost of adverse weather impacts on freight traffic, FHWA hopes to stimulate research into new safety measures for freight corridors. For example, the fog-alert system implemented by the Tennessee DOT along I-75 near Calhoun, Tennessee, has greatly decreased the number of fog-related crashes in that fog-prone area through the use of advanced road weather management technology.

GOALS AND OBJECTIVES

The primary goal of this study is to estimate the impact of adverse weather on the freight industry in 13 diverse regions in the U.S. Impacts include estimates of travel delay resulting from specific weather phenomena, and the economic impacts of these delays. This effort builds upon the work completed in 2012 discussed earlier by increasing the level of temporal and geographic details in the estimates. This project does not involve the development of a revised national estimate, but the findings could be used to develop one in the future. Specific objectives include:

- Estimates of weather-related delay under a variety of weather conditions.
- Estimates of weather-related delay in a variety of geographic settings.
- Estimates of weather-related delay in a variety of terrain.
- Estimates of weather-related delay in a variety of economic regions.

Another objective is to examine the effectiveness of different data sources in helping to estimate weather-related trucking delay.

OVERVIEW OF CANDIDATE DATASETS AND METHODOLOGY

This section summarizes criteria used to select key data sets and the overall approach to conducting the project.

Criteria for Selecting Data Sets

Descriptions of key data sources are discussed briefly below.

- **Weather Data.** There is a wide-range of weather data sources that can be used to help identify when traffic is being impacted by adverse weather. In order to be effective in this analysis, however, weather data must have the temporal and geographic detail necessary to match weather events with traffic flows. Issues related to data formats must also be considered; datasets that require excessive processing time or interpretation may not be feasible to use within the existing work scope and budget. After evaluating several approaches, the National Oceanic and Atmospheric Administration's (NOAA) Storm Events Database was used as the primary weather data source for this effort. The Methodology section of this technical memorandum details the weather sources evaluated and provides more detail on the weather dataset used in the analysis.
- **Travel-Time Data.** In order to conduct the proposed analysis, data are required for truck travel times, truck volumes, and value of truck shipments. The National Performance Management Research Data Set (NPMRDS) was proposed for use in calculating truck travel times. This information was originally used in the 2012 study, at a time when the data was

provided by the American Transportation Research Institute (ATRI). The ATRI database is now part of the NPMRDS and available through FHWA. The roadway network has been expanded and speed data are available for trucks at 5-minute intervals. The NPMRDS allows consistency across all regions considered in the study, as well as with the previous 2012 study. However, as the analysis went forward many of the truck speed observations were not consistent with the speed observations for passenger vehicles and total traffic. In general, truck speeds should not be expected to vary significantly from those of the general traffic stream, and so the general traffic speed estimates, which have the largest sample size (combined passenger and freight vehicles), were used in the analysis.

- **Freight Data.** In order to estimate the economic impact of delay, the number of trucks using the study area roads and some measure of their economic value are necessary. The project team determined that both can be obtained from the Freight Analysis Framework Version 3.5 (FAF3.5), which is described in more detail in the Methodology section of this report. The FAF, like NPMRDS, provides a consistent source of national information that can be used to derive estimates of truck volumes on National Highway System roads, as well as commodity value. These estimates can be compared to those in the FTR Transportation Intelligence[4] model used in the 2012 study because the team used the 2012 provisional data provided in the FAF3.5. This provisional data set (2012 freight data) was converted to a trip table and assigned to the network to produce flows using an algorithm approved by the FHWA.[5]
- **Congestion Data.** As noted in the work scope, the level of congestion will have a major impact on the value of the weather index. Speeds tend to drop more significantly during adverse weather on roads that are approaching capacity. The empirical tests using the data sources above provided a good measure of congestion, which could be identified during periods of good weather.

Methodology Summary

Figure 1 provides an overview of the proposed methodology for the study. As shown, a series of travel-time comparisons were developed for different weather conditions. While weather phenomena are dependent on the specific region included in the analysis, the initial set of tests focused on as wide a range of weather phenomena as possible. Case studies were selected to represent as wide a range of conditions as possible, using the following criteria:

---

[4] More information on FTR Transportation Intelligence can be found on their website: http://www.ftrintel.com/.

[5] FHWA Freight 2011—FAF Geospatial Support and Special Tabulations. Project number 008500.003.

- Population Size.
- Density.
- Estimated Level of Trucking Activity.
- Commodities Moving Into, Out of and Through the Area.
- Terrain.
- Economic Base.
- Climate.
- Perceived Level of Congestion.

Roadways within the study areas were selected based on their location within the metropolitan area (urban, suburban, exurban).

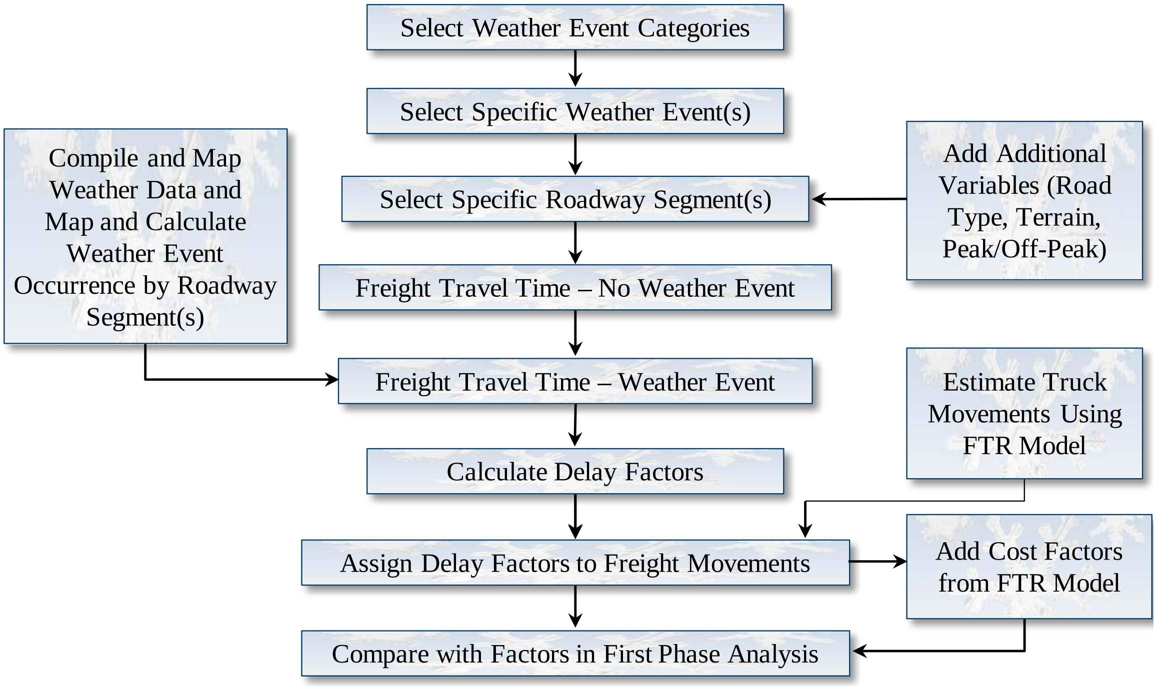


Figure 1. Flowchart. Analysis Approach.
(Source: Cambridge Systematics, Inc.)

The following sections describe the analytical work conducted, the distribution of cases, and the data sets used for the analysis.

CHAPTER 2: METHODOLOGY

SELECTION AND DEFINITION OF STUDY AREAS

In an earlier memo this project identified 13 recommended study areas after conducting thorough research into each site's weather patterns and available data sources. These recommended study areas are listed in table 3, along with their weather focus (the primary weather-related reason for recommending the study area), transportation focus (the highway component that will be investigated), and potential freight focus. The freight focus was identified primarily to make sure that an adequate variety of commodity shipments and economic activities were represented in the study. Data required to identify specific commodity flows for a specific roadway were not yet available. The initial 13 recommended study areas included two reserve study areas—Birmingham, Alabama and Salt Lake City, Utah—as secondary recommendations for the project team to keep in consideration during the process of selecting the final study areas.

Table 3. Recommended study areas from the task 2 memo.

Region	Weather Focus	Transportation Focus	Potential Freight Focus
Atlanta, Georgia	Thunderstorm warnings	Regional truck movements on the I-235 Beltway	Truckload freight
Birmingham, Alabama (reserve)	Fog	I-20 from Atlanta, Georgia to Jackson, Mississippi	Truckload freight
Chicago, Illinois	Winter conditions	Cross-town movement of rail containers by truck from Union Pacific to Norfolk Southern on I-57	Containerized freight
Columbus, Ohio	Winter conditions	Regional truck movements on I-70 East of Columbus	Truckload freight
Denver, Colorado	Winter conditions	I-70 West of Denver over the Continental Divide	Truckload freight
Lake Tahoe, California	Winter conditions	I-80 over the Donner pass between Sacramento and Reno	Containerized freight and agricultural commodities
Newark, New Jersey	Winter conditions	I-95 South of Newark	Containerized freight
Oklahoma City, Oklahoma	Thunderstorm and tornado warnings	I-35 approach from Texas to Oklahoma City	Petroleum products (tankers)
Phoenix, Arizona	None (control site)	I-10 West of Phoenix	Truckload and containerized freight
Raleigh, North Carolina	Tropical storm conditions	I-40 between Raleigh and Greensboro	Coal

Table 3. Recommended study areas from the task 2 memo. (continued)

Region	Weather Focus	Transportation Focus	Potential Freight Focus
Rapid City, South Dakota	Winter conditions	I-90 Northwest from Rapid City	Truckload freight and agricultural commodities
Salt Lake City, Utah (reserve)	Winter conditions	I-80 west from Salt Lake City west	Containerized freight
Seattle, Washington	Winter conditions	Central Washington to Seattle on I-90	Truckload freight and agricultural commodities

To select the final study areas, the project team further investigated the recommended study areas in light of available data, and produced maps of each study area detailing Interstates, major arterials, county and State boundaries, major cities, and climate divisions. Interstates were depicted as graduated truck flows using Freight Analysis Framework Version 3.5 (FAF3.5) data. Figure 2 provides an example of these maps.

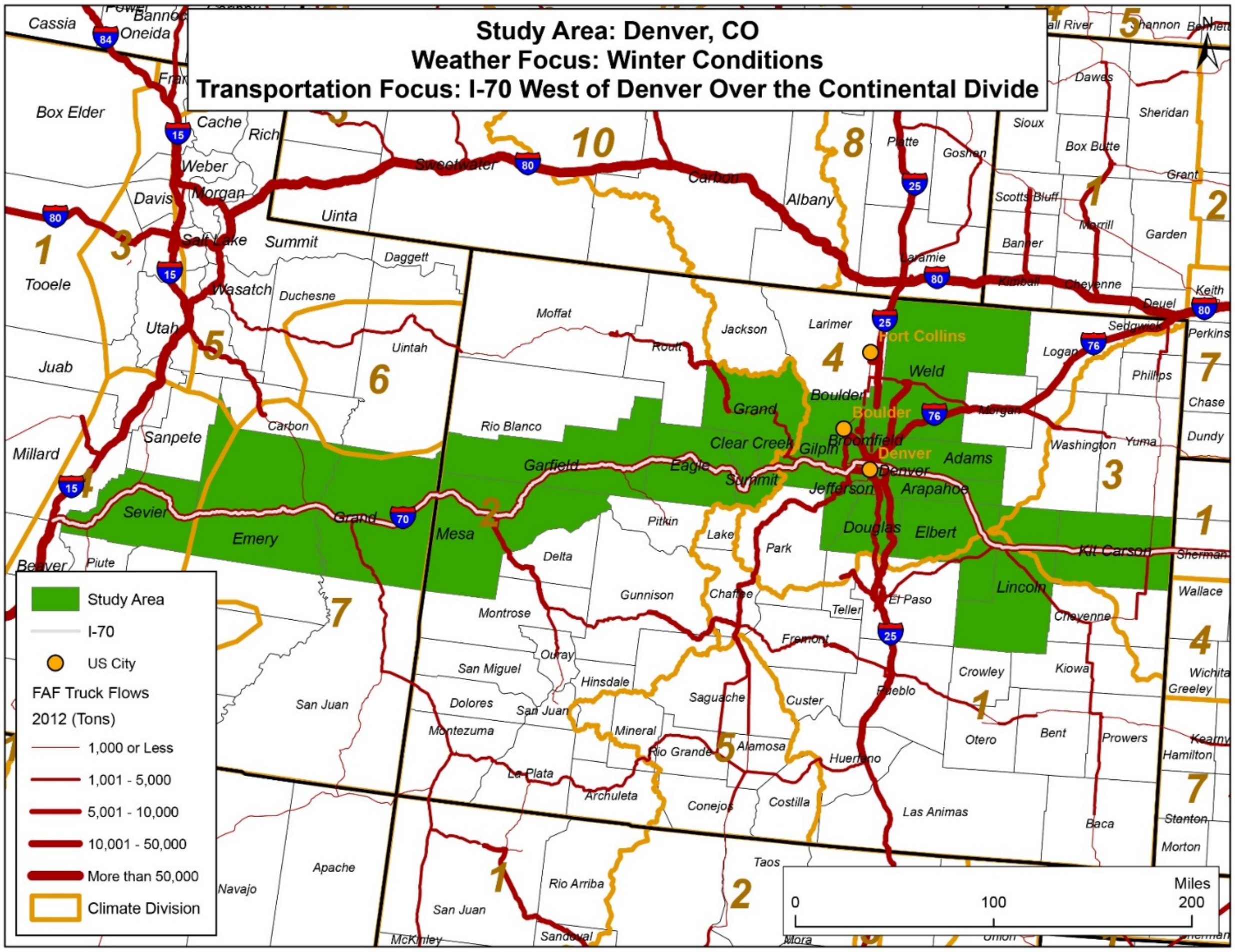


Figure 2. Map. Recommended Denver, Colorado study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

The project team used the study area maps to define a more practical and precise transportation focus for each final study area. To broaden the project's analysis of winter weather—suspected to have a large impact on freight—the reserve study area of Salt Lake City, Utah was included in the final set of study areas. Lexington, Kentucky and Pittsburgh, Pennsylvania, which had both been under consideration during earlier stages, were also added back in to the final set of study areas because both experience a broad range of weather events, including winter weather, and contain mountainous regions. The reserve study area of Birmingham, Alabama, was not included in the final set as its weather profile was very similar to that of Atlanta, Georgia. Additionally, the proposed control study area of Phoenix, Arizona was not included in the final analysis because it had only a small number of recorded weather events. The list of the final 13 study areas and transportation focuses are shown in table 4. It is important to note that these routes stretch significant distances. Therefore, even in this more focused regional analysis, weather events vary within the study areas. The impacts of this variation on the interpretation of results—as well as efforts to account for this variation in the methodology by examining each study area by county—will be further discussed in the following sections.

Table 4. Final list of study corridors.

Study Area	**Transportation Focus**
Atlanta, Georgia	The I-285 Beltway.
Chicago, Illinois	I-57 from I-94 to the north and the Kankakee/Iroquois county line to the south.
Columbus, Ohio	I-70 from I-75 to the west and the Licking/Muskingum county line to the east.
Denver, Colorado	I-70 from SR-191 in Grand, Utah to the east and the Elbert/ Lincoln county line to the east.
Lake Tahoe, California	I-80 from I-5 to the west and the California/Nevada border to the east.
Lexington, Kentucky	I-64 from I-265 to the west and the Bath/Rowan county line to the east.
Newark, New Jersey	I-78 from I-476 to the east and I-95 to the west.
Oklahoma City, Oklahoma	I-35 from I-44 to the north and U.S. 70 to the south.
Pittsburgh, Pennsylvania	I-79 from I-80 to the north and the Pennsylvania/West Virginia border to the south.
Raleigh, North Carolina	I-40 from the Davie/Forsyth county line to the east and the Johnston/Sampson county line to the west.
Rapid City, South Dakota	I-90 from the Wyoming/South Dakota State line to the west and SR-45 (Kimball) to the east.
Salt Lake City, Utah	I-80 from the Nevada/Utah border to the west and the Utah/ Wyoming border to the east.
Seattle, Washington	I-90 from I-5 to the west and I-82 to the east.

In addition to the map for the Denver, Colorado study area (figure 2, above), maps for the remaining 12 final study areas are included below as figures 3 through 14.

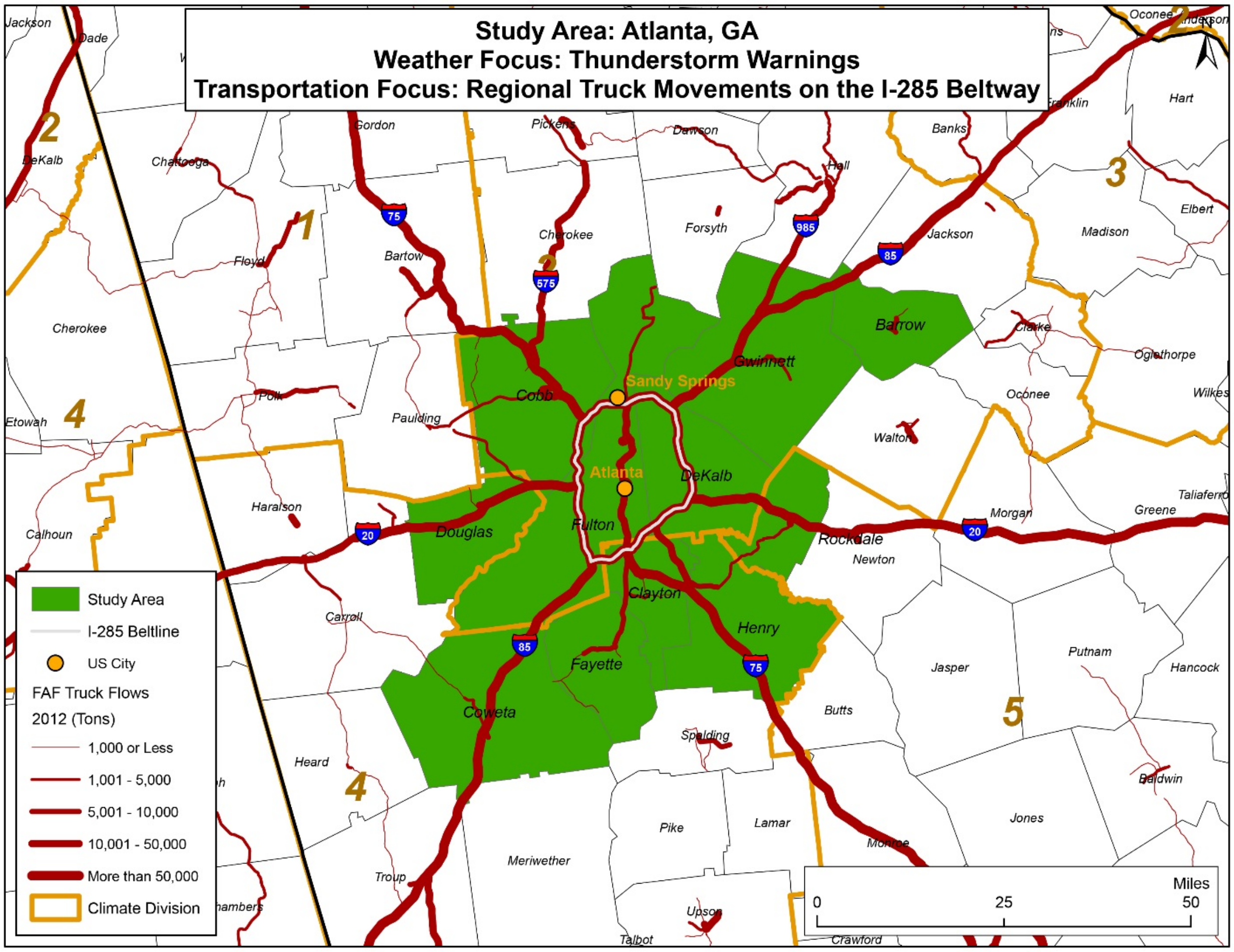


Figure 3. Map. Atlanta, Georgia study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

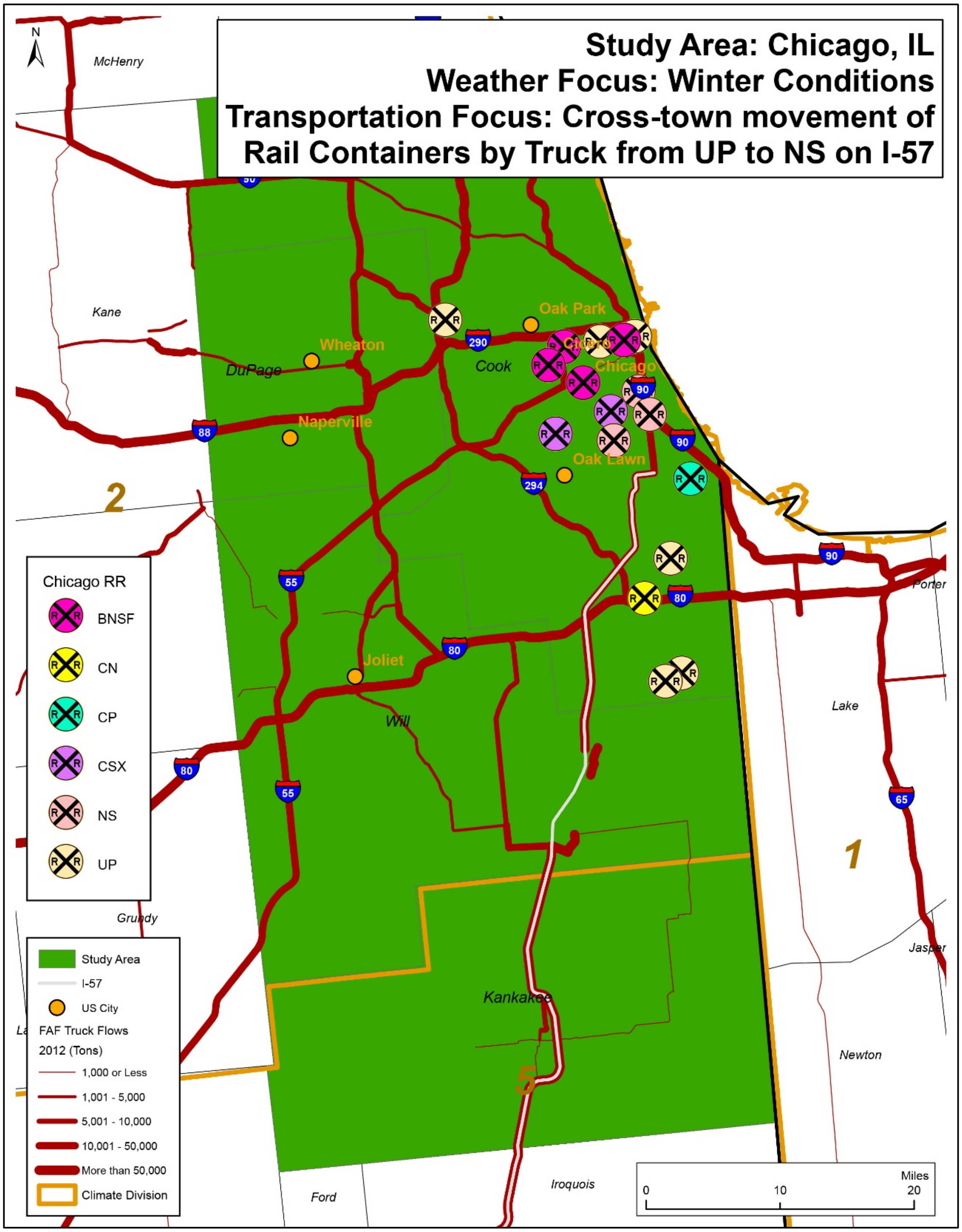


Figure 4. Map. Chicago, Illinois study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

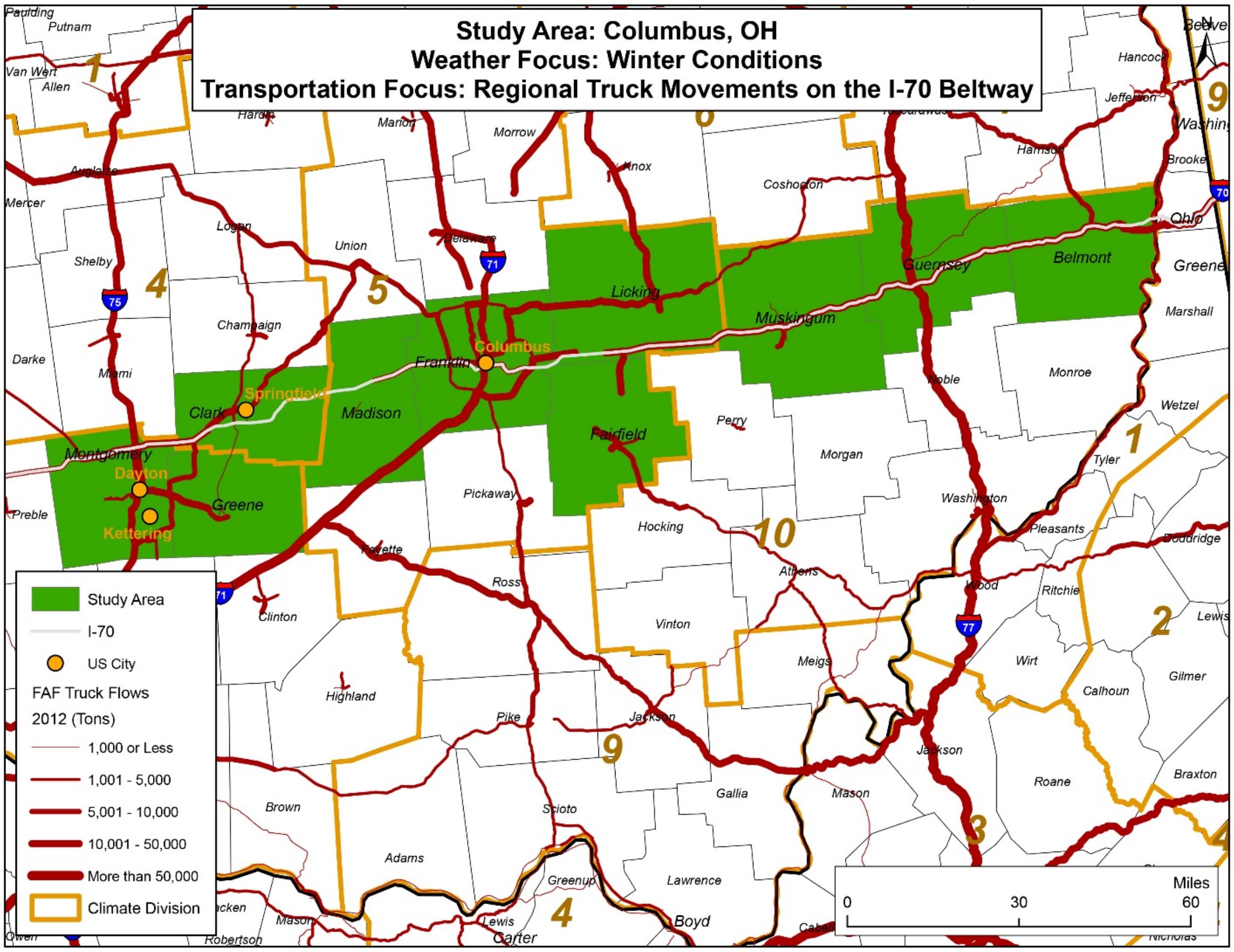


Figure 5. Map. Columbus, Ohio study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

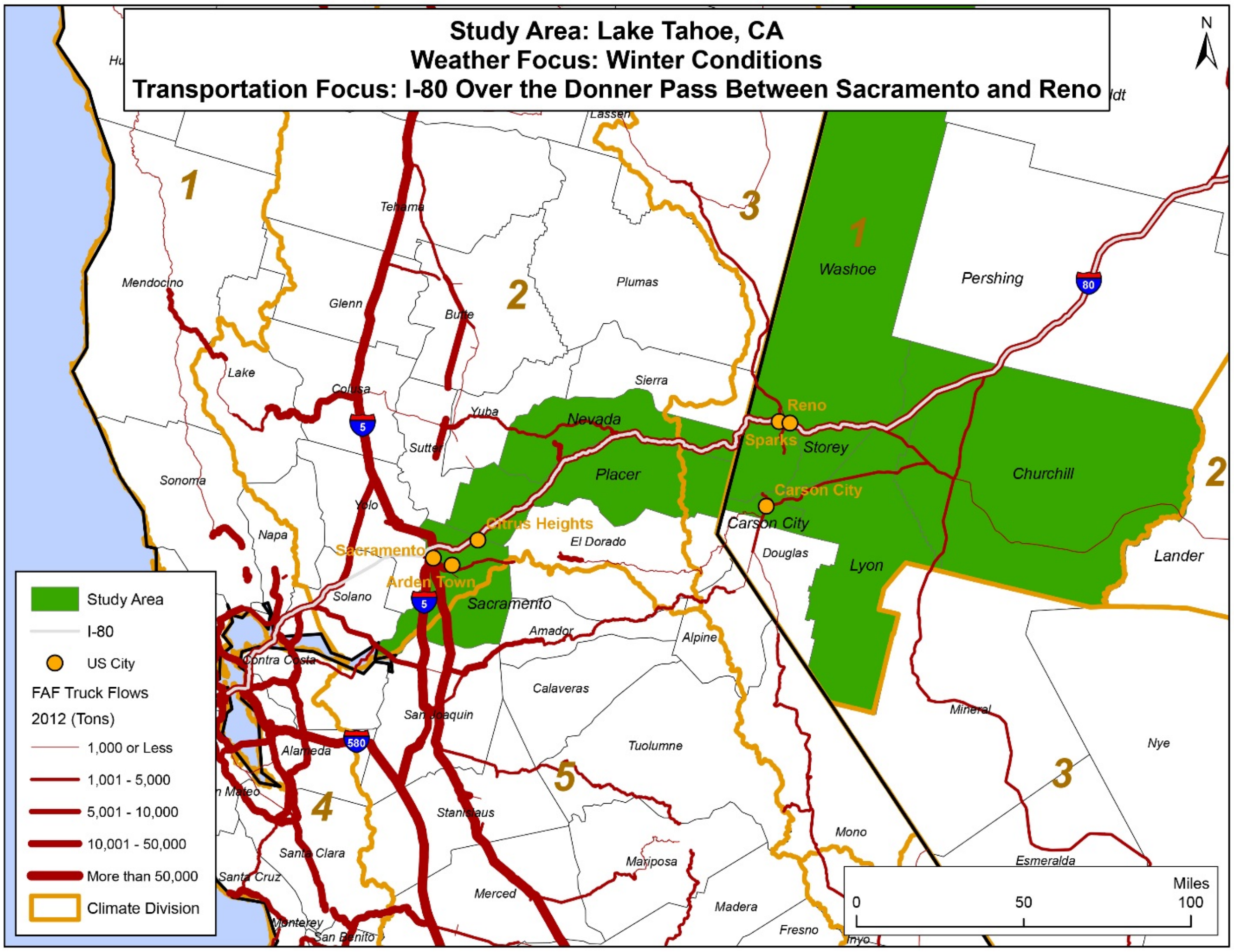


Figure 6. Map. Lake Tahoe, California study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

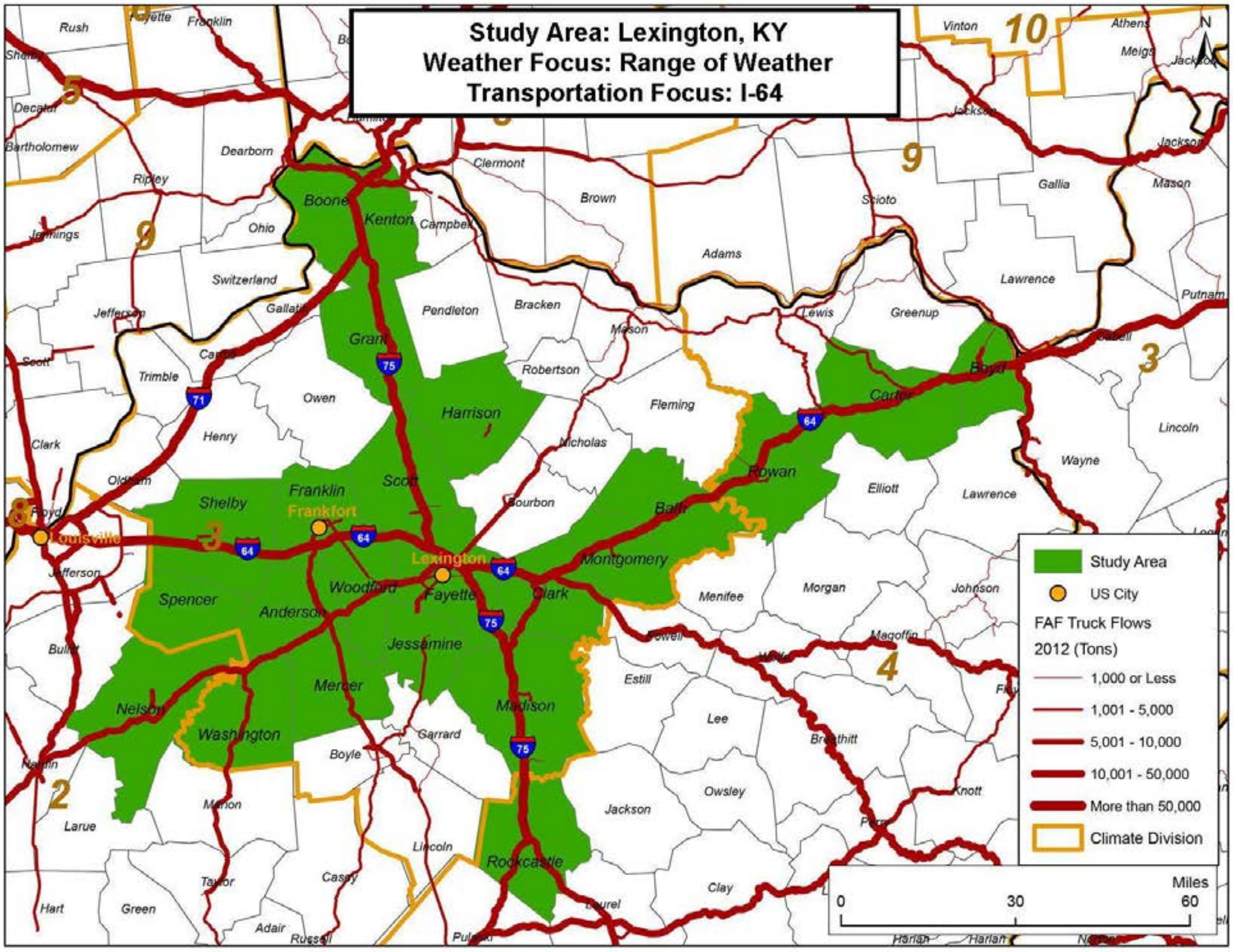


Figure 7. Map. Lexington, Kentucky study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

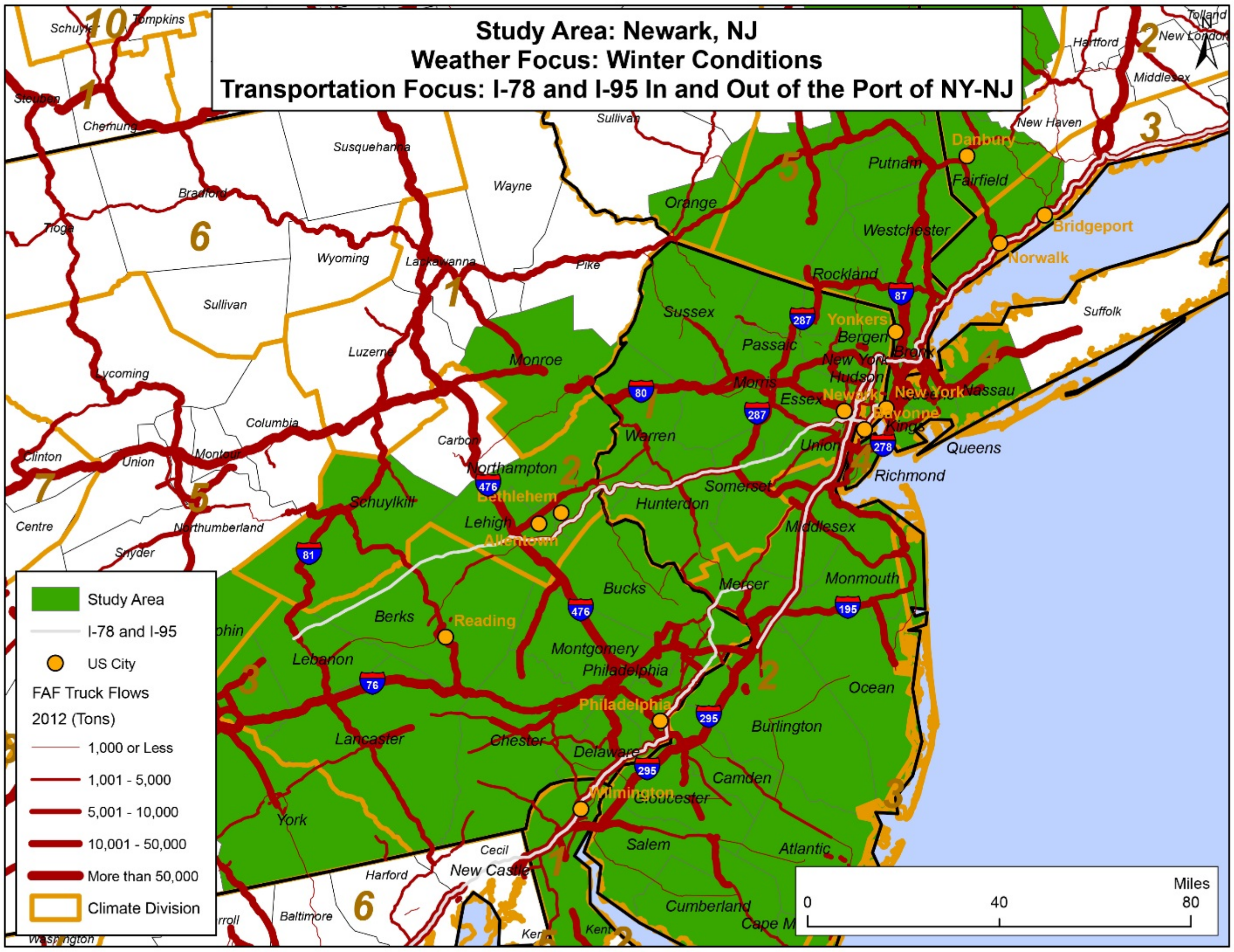


Figure 8. Map. Newark, New Jersey study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

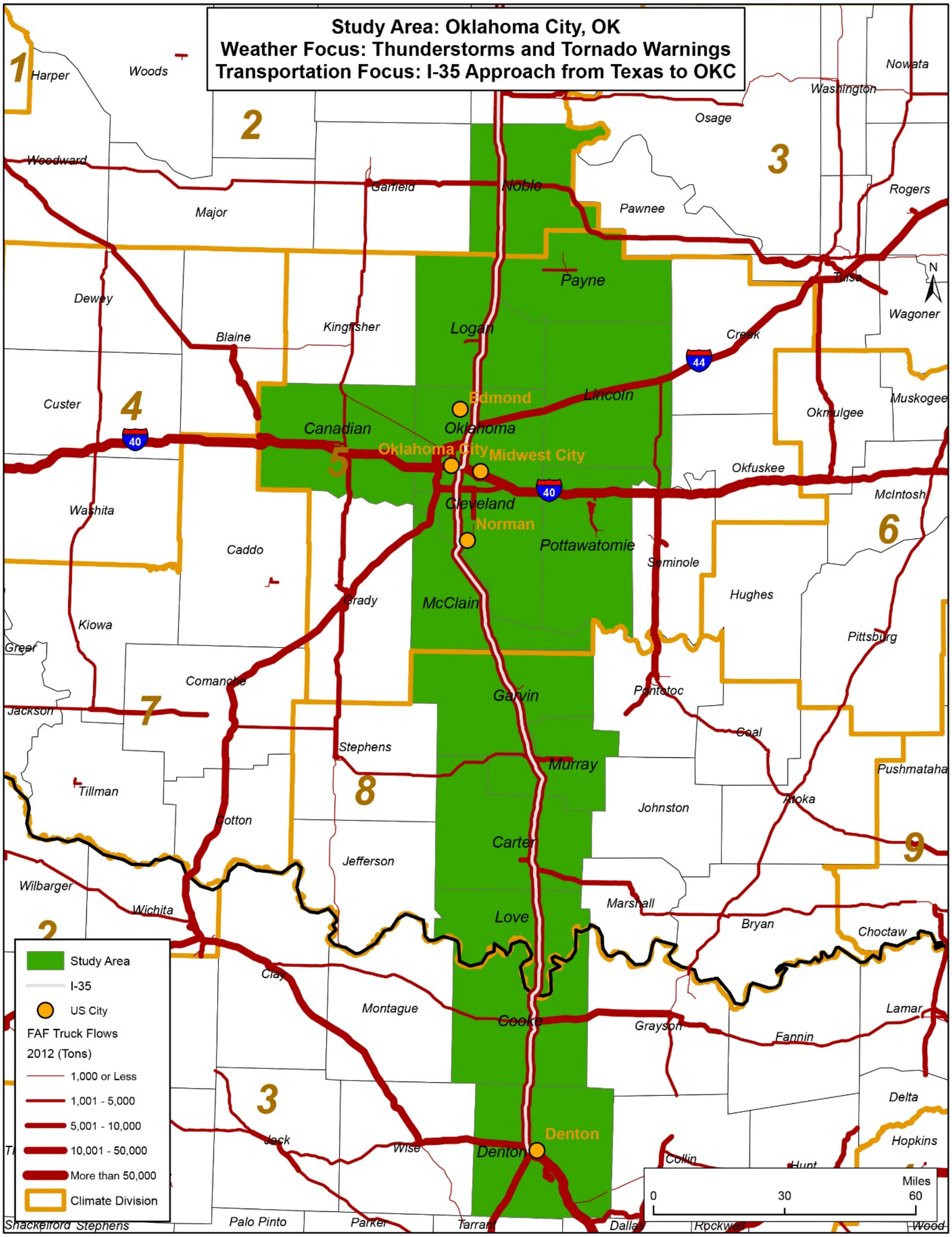


Figure 9. Map. Oklahoma City, Oklahoma study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

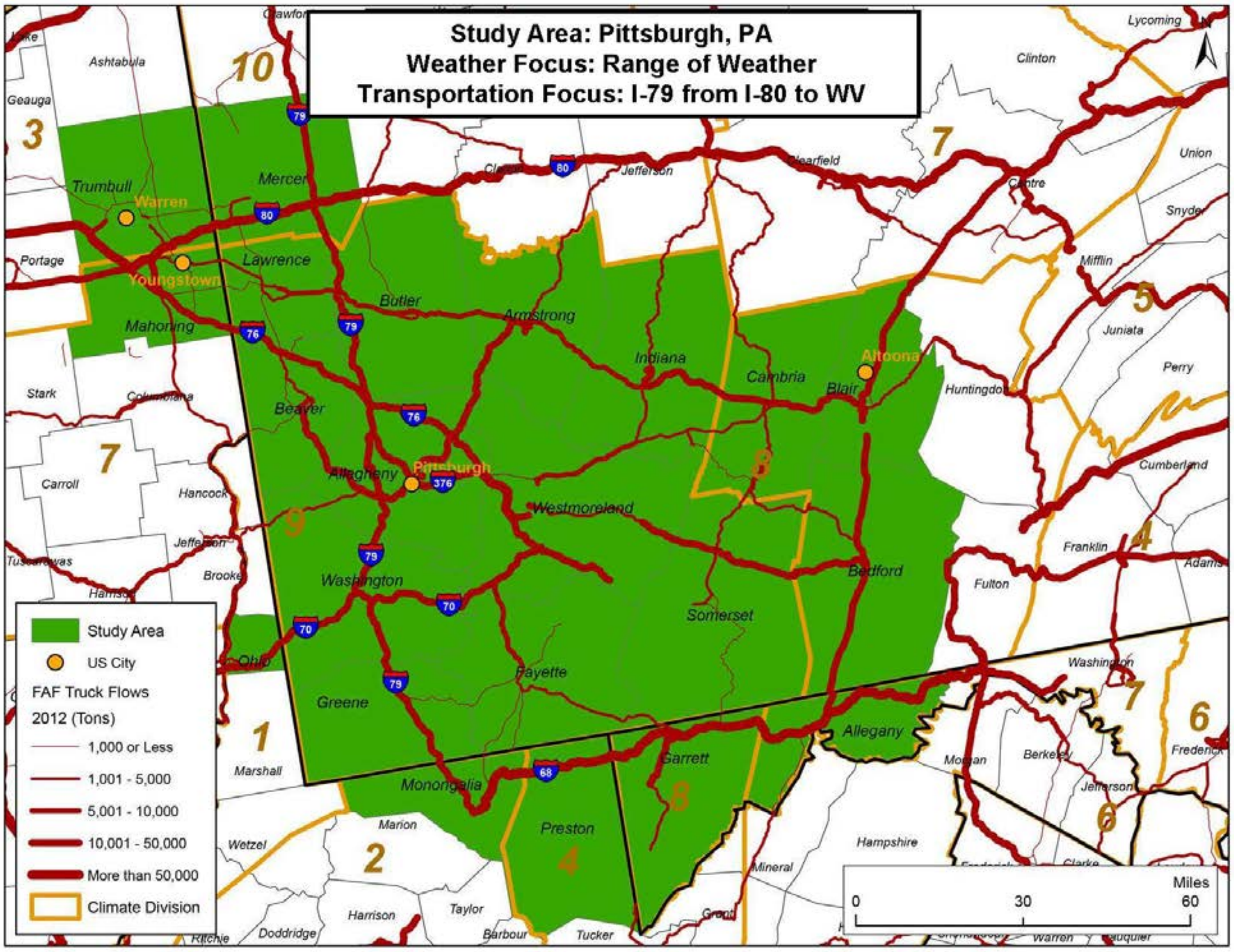


Figure 10. Map. Pittsburgh, Pennsylvania study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

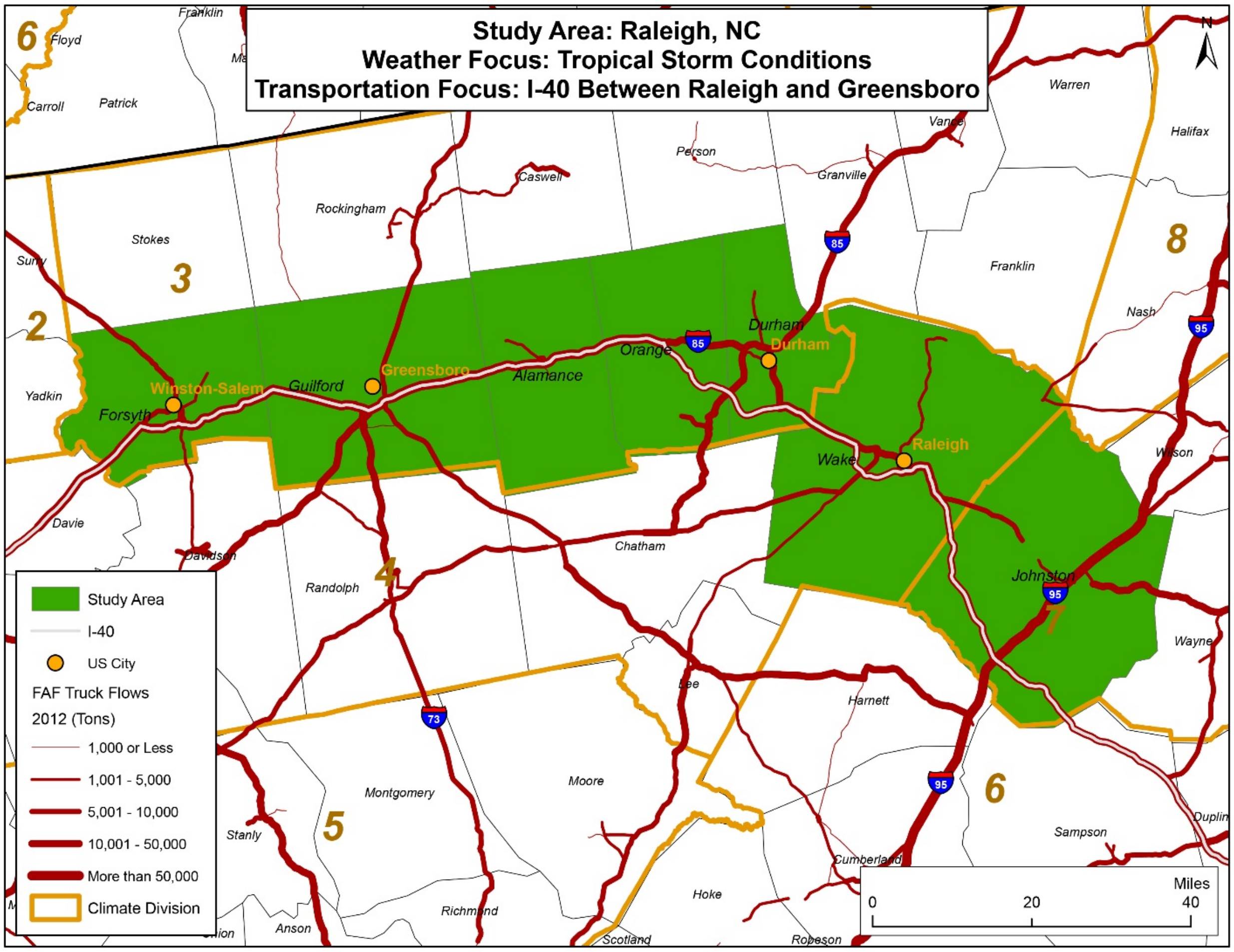


Figure 11. Map. Raleigh, North Carolina study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

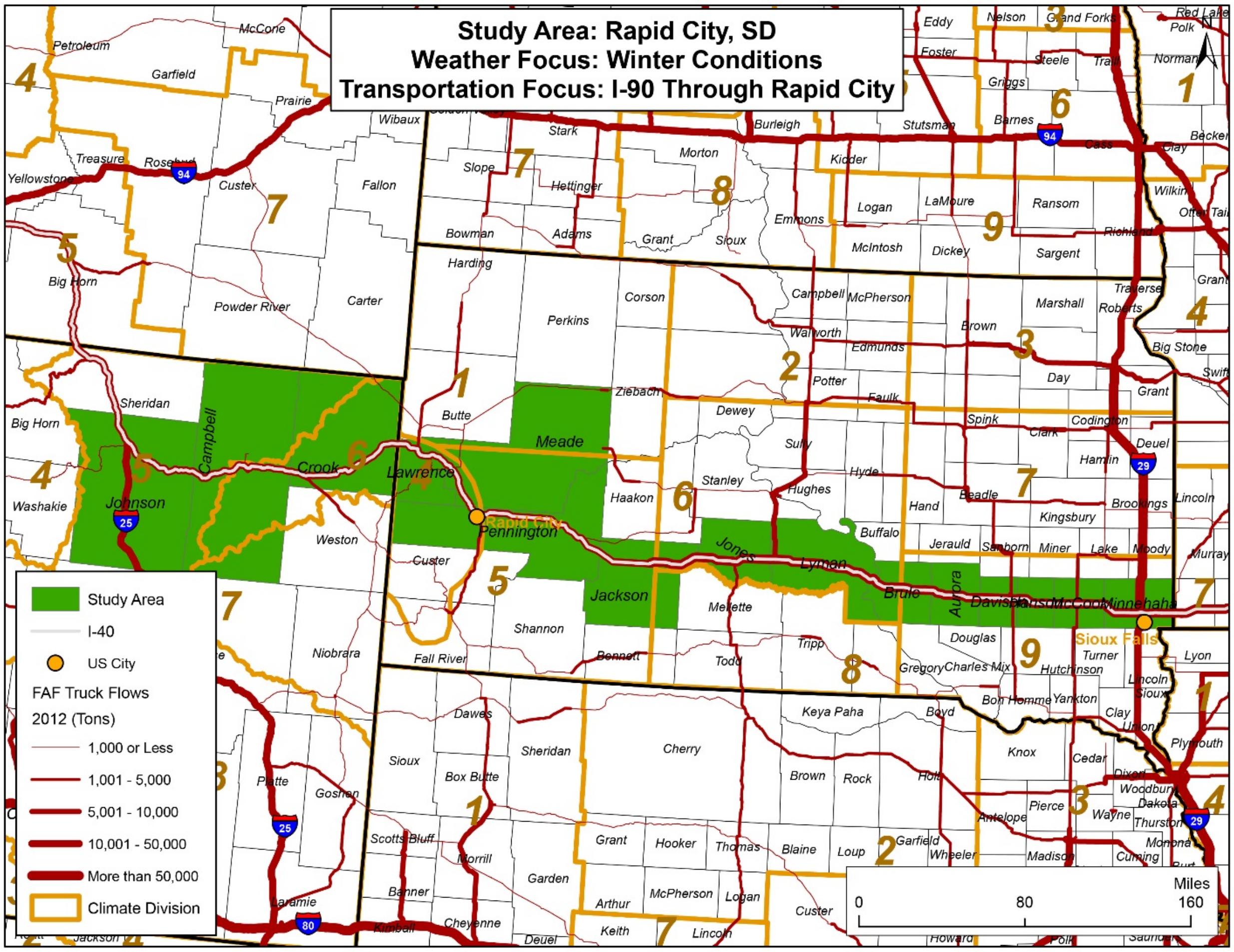


Figure 12. Map. Rapid City, South Dakota study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

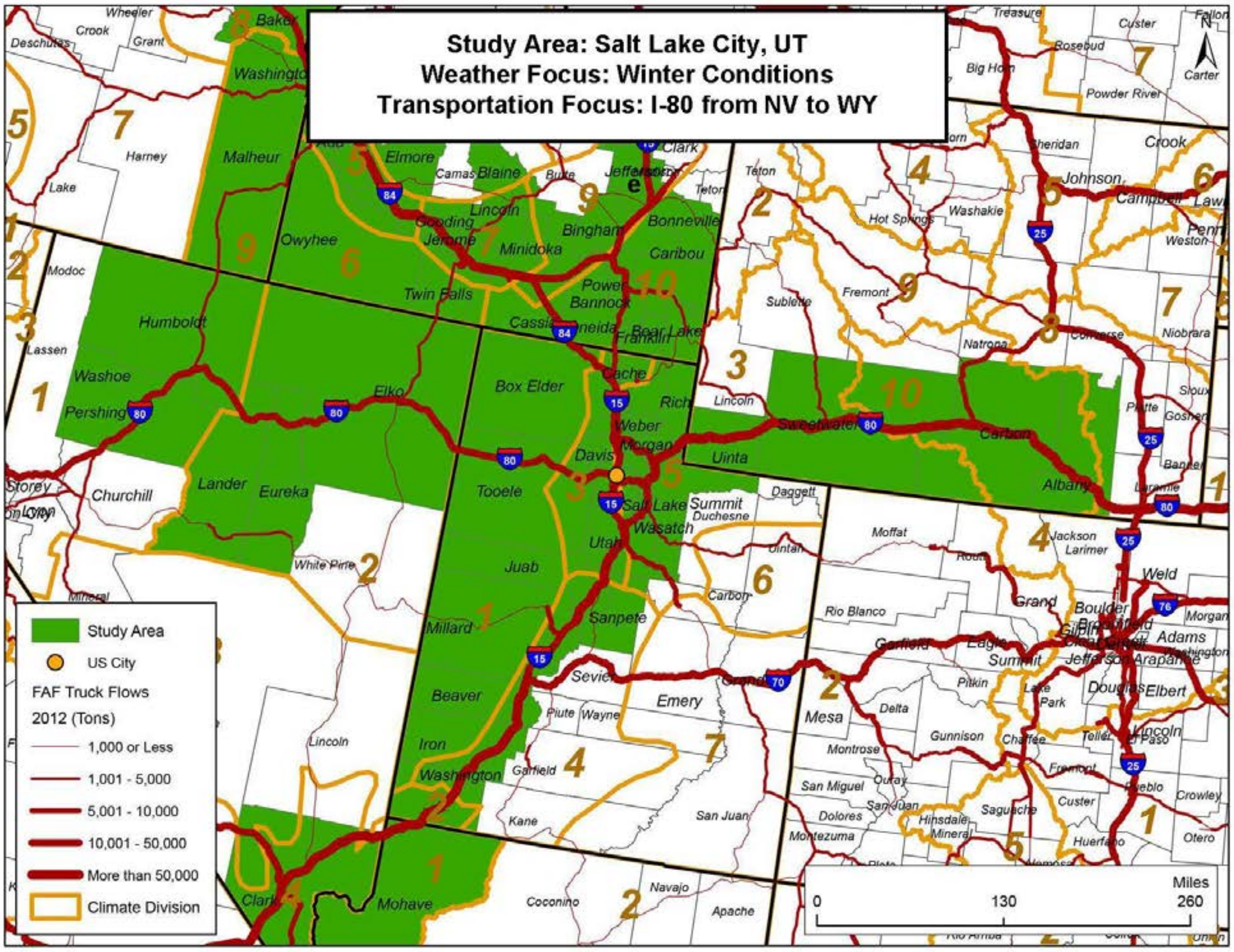


Figure 13. Map. Salt Lake City, Utah study area and transportation focus.
(Source: Cambridge Systematics, Inc.)

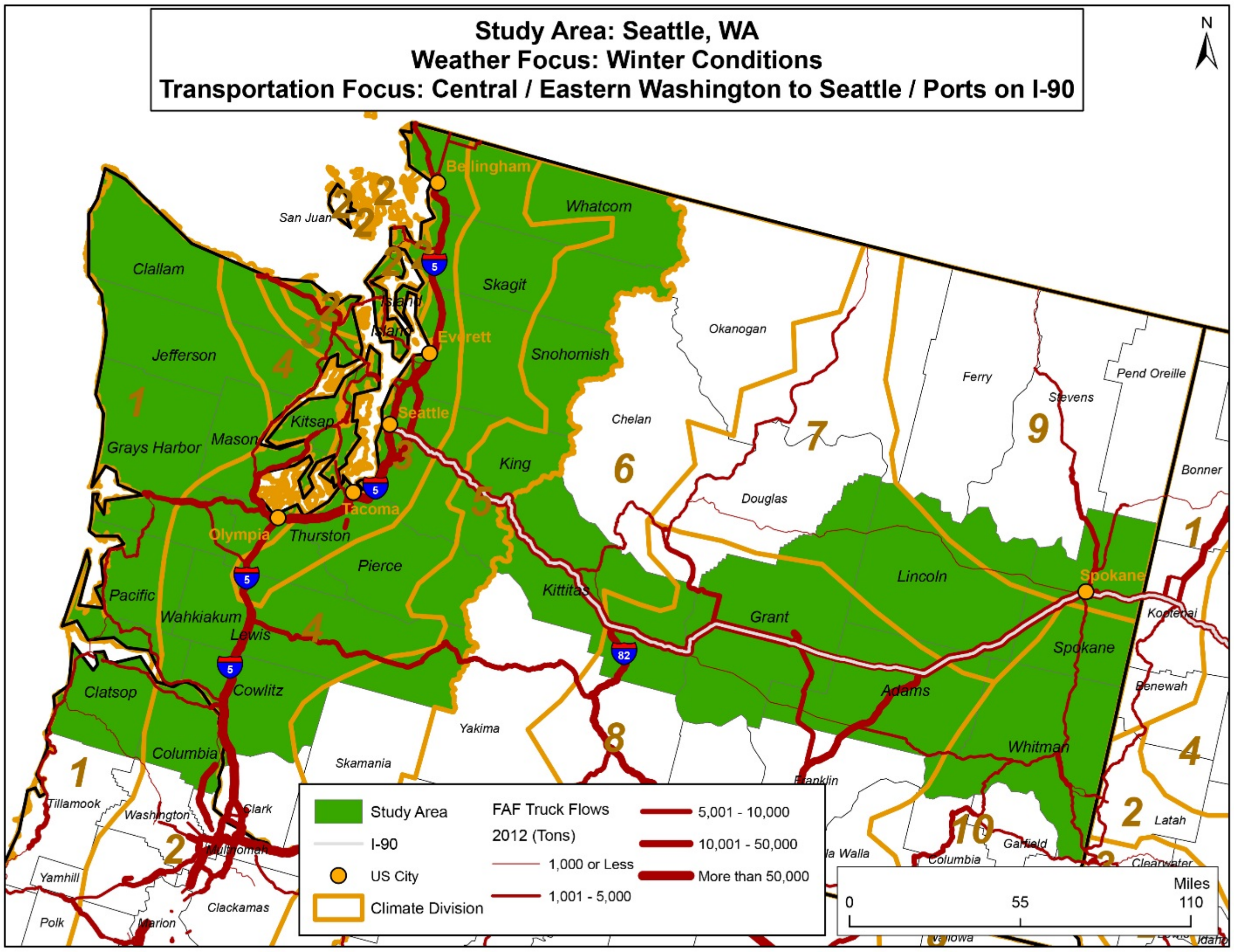


Figure 14. Map. Seattle, Washington study area and transportation focus. (Source: Cambridge Systematics, Inc.)

FINAL DATA PROCESSING METHODOLOGY

Test Cases

Given the final set of study areas, the project team chose three study areas of varying complexity (Atlanta, Georgia; Oklahoma City, Oklahoma; and Denver, Colorado) to test a methodology for processing data on travel-time, weather, and freight. The final transportation focus for each of these three study areas are shown in detail in figures 15, 16, and 17.

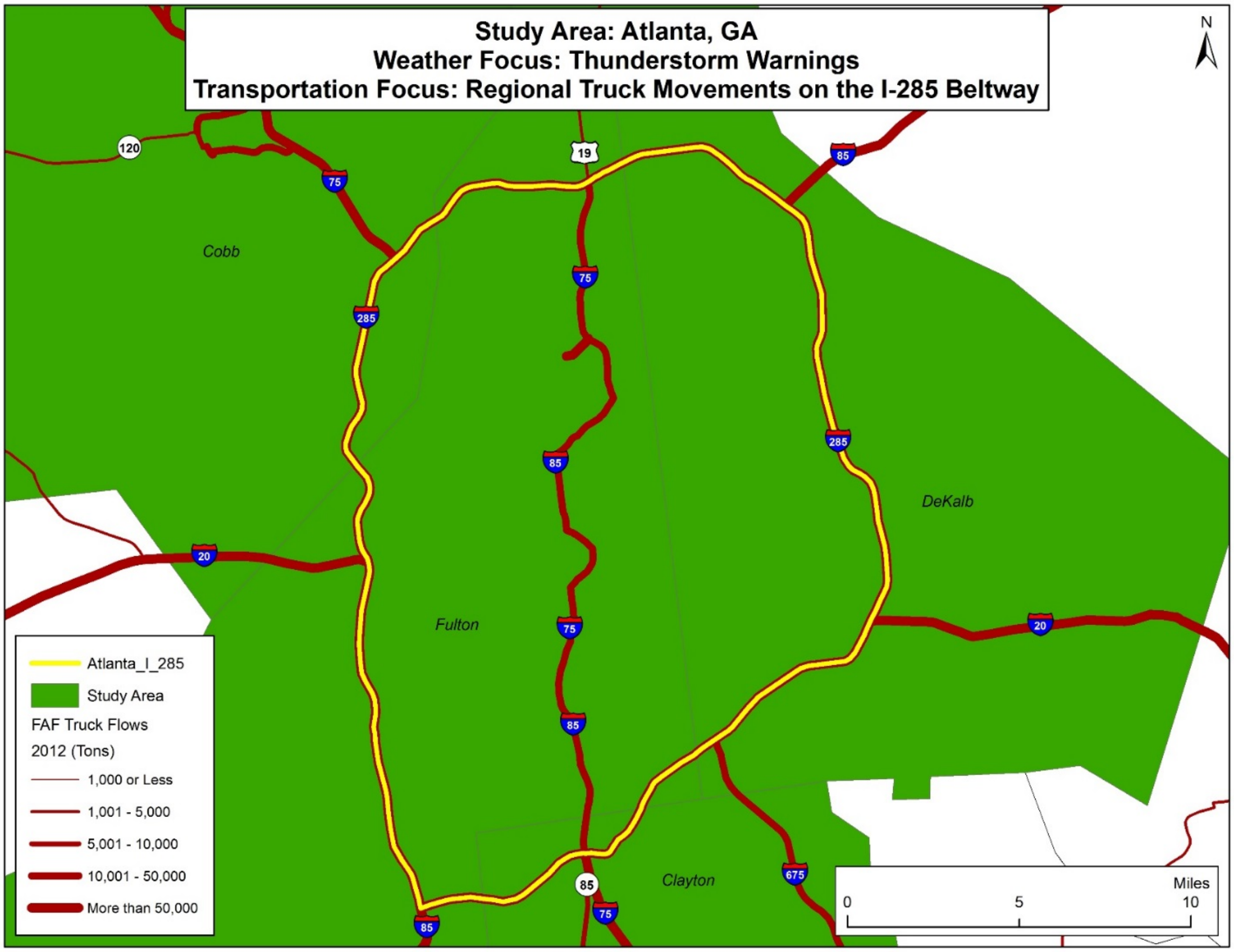


Figure 15. Map. Final Atlanta, Georgia transportation focus.
(Source: Cambridge Systematics, Inc.)

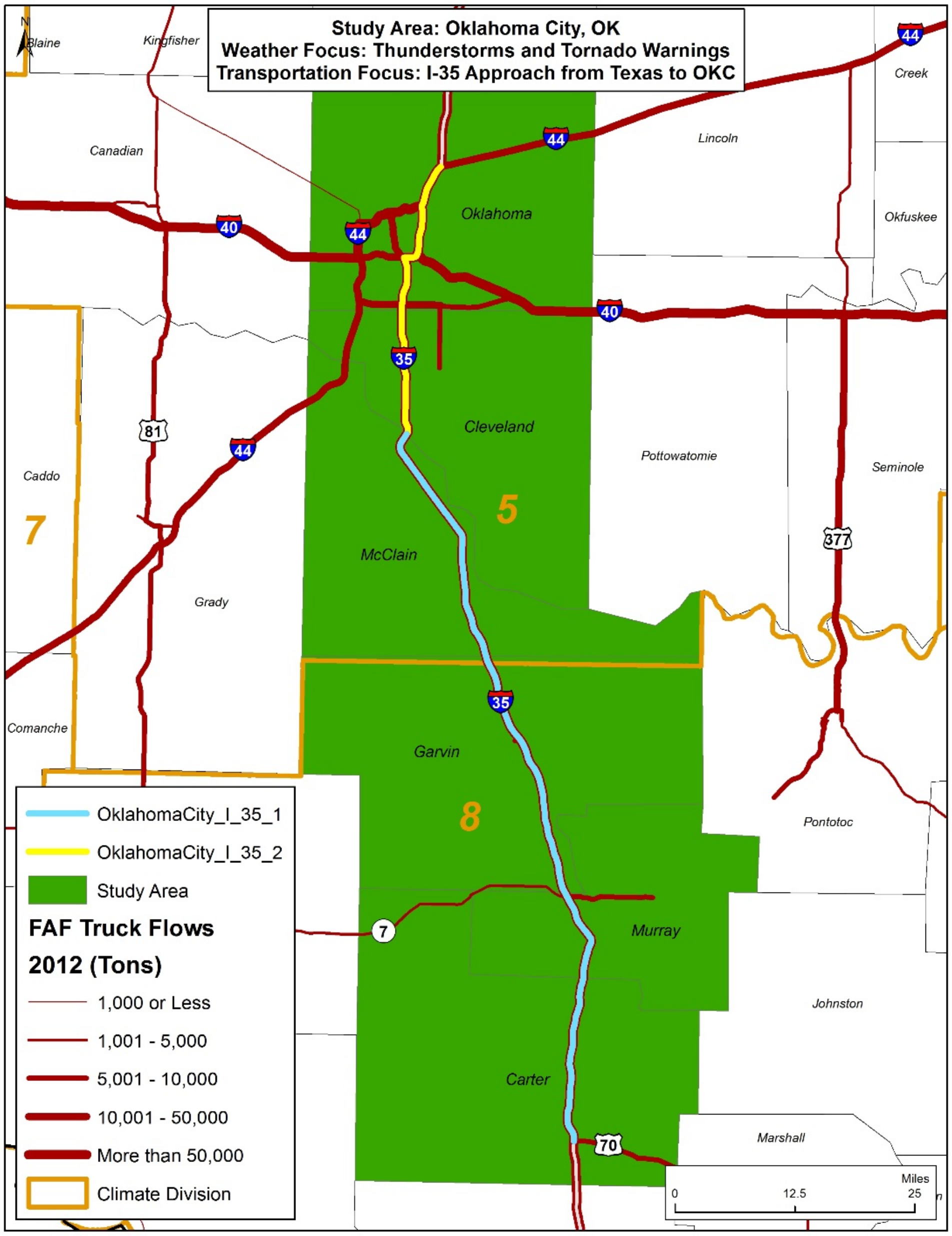


Figure 16. Map. Final Oklahoma City, Oklahoma transportation focus. (Source: Cambridge Systematics, Inc.)

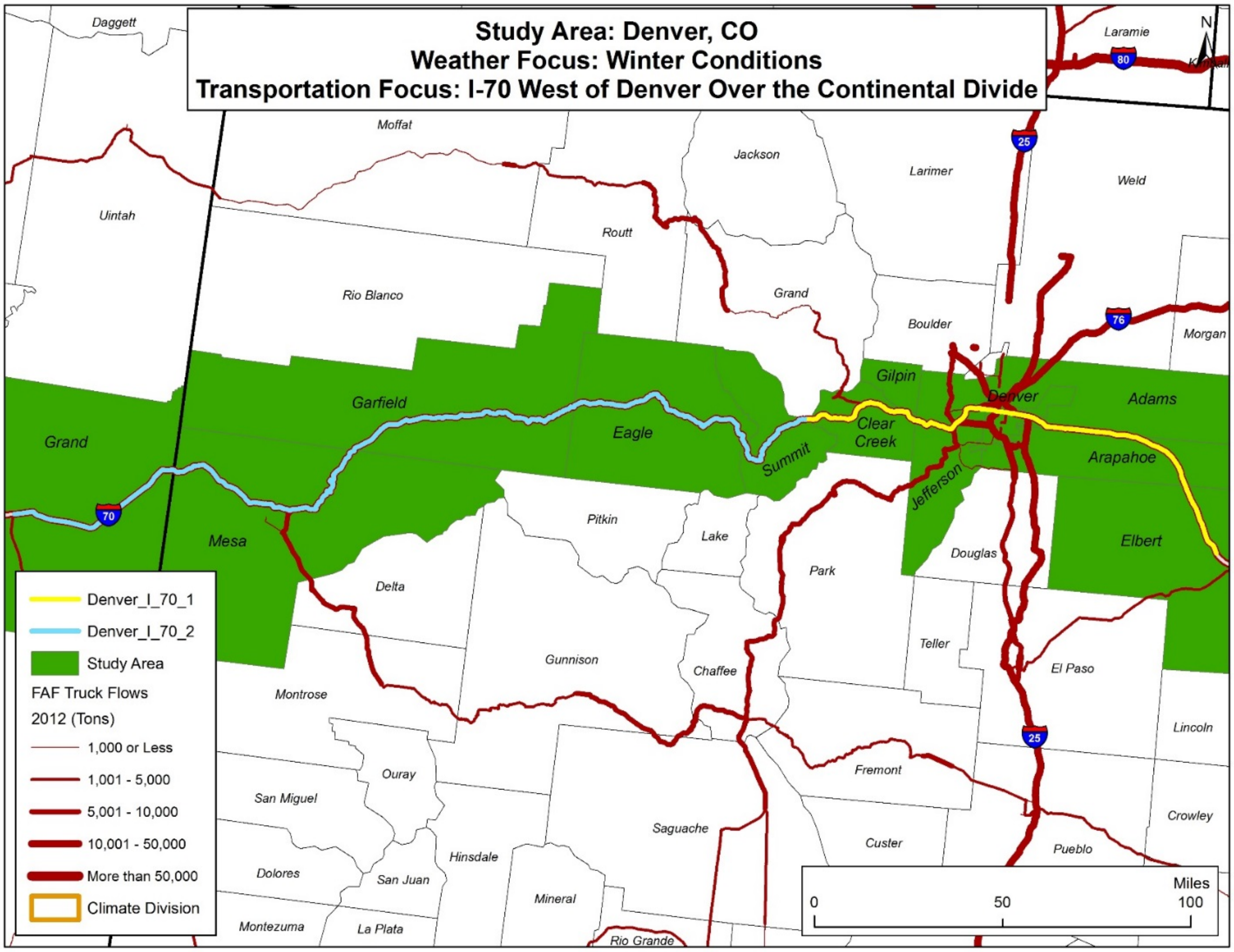


Figure 17. Map. Final Denver, Colorado transportation focus.
(Source: Cambridge Systematics, Inc.)

After working with the three test cases, the project team developed a final data processing methodology, described in detail in the section below. While the team took into consideration all data sources discussed in an earlier technical memo, the final methodology uses only three national data sets: 1) the National Performance Management Research Data Set (NPMRDS) provided by HERE's download service for travel-time data, 2) the National Oceanic and Atmospheric Administration's (NOAA) Storm Events Database for weather data, and 3) Federal Highway Administration's (FHWA) Freight Analysis Framework Version 3.5 (FAF3.5) database for freight data. These selections allow consistent data comparisons between study areas, as well as within individual study areas over time. More information on each of these data sets can be found at the following Web sites:

1. NPMRDS via HERE: https://here.flexnetoperations.com/.
2. NOAA's Storm Events Database: http://www.ncdc.noaa.gov/stormevents/.
3. FAF3.5: http://faf.ornl.gov/fafweb/Default.aspx.

One of the objectives of the study was to use the most recent data sets available for the analysis in order to capture the most recent traffic speeds, weather events, and freight flow data. The reporting format of HERE data changed significantly in the middle of 2013. In order to maintain consistency the analysis period began with the HERE data in July 2013 and extended to August 2014. While both the HERE and Storm Events database were current through August 2014, the FAF data was only current through 2012. Given this, FTR Transportation Intelligence models were employed to generate economic impacts for 2015 (the year of the analysis) from this data.

Travel-Time Data: National Performance Management Research Data Set/HERE

The NPMRDS downloaded from HERE's online service (referred to hereafter as "HERE" data) provides data on average travel times for all vehicles, average travel times for passenger vehicles, and average travel times for freight vehicles along the National Highway System (NHS), which carries a large proportion of freight truck traffic.

This data set presented several challenges in adapting the data to this research application. First, the basic unit of roadway in the HERE data is called the Traffic Management Code (TMC). These very small road segments are intended to be used by local Traffic Management Centers, in which trained human operators process traffic and roadway data to implement incident management plans and Intelligent Transportation Systems (ITS) technology. TMCs generally do not map well to other roadway identification codes and thus need to be combined in order to match the data for other roadway segments, such as those used in the FAF data.

Moreover, the TMC data itself is presented in 5-minute "epochs" for each State and each date. The epoch only appears in the data set if a vehicle (of any type) was on the roadway during that epoch. This means that there is an inconsistent number of records per TMC per date. Because the length of each TMC is known, the project team converted average travel times for all vehicles, passenger vehicles, and freight vehicles into miles per hour for each epoch.

Another common issue is that HERE data is actually comprised of two different data sources: it uses NPMRDS data for passenger vehicles but relies on American Transportation Research Institute (ATRI) data for freight vehicles. As a result there were many instances in which truck speeds were greater than passenger vehicle speeds, but the travel time for all vehicles was either greater or less than both the truck and passenger vehicle travel times. This is at least results from the fact that the truck-only travel-time data was oftentimes based on small samples. The team, therefore, did not have confidence in the truck-only data and decided to use the travel-time observations for all vehicles instead. The travel-time observations for all vehicles were based on larger sample sizes and, thus, were more stable. Since, in most cases, truck speeds are not likely to vary significantly from those of general traffic, the team felt that it was reasonable to make the assumption that truck speeds would be the same as general traffic.

HERE provided the data as .csv files for each month by year and by State. Within each file, there were two linkage files, one called "Monthly_Static_File.csv" and a Microsoft Access database called NPMRDS.mdb. NPMRDS.mdb contained a table that was designed to connect to each month of data in order to translate the epochs into geographical information system (GIS) shapefiles. Because the .csv files were too large for most general software, including Esri ArcGIS and Microsoft Access (which was what HERE's user guide recommended), the project team decided to pull the data into Microsoft Access by linking it rather than importing it. Towards this end, all file and field naming conventions were standardized so that one set of queries and one macro could access the needed data. The output of this process was automatically assembled in a new set of final databases, which was also linked to save space.

Weather Data: National Oceanic and Atmospheric Administration's Storm Events Database and National Land Data Assimilation Systems

The project team used the NOAA's Storm Events Database (hereafter the "storm database") and the National Land Data Assimilation Systems (NLDAS) as its primary sources of data on weather events, including event type, State, county, date, time (by hour of the day), and magnitude (e.g., inches of snow per hour). Since weather does not impact traffic most of the time, it was necessary to strategically identify and correlate bad weather events to the travel-time and freight data. The assumption here is that, if weather has any significant impact on traffic, it will occur during relatively major weather events. To this end, all major weather events in the 13 study areas were identified by time and place using the storm database.

The Storm Events Database documents the occurrence of storms and other weather phenomena having significant intensity to cause loss of life, property damage, and/or disruption to commerce, which is the definition of a "major" weather event used in this study. It also documents rare or unusual weather phenomena, such as snow flurries in South Florida, and significant meteorological events, such as record maximum and minimum temperatures or precipitation that occur in connection with another event. The database currently contains information from January 1950 to June 2015; however, due to changes in data collection and processing over time there are unique periods of record available depending on the data type. The National Climatic Data Center (NCDC) has performed data reformatting and standardization of weather event types, but has not changed any values for data on locations, fatalities, injuries, damages, etc. Table 5 on the following page displays the range of weather event types available in the storm database.

The NLDAS data set—which assimilates data from a large range of sources—was then used in the test phase for the actual correlation of detailed weather data gridded to highway segments,[6] specifically for the identified major weather events to the travel-time and freight data. While this provided more precise location of events, the data processing requirements to use this information for all 13 case studies could not be met within project budget and schedule. Both the size of database and the use of different GIS projection systems made it difficult to match NLDAS data to the HERE and FAF databases.

---

[6] The NLDAS is model gridded data that assimilates data from various sources, such as Meteorological Assimilation Data Ingest System (MADIS), Road Weather Information System (RWIS), Automated Surface Observing System (ASOS), and mesonets. The analysis data, not the forecast projection, were used. Detailed data for 8-kilometer grids matched to highway segments.

As a result, the Storm Events Database was used as the basis for identifying weather conditions. This allowed major events to be located by time, by county, and by climate region boundary.[7] While this methodology did not necessarily locate a weather event exactly over a roadway at a specific time (it only associates weather events reported in a given county with the roadways in that same county), it provided a good proxy for the impact of weather events given the currently available data. Since these weather events were classified as major events with relatively wide geographic impact in most cases, it is reasonable to assume that most major study area roadways within the same county as the weather event in question were exposed to the weather event. It is important to note, that the size of the county will influence the results. In general urban counties are smaller in size than rural counties. It is, therefore, more likely that there will be a better match between the reported weather and actual roadway conditions on the more heavily traveled urban roads. Further, actual roadway impacts were inferred from exposure and proximity to weather events; this series of assumptions is important to bear in mind in interpreting the findings of this analysis. It should, however, be noted that the HERE data was compressed from 5-minute raw data into hourly time periods, which increases the likelihood that, over the course of an hour, the weather events in question occurred over the study area roadways.

Table 5. Weather event types included in National Oceanic and Atmospheric Administration's Storm Events Database.

Astronomical Low-Tide	Hurricane (Typhoon)
Avalanche	Ice Storm
Blizzard	Lake-Effect Snow
Coastal Flood	Lakeshore Flood
Cold/Wind Chill	Lightning
Debris Flow	Marine Hail
Dense Fog	Marine High Wind
Dense Smoke	Marine Strong Wind
Drought	Marine Thunderstorm Wind
Dust Devil	Rip Current
Dust Storm	Seiche
Excessive heat	Sleet
Extreme Cold/Wind Chill	Storm Surge/Tide
Flash Flood	Strong Wind
Flood	Thunderstorm Wind
Frost/Freeze	Tornado
Funnel Cloud	Tropical Depression
Freezing Fog	Tropical Storm
Hail	Tsunami
Heat	Volcanic Ash
Heavy Rain	Waterspout

---

[7] Records in the storm database were organized by county and/or by zone. A zone might be comprised of several counties, or it might refer to a local area designated by the National Weather Service. Such inconsistencies made it at times difficult to locate the relevant records for this project's study area and required manual look-up to match the climate zone and correct county.

Table 5. Weather event types included in National Oceanic and Atmospheric Administration's Storm Events Database (continued).

Heavy Snow	Wildfire
High Surf	Winter Storm
High Wind	Winter Weather

Many of the weather event types presented in table 5 are not applicable to the study areas examined in this project. The entire storm database was downloaded and compiled into a Microsoft Access database in an effort to be comprehensive. For the final analysis, however, only the 25 most relevant weather event types, shown in table 6 below, were analyzed. The notable missing weather event type from both the storm database and the final analysis is light rain. This is because, if only light rain occurred, the event did not meet the criteria for inclusion in the storm events database. However, many of the rain events in the database probably included a period of light rain toward the beginning or end of the storm.

Table 6. The 25 weather event types included in the final analysis.

Avalanche	Heavy Rain
Blizzard	Heavy Snow
Cold/Wind Chill	High Wind
Dense Fog	Ice Storm
Excessive Heat	Lake-Effect Snow
Extreme Cold/Wind Chill	Lightning
Flash Flood	Strong Wind
Flood	Thunderstorm Wind
Freezing Fog	Tornado
Frost/Freeze	Wildfire
Funnel Cloud	Winter Storm
Hail	Winter Weather
Heat	

The project team processed the weather data to produce a final data set of all relevant records with State, county, date, time, weather event type, and magnitude. Since there were several instances in which multiple storm events were recorded in one day, the data remained organized by storm event and each storm event was given a unique identifier. Each storm event included the time four hours before and four hours after the recorded time of the storm event (t=0). Care was taken to ensure that storms crossing the midnight hour were coded as a single storm event. Finally, the processed data from the storm database was linked to the final HERE databases.

Freight Data: Freight Analysis Framework Version 3.5

The Federal Highway Administration's Freight Analysis Framework Version 3.5 (FAF3.5) provides estimates of tonnage, value, and domestic ton-miles by region of origin and destination. The project team selected the 2012 FAF3.5 data over the 2007 FAF3 data—which would have also allowed FAF estimates to be separated by commodity types—because the 2007 FAF3 data would have been outdated relative to the 2012 to 2014 weather and travel-time data used in this analysis.

The FAF3.5 data includes origin-destination tables that are delivered on a static roadway network. Under a separate contract Cambridge Systematics, Inc. developed an “assignable” network which allows future FAF origin-destination tables to be assigned to the roadways. For the analysis at hand, the FAF3.5 assigned network was used and matched to the HERE and Storm Event database. The following paragraph describes this process in more detail.

Using Esri ArcGIS 10.2, the FAF3.5 data was overlaid with HERE data linked to a shapefile. The FAF3.5 data was organized as FAF segments, which were typically much longer than the HERE data links and were loaded with daily 2012 truck tonnage in kilotons. FAF segments tended to start and end at interchanges because this is where trucks typically enter or exit the highway system. The process of matching FAF3.5 data to HERE data in ArcGIS was done manually. As is common with data from different sources, the FAF3.5 and HERE data sets did not use the same projected coordinate systems and so care was taken to correct and match the projections of both files. Further, the FAF3.5 data is a centerline data set (one line used for all traffic) while the HERE data is bidirectional (two lines—one for each side of the highway). Since the raw FAF data includes tonnage and is bidirectional, conversion of tonnage to truck volumes was required as well as assignment based on direction. The assignment of FAF version 3.5’s 2012 Origin-Destination table to an assignable highway network was done by Cambridge Systematics using methods that it developed for FHWA. Additional adjustments were made to truck volumes during the weather index analysis, using data from the FTR freight model. Overall both the HERE and FAF3.5 data sets were robust and complete, except in a few rare cases when a record from one data set was missing or the data was null.

Once linked, The FAF3.5 data was checked for consistency. As a final step, the project team added pertinent information such as county and study area name to the FAF3.5 records. The data set was then linked to the final databases.

FINAL DATABASES

For the final databases, each of the three data sets was carefully combined so they produced data by storm event. Storms were county-based, in that storm event reports are broken down by county, and, in some cases, by weather zone in the database. Reports of storm events are received from counties and other sources and combined with National Weather Service (NWS) data. Given this method of reporting, roadway segments in a given county were assumed to have experienced all storms associated with that county. Real-world experience dictates that this is not always the case, especially for certain types of storms. However, for larger weather events that typically impact traffic, such as winter storms, it is likely that a large proportion of the county experienced the storm and so it has been assumed that the entire county experienced the storm. The final data set included the time four hours before and four hours after each storm, an identifier for these records, an identifier for the storm event record, a weekday flag, a holiday flag, county, study area, and total storm duration. Since the HERE data contained a full set of the records for the 14-month analysis period, periods with no storm event could be identified and matched with storm event periods to determine the weather delay index. The availability of 24-hour data allowed flexibility in identifying the time periods when recurring congestion impacted the subject roadways. Periods with and without storm events could be matched by day of week and time of day.

CHAPTER 3: RESULTS

ATLANTA PROTOTYPE

As a first step in the data analysis process, the project team used the Atlanta, Georgia study area as a prototype to explore the implications and limitations of the data. The Atlanta data contained 23 major weather events. A few major weather events had more than one condition (e.g., lightning and thunderstorm winds) so a total of 29 separate weather events were analyzed for their impact on the 23 different Freight Analysis Framework (FAF) highway segments in Atlanta. Based on these numbers, the project team felt that there was sufficient data to draw meaningful general conclusions in the study area, although not enough data to differentiate between weather types. The cumulative analysis of all 13 study areas, discussed in the Cumulative Results section below, had a sufficient sample size to achieve good statistical significance in differentiating between weather types.

Exploring the time-of-day effects in Atlanta revealed that Atlanta has asymmetrical rush hours in terms of average speed (miles per hour)—specifically, the speed decrease is more acute during the morning rush hour than the evening rush hour, as shown in figure 18. Both rush hours also started earlier than expected. These findings suggest that time-of-day effects may be a critical variable in determining the impact of weather on freight.

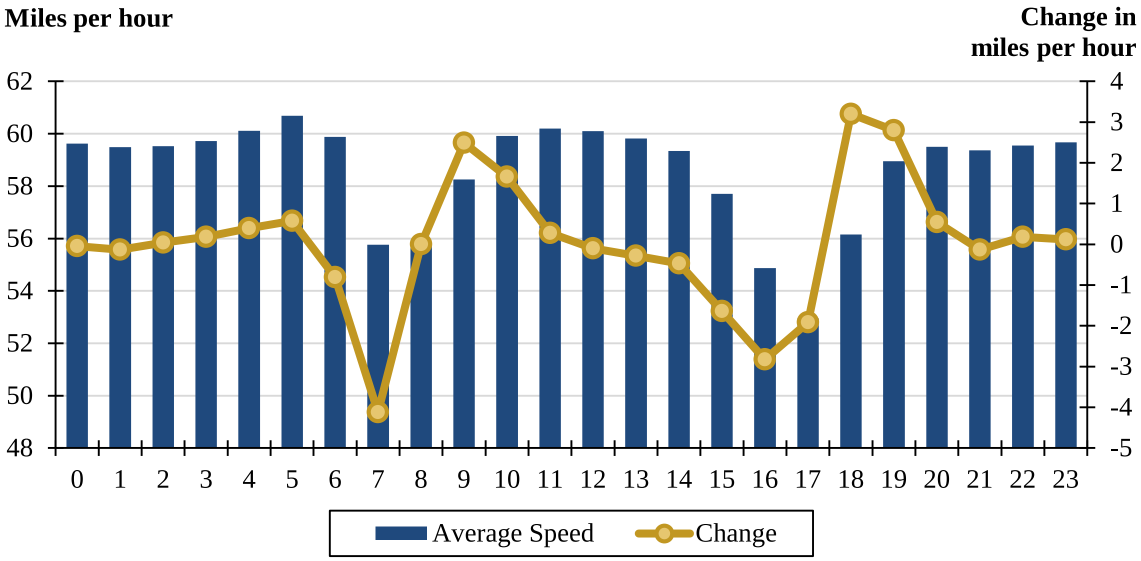


Figure 18. Chart. Time-of-day effects in the Atlanta, Georgia study area, averaged over all 23 Freight Analysis Framework segments.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The project team also explored potential lead and lagging effects of different weather events using the Atlanta data. Although the sample sizes were too small to draw conclusions by weather event type, this analysis highlighted areas to focus on in the broader analysis. The four-hour periods before and after the reported event (hour 0) were evaluated in this study. Some events did last longer but the team felt that comparisons between different weather events and different geographic areas could be more easily made if consistent time periods were used. Figure 19 illustrates that the impacts of weather events—in terms of change in speed relative to the previous hour—are concentrated around the time of storm (hour 0) and that recovery is generally quick. Winter weather events, however, are an important exception. Ice storms (shown in gold) appear to have a lead effect while winter storms (shown in red) demonstrate a large lagging effect. Regarding the lead effect, there are several reasons why traffic speeds may slow down prior to the reporting of the storm. These include 1) delayed reporting of the storm, 2) weather conditions beginning with light precipitation before the storm is reported, and 3) forecasts of poor weather conditions which encourage drivers to leave early for their destinations, resulting in increased traffic and congestion. Lagging effects, on the other hand, are likely to do with issues such as delays in snow and ice clearance times or congestion that has built up since the beginning of the storm.

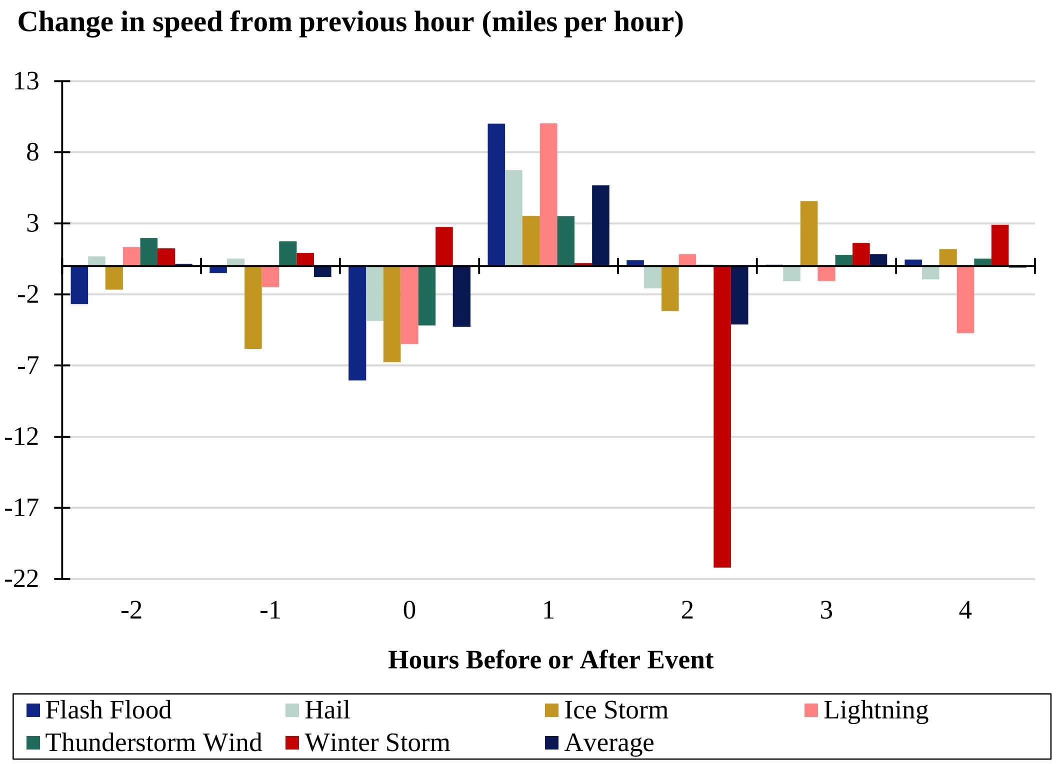


Figure 19. Chart. Effects of different weather events over time in Atlanta, Georgia. (Source: Noel Perry, Cambridge Systematics, Inc.)

These analyses led to a key initial conclusion that time of day matters when it comes to the impact of weather on traffic. Figure 20 below shows the maximum (peak) effects of weather by time of day, revealing that the largest impacts are clearly concentrated around rush hour periods, particularly during the evening rush hour. This is likely because thunderstorms, one of the most frequent major weather events in Atlanta, often occur in the afternoon and evening. The hour-20 events in figure 20 included a flash flood, a discontinuous event that could have produced a range of impacts on the roadways that would overwhelm traffic, including standing water on the roadways, flash floods on arterials that caused regional backups, or a flash flood on the Interstate itself.

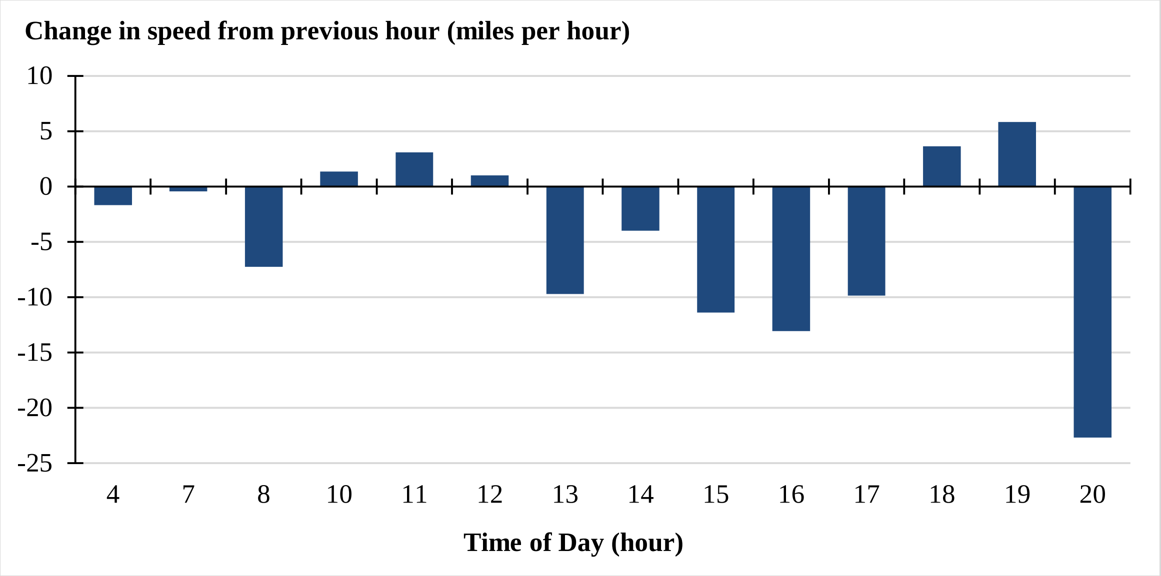


Figure 20. Chart. Change in speed from previous hour for all analyzed weather events in Atlanta, Georgia.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The data also suggests that the location of the FAF highway segment may matter, but the sample sizes were too small to draw conclusions and the differences between FAF segments were moderate. To avoid the danger of drawing conclusions with small sample sizes, this part of the prototype analysis was not carried forward to the cumulative analysis.

CUMULATIVE RESULTS

The results of the cumulative analysis of all 13 study areas are described below. As discussed in the Final Data Processing Methodology section, it is important to bear in mind the limitations of the methodology and data used in the analysis while interpreting these results. Mainly, weather events were associated with roadways based on county—meaning that all study area roadway segments in a given county were assumed to have been exposed to weather events reported within the same county. This assumption was necessary in order to conduct the desired analysis using current data sources, but it also introduced some uncertainty into the analysis. Specifically, it is not certain that all roadway segments were exposed to a weather event that occurred in the same county; the likelihood of exposure depends on the size of the weather event and geographic variation within the county. Further, even if a roadway segment was exposed to a given weather event, it is not certain that the weather event significantly impacted roadway conditions. The methodology, however, infers roadway condition impacts from weather event exposure and proximity. Other aspects of the methodology, however, increase confidence in these assumptions and help to counter uncertainty. For example, the weather events analyzed were generally large storms, increasing the probability that a given roadway in the same county was impacted. Additionally, the HERE data was compressed from 5-minute raw data into hourly time periods, which increases the likelihood that, over the course of an hour, the weather events in question occurred over the study area roadways. With these limitations in mind, the results of the cumulative analysis are presented below.

The sample size of weather events across all 13 study areas was sufficiently large to achieve good statistical significance. Figure 21 shows the total number of weather events by type across all 13 study areas—several types have numbers in the thousands.

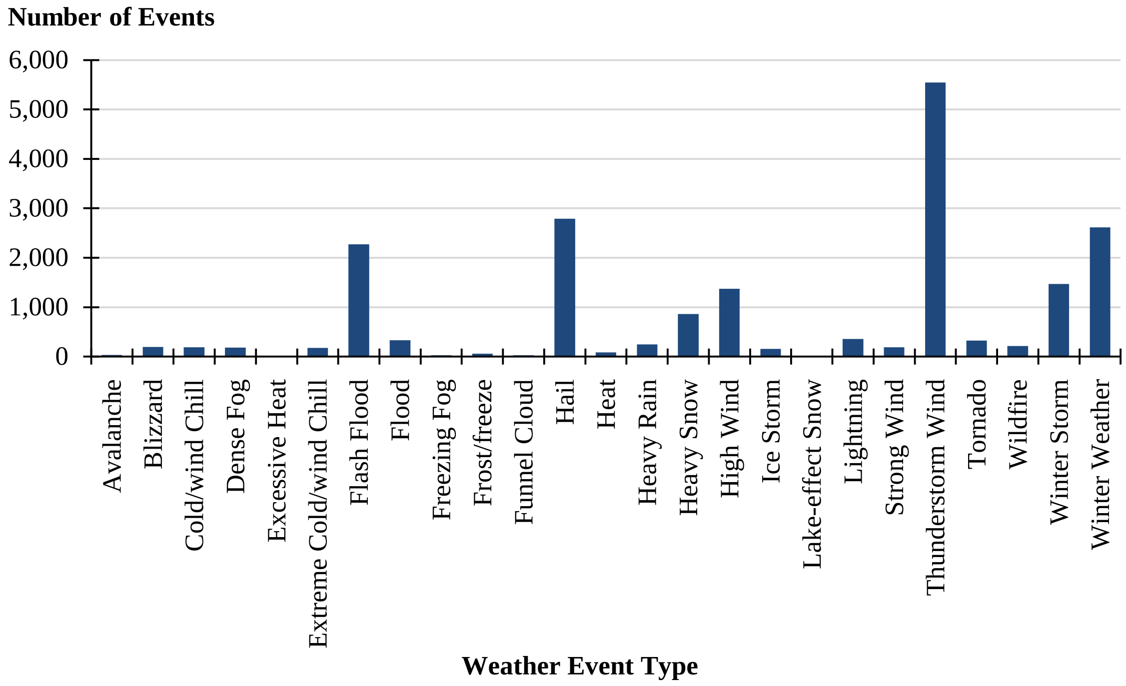


Figure 21. Chart. Number of weather events by type across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The weather events associated with the 13 study areas did not always correlate with decreased traffic speeds relative to similar time periods when weather events did not occur. Figure 22 demonstrates that time periods during the weather events under consideration were only associated with reduced travel speeds 52 percent of the time, when compared to similar time periods when there was no adverse weather. The rest of the time, these weather events were associated with no change in travel speeds (16 percent of the time) or even an increase in travel speeds (32 percent of the time). These numbers serve as a reminder that when changes due to weather are small, other factors can easily outweigh the impact of weather on traffic. Similarly, since the methodology infers road impacts from weather events, these numbers serve as a further reminder that a weather event does not always translate into negative roadway impacts. In addition the temporal resolution of the weather data is coarse (hourly data are being used) and may not reflect the actual timing of events. These events may come on gradually with no discernible impacts initially (e.g., the weather event may have started 45 minutes into hour 0). Another factor is the possibility that in some cases the highway segment in question was not affected by an associated weather event in the county, as discussed above. All things considered, figure 22 again illustrates the limitations of the project's data and assumptions while still revealing an important trend—that overall statistically significant decreases in speed were found to be correlated with most weather events.

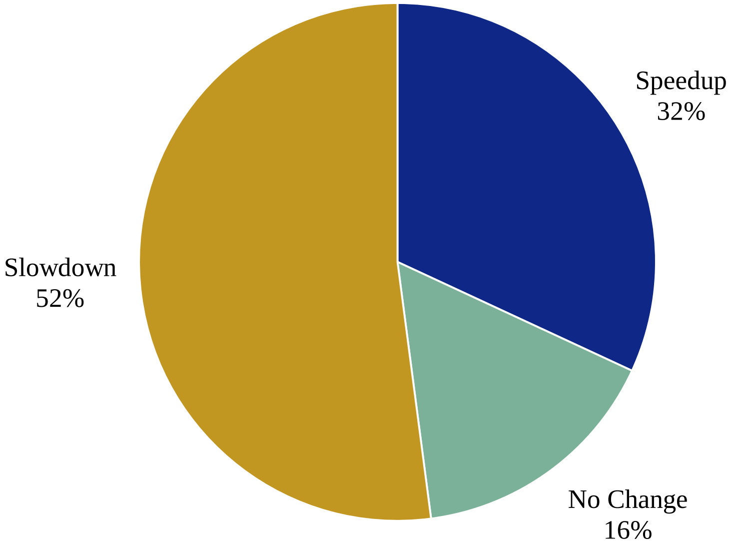


Figure 22. Chart. Travel speeds during time periods with weather events relative to similar time periods under normal conditions.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Figure 23 shows that, of all FAF segments across all 13 study areas, only 21 percent of segments were characterized by irregular traffic flow (i.e., experienced morning and evening rush hour congestion. The term "irregular flow" is used here to describe segments that have a statistically lower-speed during peak hours, while "even flow" is used to describe segments where there is no statistically significant change in speed over the course of the day. The Atlanta prototype indicated that time of day influences the magnitude of weather impacts on traffic. Time of day, however, may have a smaller influence over the impacts of weather on the even flow highways which comprise 79 percent of all segments, compared to the less common irregular flow highways.

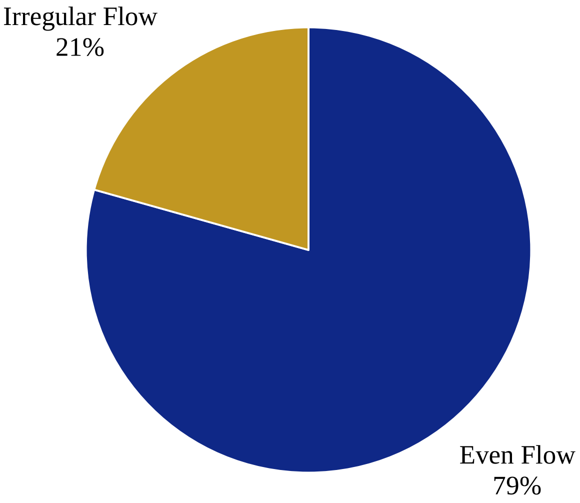


Figure 23. Chart. Freight Analysis Framework segments across all study areas characterized by the nature of traffic flow.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Still, the insights from the Atlanta prototype are confirmed at the cumulative-level when the average loss in speed (miles per hour) during weather events on irregular flow highway segments is compared to the average loss in speed on even flow segments. Figure 24 shows that for all weather events (i.e., weather events that decrease, increase, or do not change travel speeds) and for only those that are correlated with decreased speeds, irregular flow roads suffer more in terms of loss in speed during weather events.

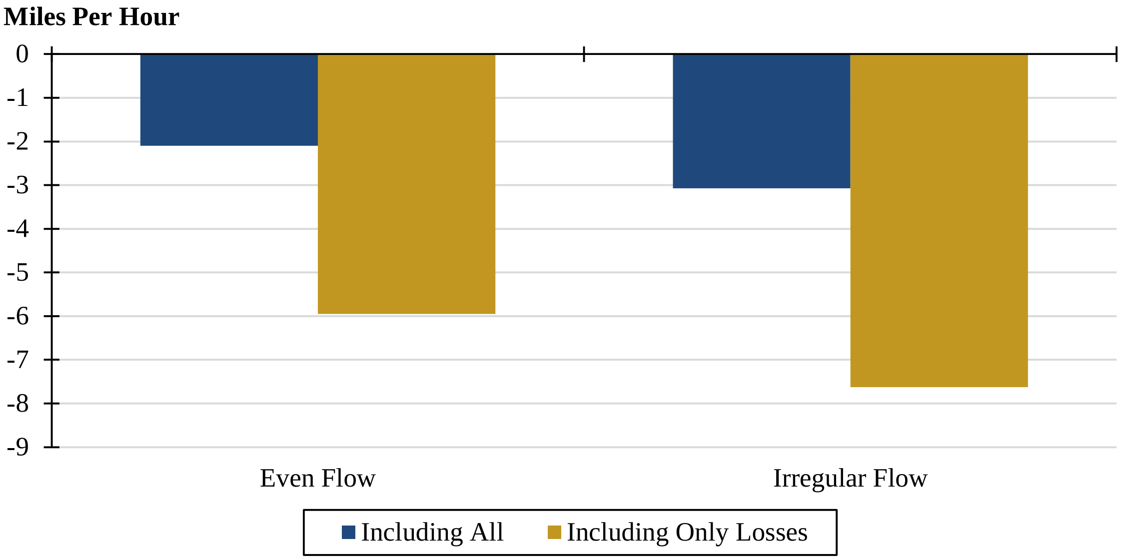


Figure 24. Chart. Average loss in speed on even flow versus irregular flow roads for all weather events ("All") and for only weather events that decrease speeds ("Only Losses"). (Source: Noel Perry, Cambridge Systematics, Inc.)

The reason for this, however, is more subtle than simply the effects of rush hour combined with the effects of weather. Figure 25 shows that irregular flow highways in the 13 study areas are on average busier and experience more truck traffic each day.

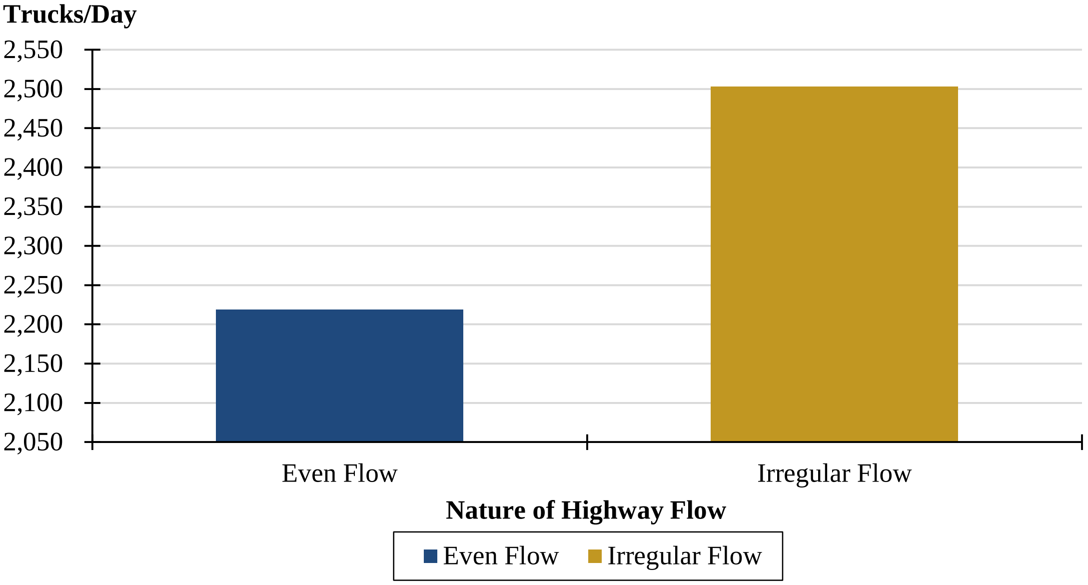


Figure 25. Chart. Trucks per day on even flow and irregular flow highways. (Source: Noel Perry, Cambridge Systematics, Inc.)

From this, one might expect that irregular flow highways are kept closer to their capacity limits during all hours of the day, not just during rush hour periods. Indeed, figure 26 confirms this by showing that irregular flow highways experience greater losses in speed during weather events that occur in the middle of workday as well. Figure 26 shows that even flow highways still suffer relatively more during rush hour periods than they do during off-peak periods, reinforcing that—to some extent—time of day matters for both irregular flow and even flow highways.

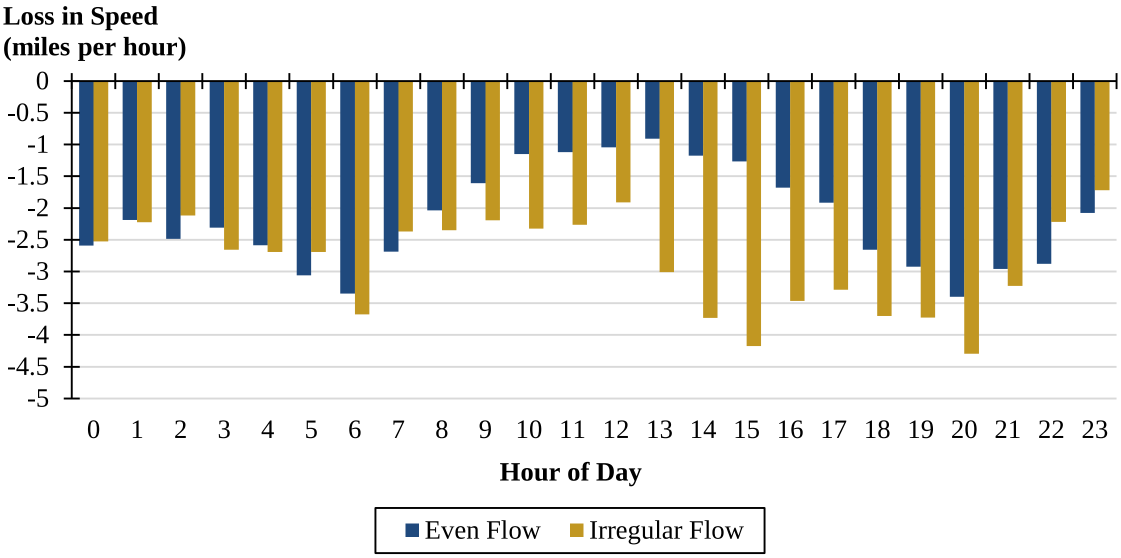


Figure 26. Chart. Average reduction in travel speeds due to weather on even flow versus irregular flow roads for each hour of the day.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The project team also examined average travel speeds across all 13 study areas throughout the day during normal weather conditions to get a sense of baseline conditions along these highway segments. Figure 27 demonstrates that, even during normal weather conditions, people tend to drive faster during the daytime on both weekdays and weekends. This is important to keep in mind when considering the impact of nighttime weather events on travel speeds.

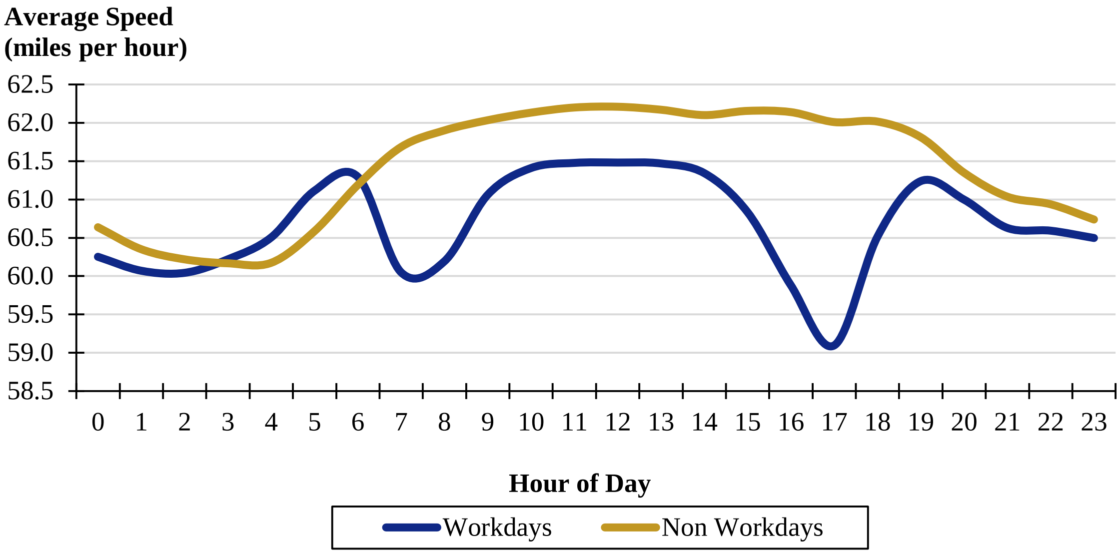


Figure 27. Chart. Average speed by hour under normal weather conditions.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Average speed during normal weather conditions also was broken down by study area size—small, medium, and large—based on the population and economic intensity of the metropolitan area associated with the study area. Figure 28 shows that, again, people tend to drive faster during the daytime in study areas of all sizes. Additionally, study areas within smaller regions (e.g., Lake Tahoe, California) enjoy higher travel speeds all hours of day, although the overall pattern is very similar to that of medium and large study areas.

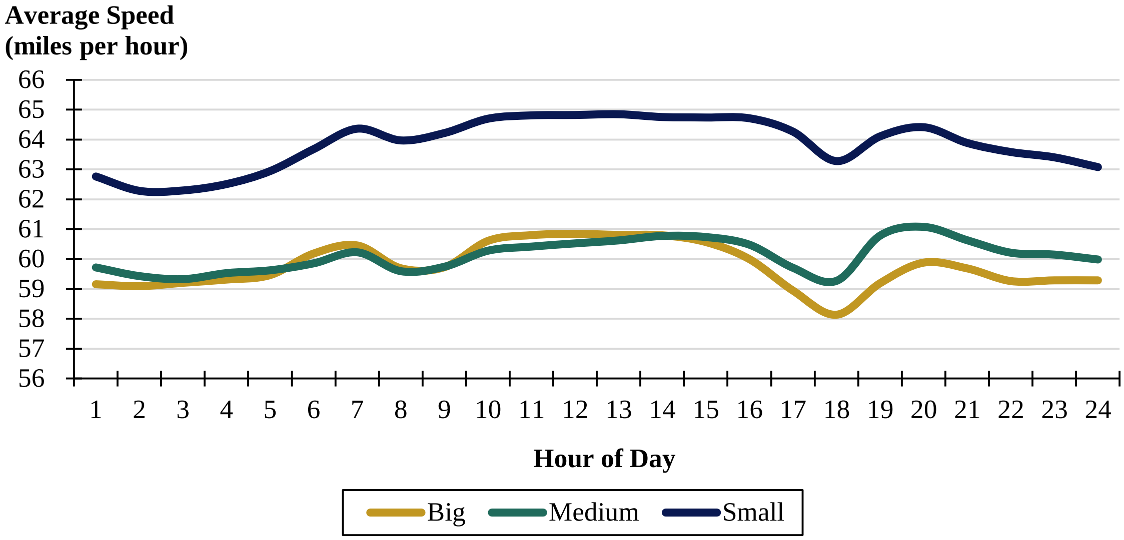


Figure 28. Chart. Average speed by hour for small, medium, and large study areas under normal weather conditions
(Source: Noel Perry, Cambridge Systematics, Inc.)

When weather events are introduced to these highway segments, average speeds decrease for a number of hours both before and after the event. Figure 29 illustrates that when all weather events and all study areas are considered, speeds begin moderately decreasing three hours prior to the weather event, decrease the most during the first hour of the event, and then maintain a depressed state for the next several hours. The larger decreases in speed during the hours after the event indicate that the impact of weather on traffic generally has a lagging effect. The decreases one to three hours prior to the event were very small and could reflect increased traffic due to people trying to get home prior to the event or light precipitation that has not yet been recorded as a major storm. It should be noted again here that in some cases the impact of weather events over time may be partly affected by weather events moving around the county, as weather events were associated with highway segments based on county.

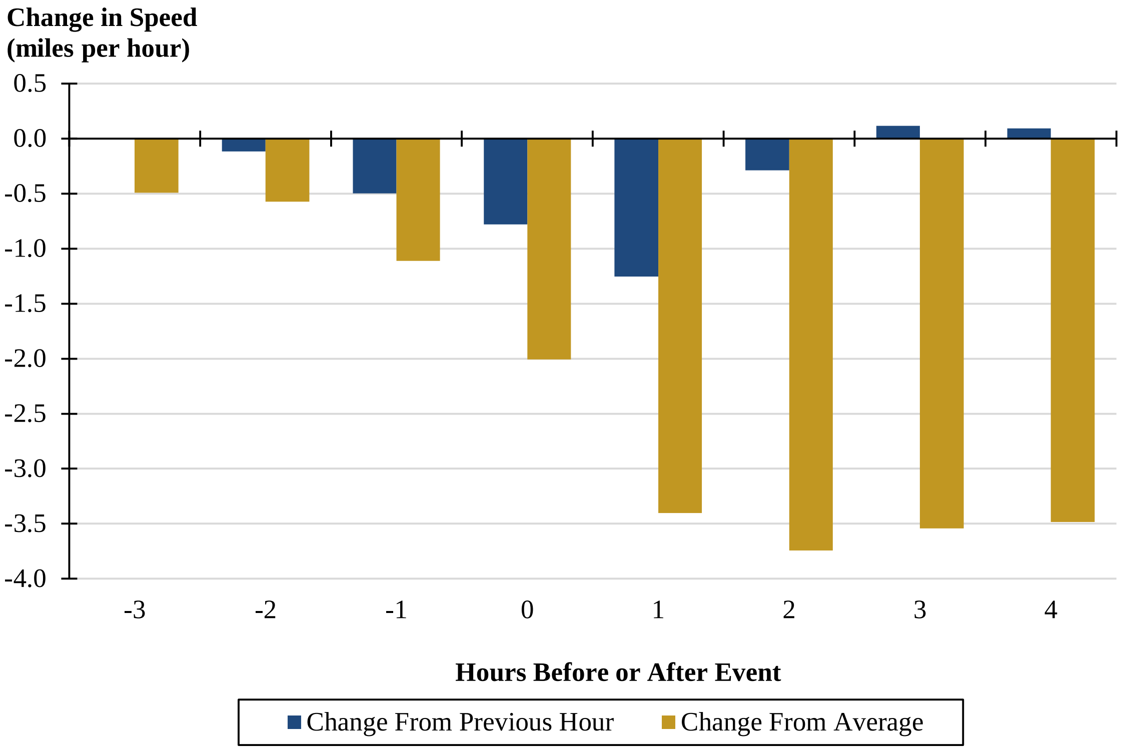
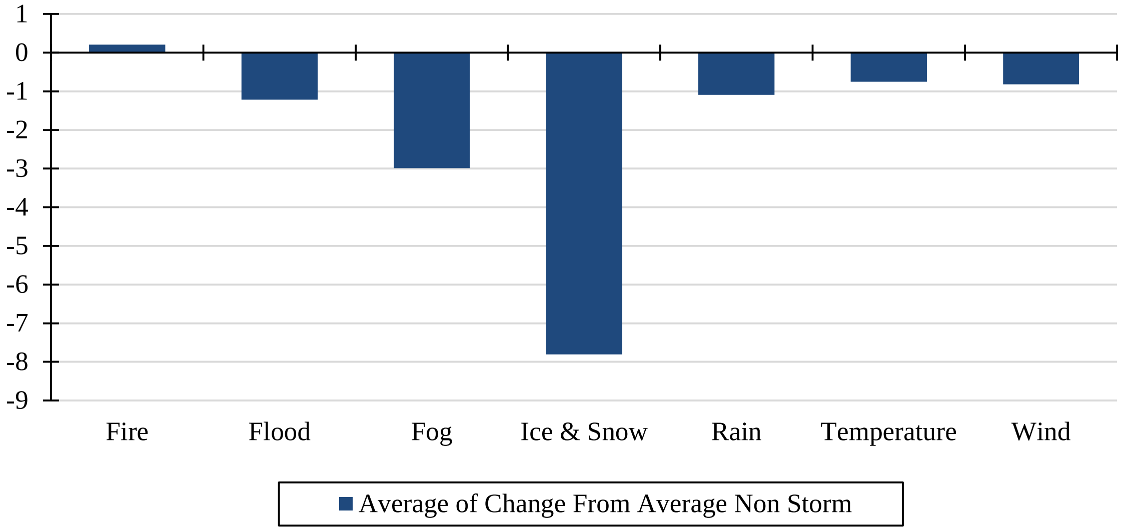


Figure 29. Chart. Change in speed (miles per hour) due to weather events over time, averaged across all weather events and study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Figure 30 explores the lagging effect in greater depth, showing the average decrease in speed four hours after a weather event compared to normal speeds for a range of weather event types. For most weather event types, only moderate speed reductions persist after four hours. For ice and snow, however, figure 30 shows a strong lagging effect—average speeds are still almost 8 miles per hour lower than normal speeds after four hours. This finding indicates also that winter storms have a relatively large impact on traffic conditions compared to other weather event types.[8] As a note, the weather event category called Temperature in figure 30, as well as in following figures, is a combination of the Excessive Heat and Extreme Cold/Wind Chill categories in table 6. This category is intended to represent extreme temperature weather events.



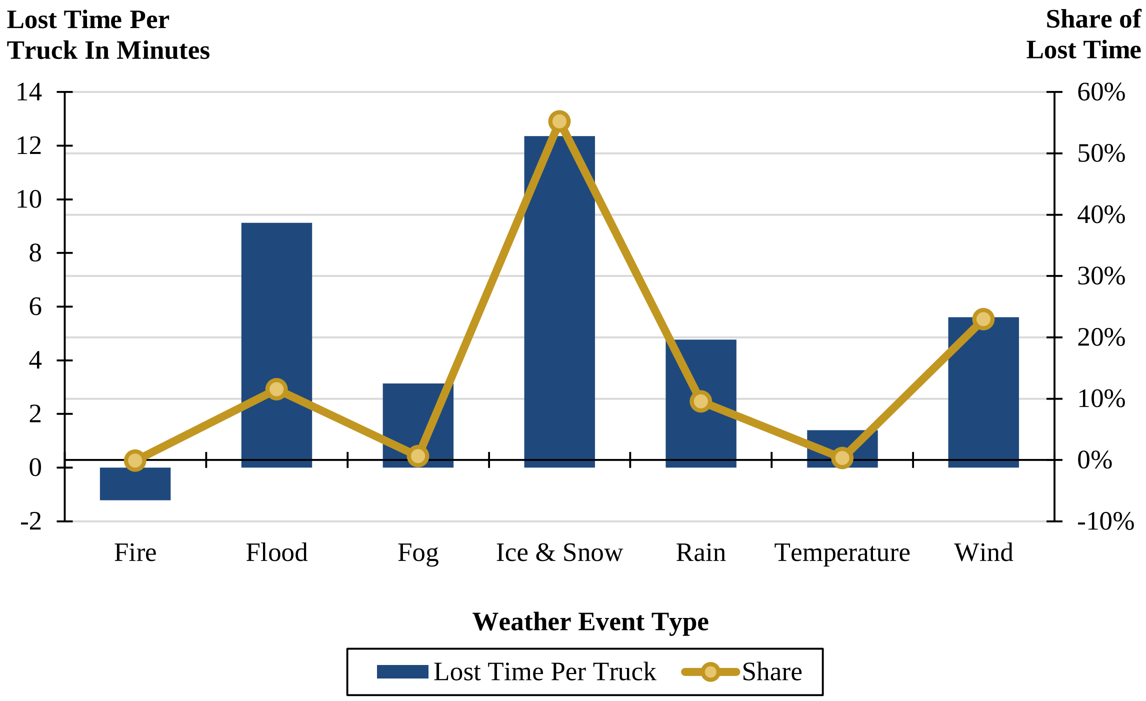
Note: Temperature includes Extreme Cold/Wind Chill and Excessive Heat

Figure 30. Chart. Lagging Effect: Change in speed four hours after different types of weather events, across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The large impact of winter storms is further shown in figure 31, which demonstrates that ice and snow are associated with over half of all travel time lost during weather events across all study areas. This share of lost time equates to about 12 minutes per truck. It should be noted here that most wind events also included other events such as heavy rain and snow, thereby making it difficult to isolate wind impacts.

---

[8] The very small increase in speed seen four hours after fire events is difficult to attach meaning to, as it is not known whether smoke was being blown in such a way that decreased visibility on the actual roadway. One possible hypothesis for the small speed increase is that people on average drive faster during dry, summer days when fire is more prevalent. It should also be noted that fire was a relatively rare event.



Note: Temperature includes Extreme Cold/Wind Chill and Excessive Heat

Figure 31. Chart. Winter weather accounts for over half of all lost time: Weather effects by weather event type, across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Sorting weather events by the magnitude of their inferred impacts on traffic instead of by weather event type, as shown in figure 32, reveals that 66 percent of weather events are associated with only moderate reductions in speed (defined here as a less than 10 percent decrease in speed) and cumulatively account for just 20 percent of total lost time. Conversely, the 10 percent of weather events that are associated with the largest speed decreases (ranging from a 40 percent to a 10,000 percent decrease in speed in this project’s study areas) account for 56 percent of total time lost (highlighted with red circles). These findings suggest that a small percentage of high-impact weather events are behind the majority of weather-related freight costs in the areas studied.

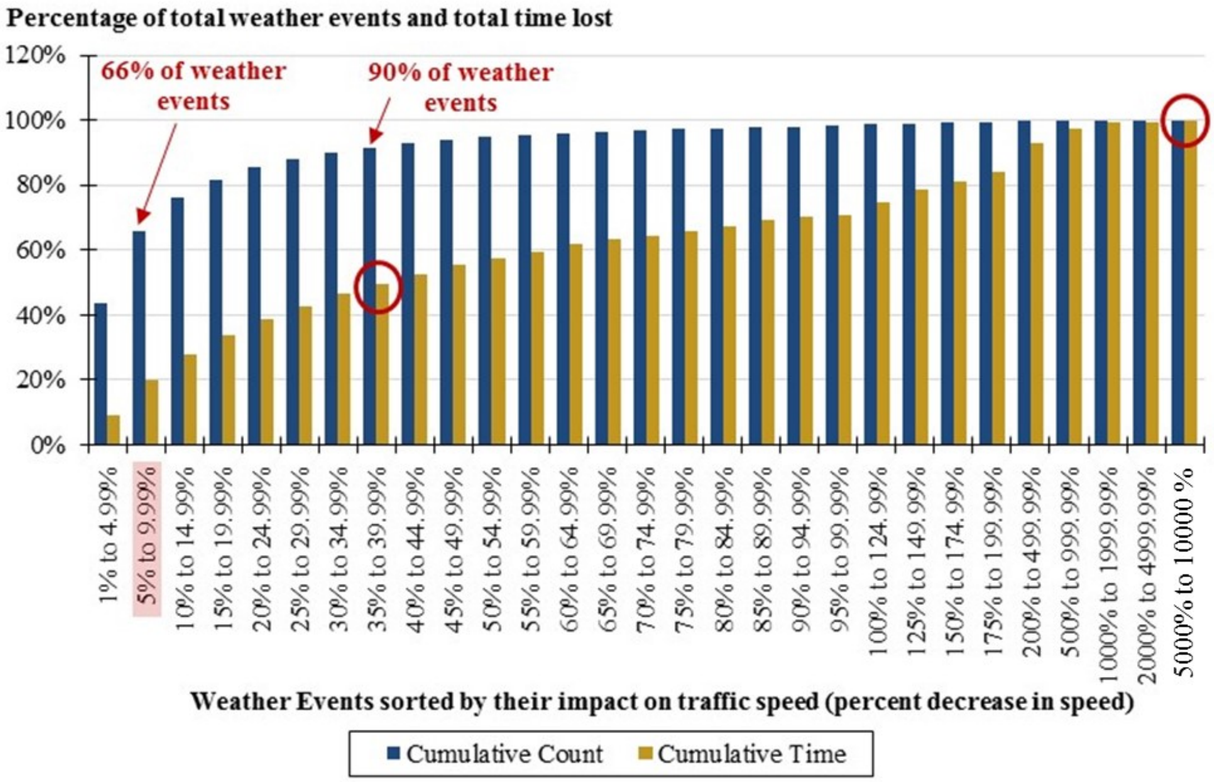


Figure 32. Chart. The cumulative share of weather events and time lost when weather events are sorted by their impacts on traffic speed (percent decrease in speed).
(Source: Noel Perry, Cambridge Systematics, Inc.)

Bringing together figure 31 and figure 32, figure 33 reveals that almost half (49.1 percent) of time lost due to weather events that are associated with a large impact on traffic (defined as weather events associated with a decrease in speed greater than 10 percent) are in the category of Ice and Snow. Wind (24.9 percent), Rain (12.4 percent), and Flood (12.4 percent) also account for a significant proportion of time losses associated with these large-impact events.

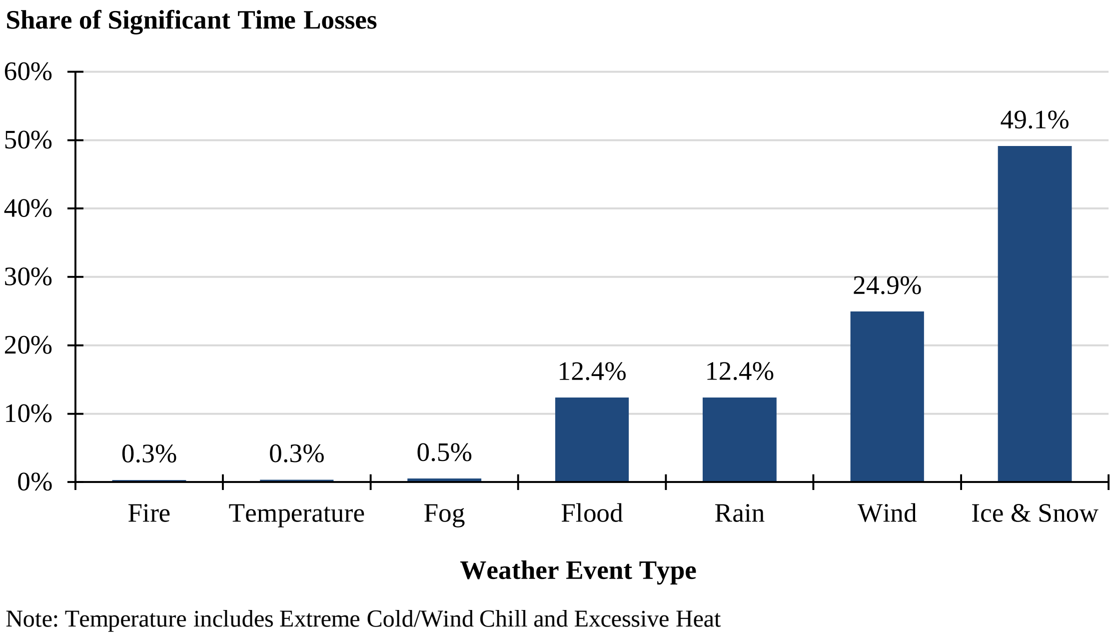


Figure 33. Chart. Weather events associated with large impacts on traffic (greater than 10 percent decrease in speed) sorted by weather event type. (Source: Noel Perry, Cambridge Systematics, Inc.)

Exploring this trend further, figure 34 demonstrates that Ice and Snow account for an even larger proportion of time lost due to the *highest* impact weather events (defined as weather events associated with a decrease in speed greater than 50 percent) with a 57.5 percent share of total time lost. Similar to figure 33, Wind (18.9 percent), Flood (12.5 percent), and Rain (10.6 percent) account for a significant share of lost time at this level of impact as well.

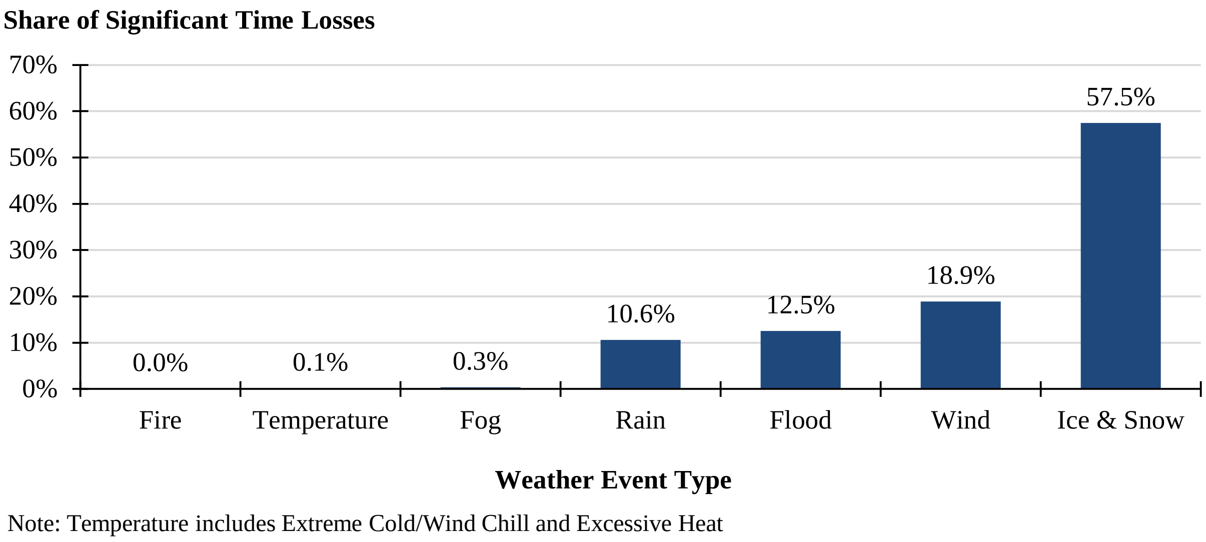


Figure 34. Chart. Weather events associated with the worst impacts on traffic (greater than 50 percent decrease in speed) sorted by weather event type.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Given the larger than expected impact of Wind on traffic across all study areas, the project team investigated its impact on each individual study areas. Figure 35 demonstrates that Wind is associated with relatively large reductions in speed in the Lake Tahoe, California study area, where these events decrease speeds by approximately 6 miles per hour on average. Indeed, the Lake Tahoe region is troubled by dust and sandstorms, especially after heavy sanding for traction during snowstorms. The Lake Tahoe study area includes I-80 across the Donner Pass, which frequently sees snowfall and, therefore, would also need sanding.

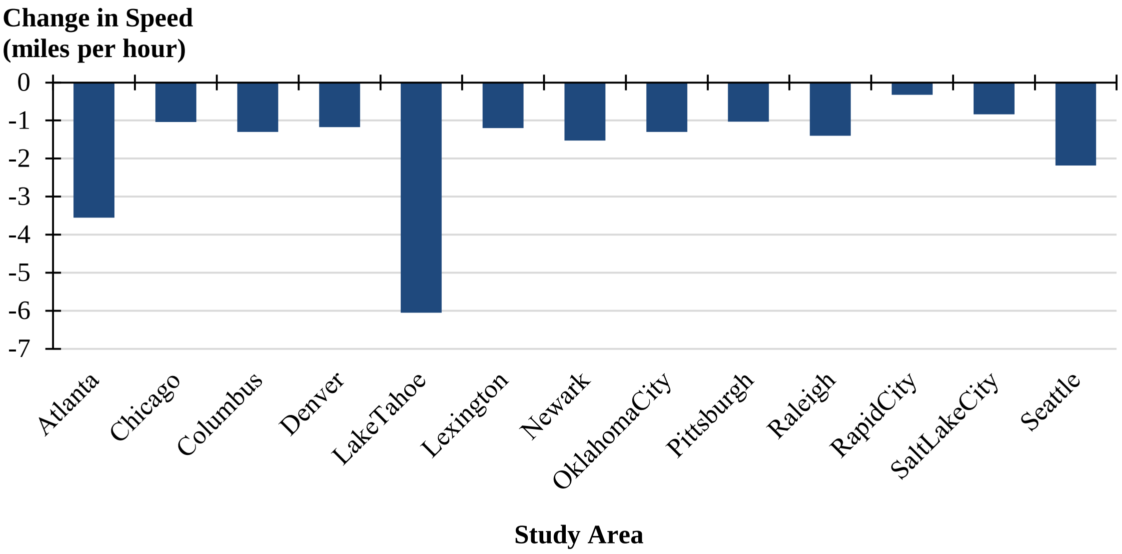


Figure 35. Chart. The impacts of Wind weather events in each study area.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The final stage of the cumulative analysis was to assign truck volumes to the FAF segments in each study area during the hours of interest, meaning during interactions between the FAF segments and weather events under study. In total, there were 413 million truck passings per year across all 13 study areas. Figure 36 shows the average number of truck passings per year in each study area during weather events. Across all study areas, 9 million truck passings, or 2.2 percent, occurred during weather events.

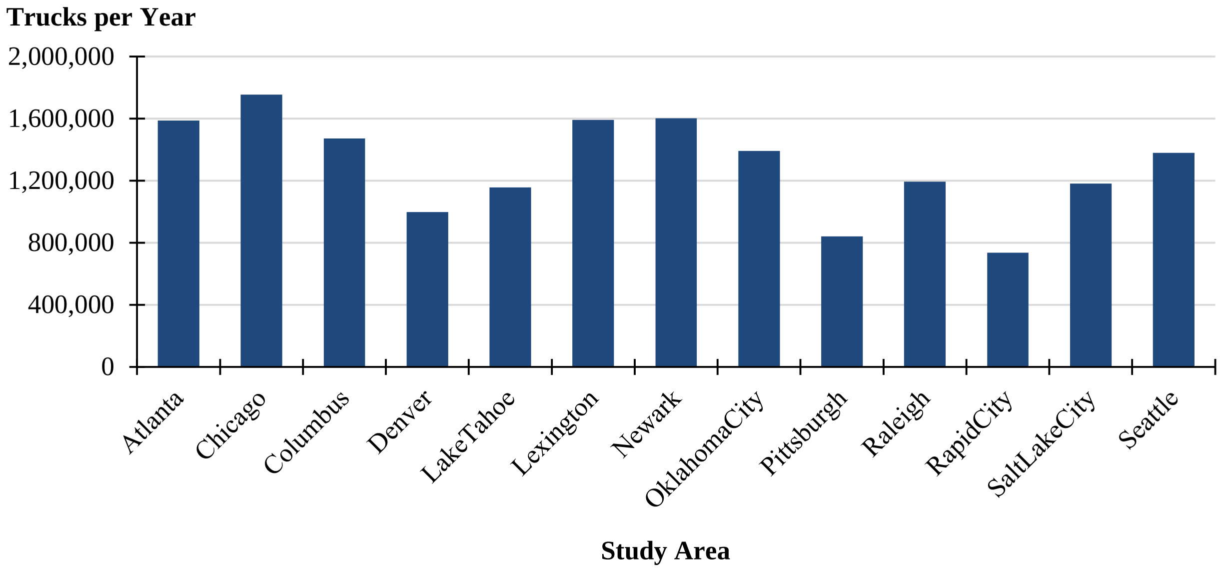


Figure 36. Chart. Average number of trucks per year passing through each of the 13 study areas during weather events. All 13 study areas together see 413 million truck passings per year total, with 9 million, or 2.2 percent of these passings occurring during weather events. (Source: Noel Perry, Cambridge Systematics, Inc.)

The data shown in figure 36 however, did not match well with the FAF3.5 data for certain study areas. Figure 37 below shows that for Columbus, Ohio; Newark, New Jersey; and Rapid City, South Dakota (highlighted with red circles) the FAF3.5 data differs greatly from the truck volumes shown in figure 36. The project team adjusted the FAF volumes for these study areas and others to better reflect the data in figure 36. These adjustments were based primarily on truck volume and distribution data compiled by Transportation Economics, part of the study team.

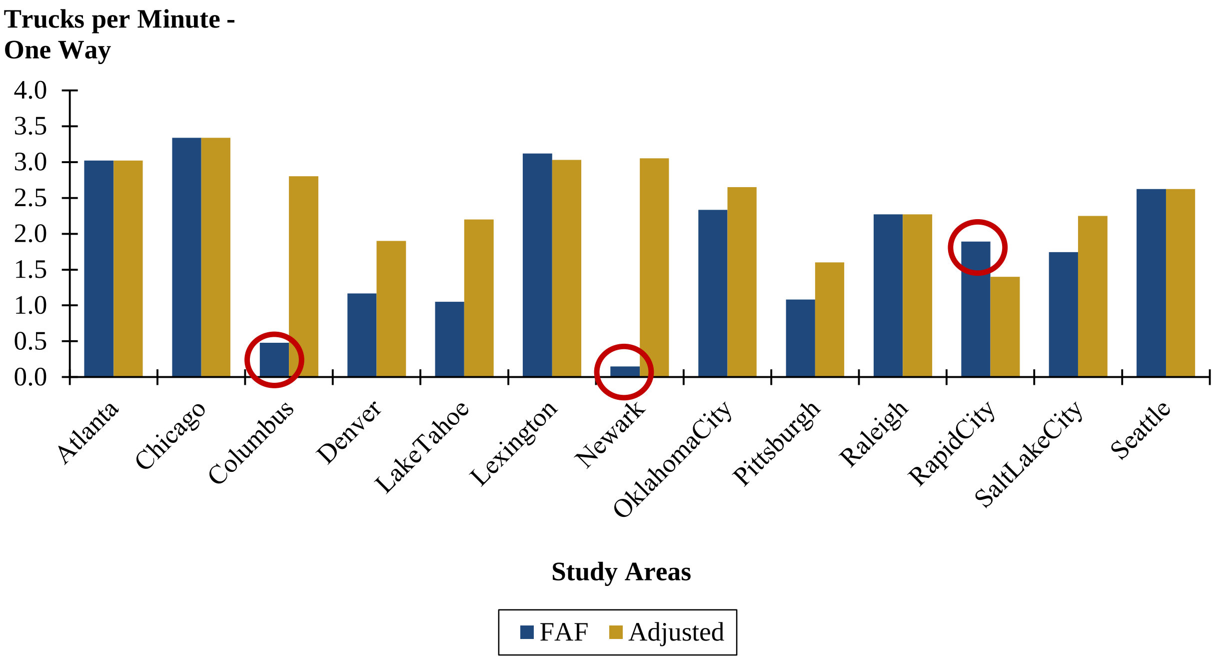


Figure 37. Chart. Raw Freight Analysis Framework volume data ("FAF") and adjusted Freight Analysis Framework volume data ("Adjusted") for each study area.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Moreover, the FAF3.5 data was at times inconsistent within study areas, such as the data for Lake Tahoe, California. As demonstrated in figure 38, the project team examined these more fine-grained inconsistencies in the data and made adjustments as needed at this level as well.

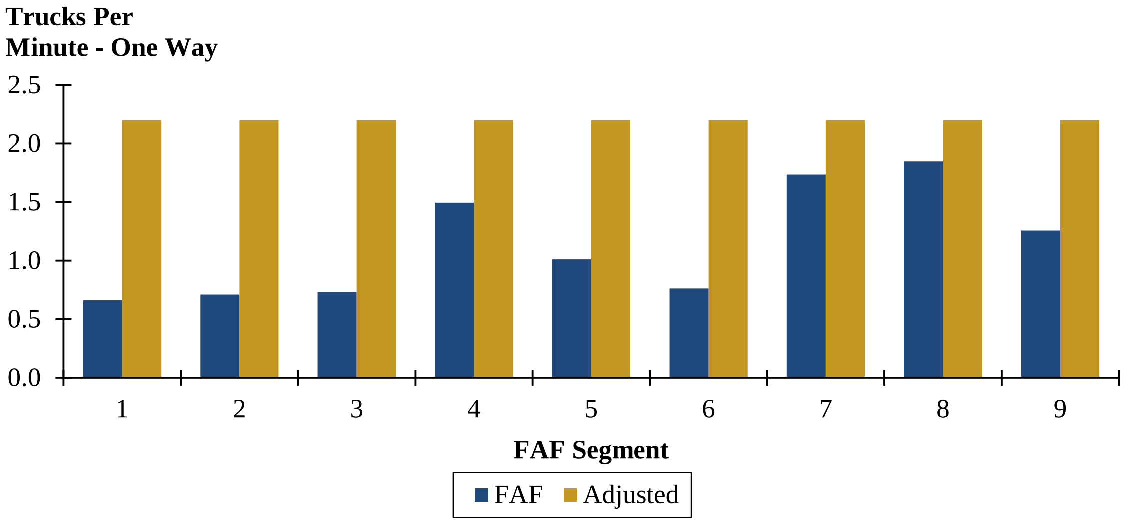


Figure 38. Chart. Raw Freight Analysis Framework volume data ("FAF") and adjusted Freight Analysis Framework volume data ("Adjusted") for individual Freight Analysis Framework segments within the Lake Tahoe, California study area
(Source: Noel Perry, Cambridge Systematics, Inc.)

The adjusted FAF truck volumes were then distributed across the day using Transport Economics research. Figure 39 illustrates these adjusted and distributed volumes for both even flow and irregular flow roads.

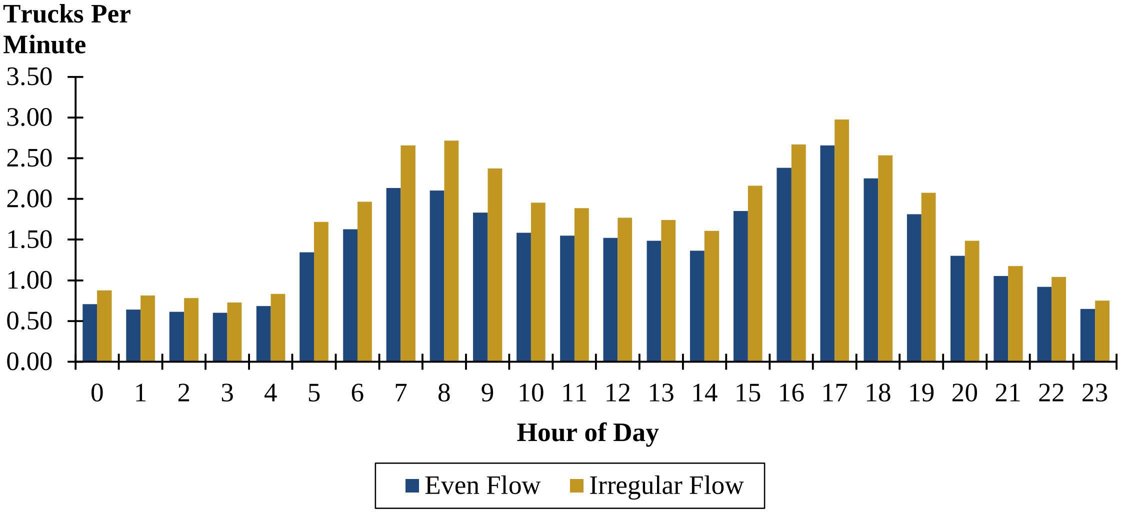


Figure 39. Chart. Distribution of adjusted Freight Analysis Framework volumes across the day using Transportation Economics' research, for even flow and irregular flow highways, across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The adjusted FAF volumes also were distributed across the day for workdays and nonworkdays, as shown in figure 40. The assumption behind this distribution was that nonworkdays have half the volume of workdays, in aggregate across the entire day.

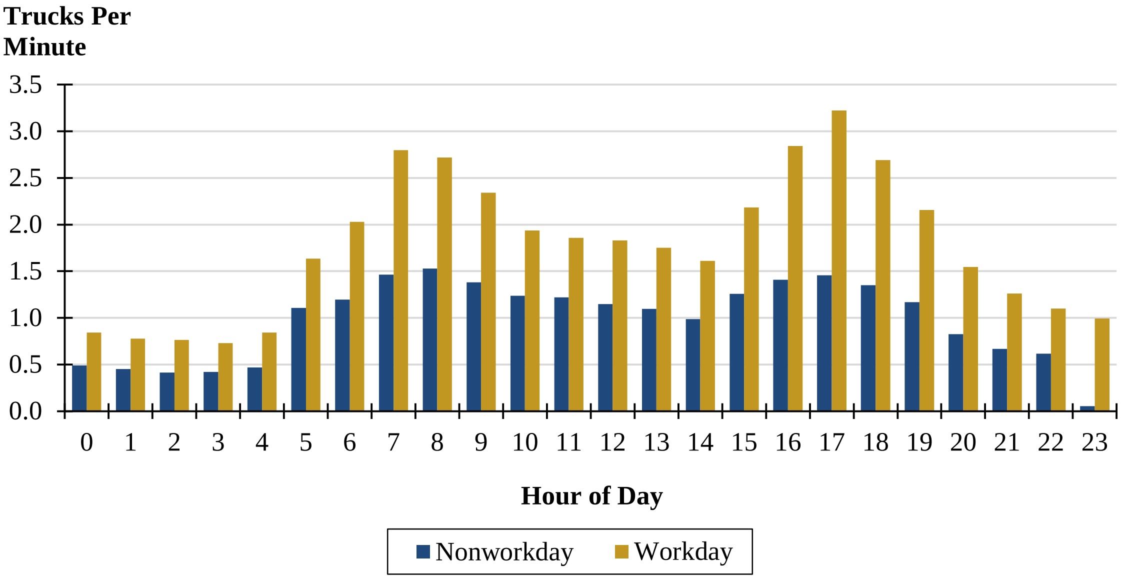


Figure 40. Chart. Distribution of adjusted Freight Analysis Framework volumes across the day using Transportation Economics' research, for workdays and nonworkdays across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

The project team then determined the length of each FAF segment (in miles) and the amount of time trucks spend passing through each FAF segment, or segment travel time (in minutes). The results, shown in figure 41, reveal that the average length of FAF segments is very small (less than 1.375 miles) and that the average travel time is similarly small (approximately 1.395 minutes).

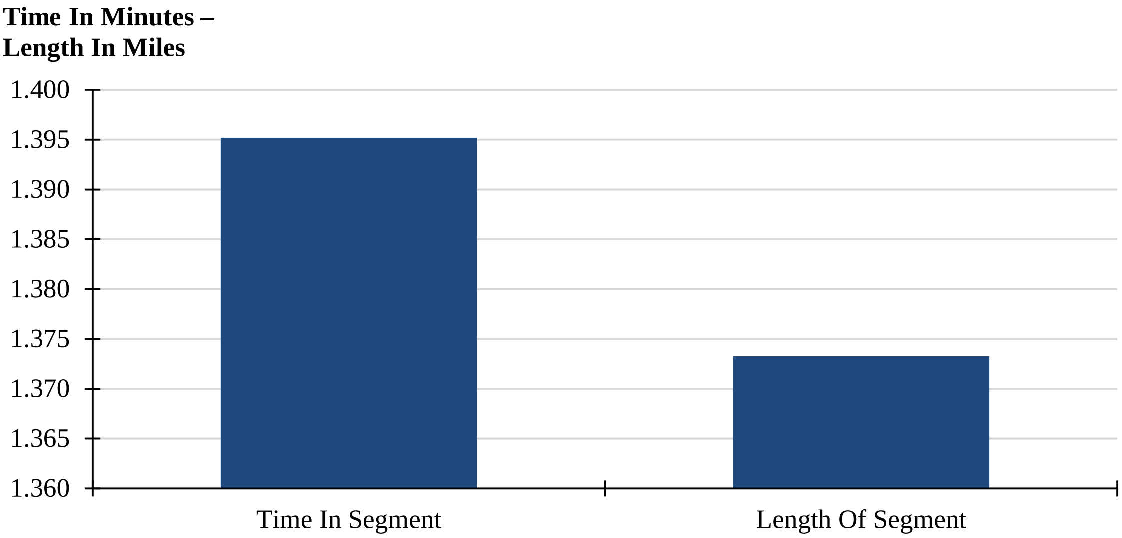
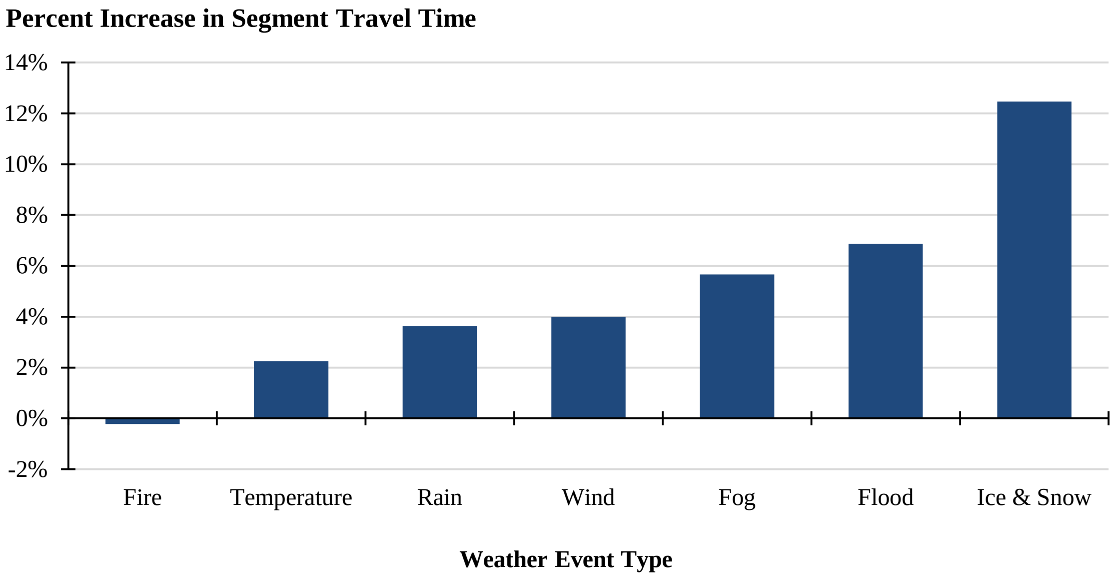


Figure 41. Chart. Average length and travel time of Freight Analysis Framework segments across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Building on this analysis, the percent increases in FAF segment travel times were calculated for the primary weather event types in the project's study areas, as shown in figure 42. In keeping with earlier findings, Ice and Snow are correlated with the largest percent increases in segment travel time, while Flood, Fog, Wind, and Rain are also associated with notable percent increases in travel time.



Note: Temperature includes Extreme Cold/Wind Chill and Excessive Heat

Figure 42. Chart. Percent increase in Freight Analysis Framework segment travel times for different weather event types, across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

It is important to note, however, that these percent increases varied widely among study areas. Figure 43 shows that the standard deviation of the average percent increase in travel time was greater than the average for all primary weather event types.

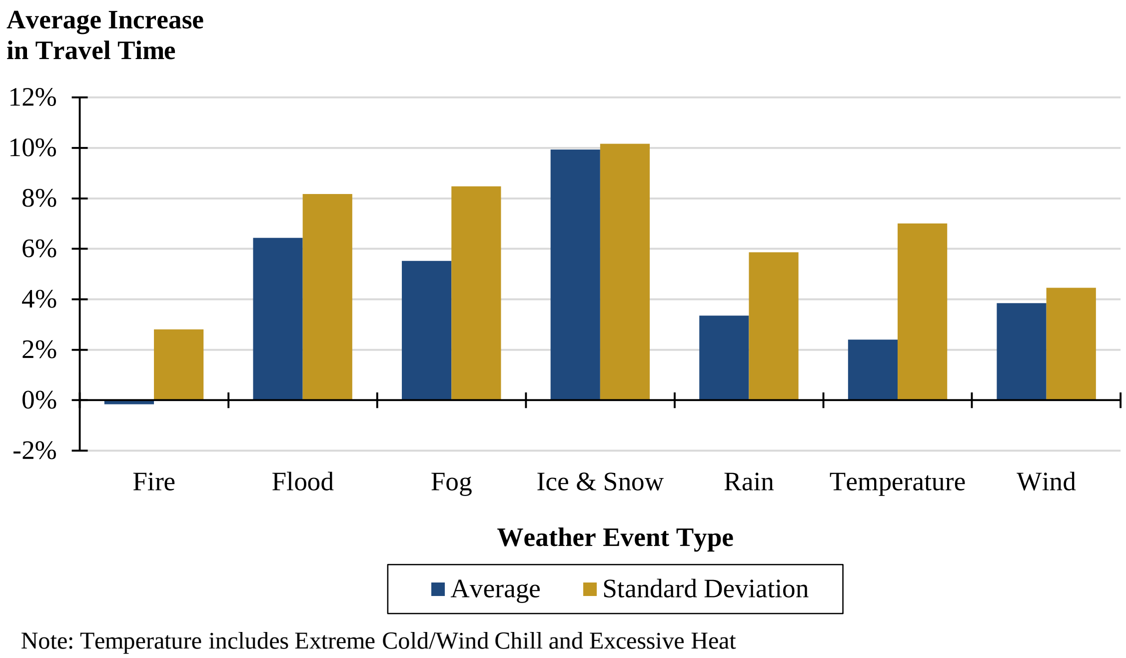
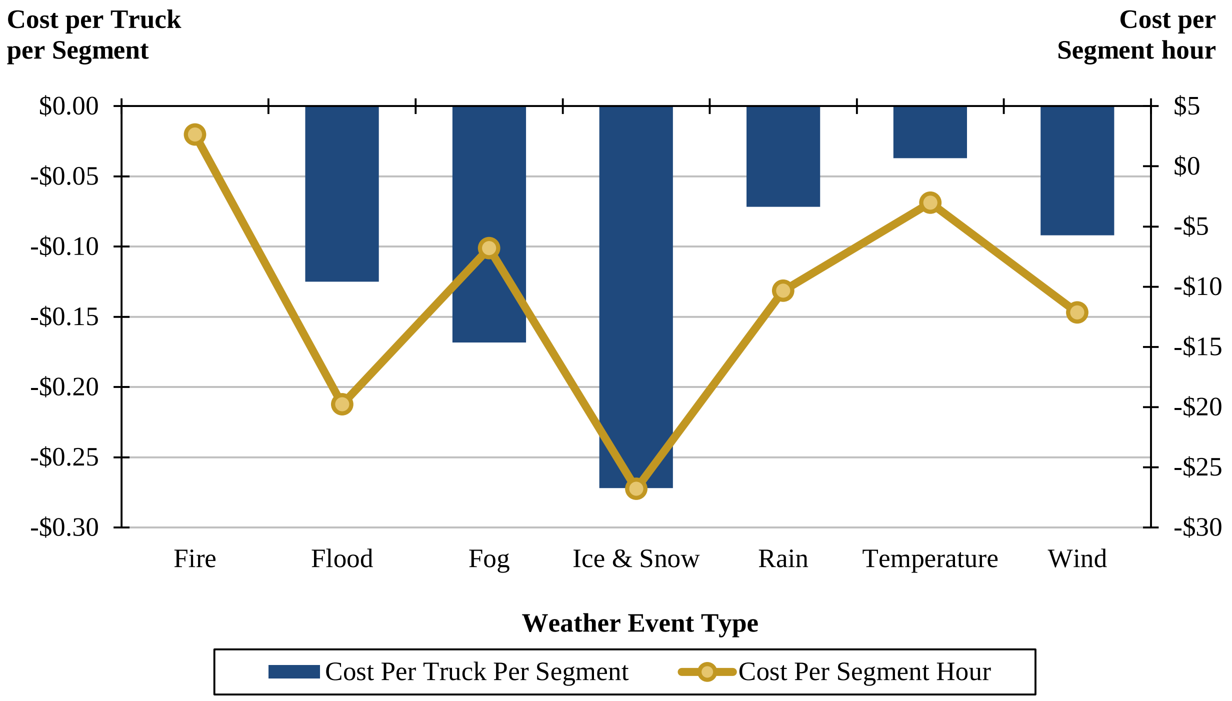


Figure 43. Chart. Differences in travel time impacts between and within weather event types, across all study areas.
(Source: Noel Perry, Cambridge Systematics, Inc.)

Finally, the project team used data from across all study areas to calculate the average costs associated with different weather event types in terms of costs per truck per segment and in terms of cost per segment hour, as shown in figure 44. These costs should be understood as lost (negative) revenue. The total cost associated with all weather event types and all study area highway segments is $3.8 million per year. These calculations are relative to the average cost of trucking, which includes good and bad weather, and assume a time-cost of $130 per hour for a heavy truck. Safety risks and delay costs are not accounted for in this analysis.



Note: Temperature includes Extreme Cold/Wind Chill and Excessive Heat

Figure 44. Chart. Costs of weather events by type in terms of cost per truck per segment and cost per segment hours.
(Source: Noel Perry, Cambridge Systematics, Inc.)

CHAPTER 4: CONCLUSION

The analysis presented in this report indicates that, overall, weather events have a significant negative impact on traffic speeds—and, therefore, the freight industry—when analyzed at the regional level. In this report's study areas alone, decreased traffic speeds due to the weather events analyzed are estimated to cost the freight industry 3.8 million dollars per year. This estimate is relative to the average cost of trucking, which includes both good and bad weather. To put this estimate in some context, the roadways covered in this study constituted roughly 1,500 miles, or just under one percent of the National Highway System (NHS). Approximately 44 percent of all traffic moves on the NHS so this analysis does not represent delays that occur on regional and local highways.

The regional analysis allowed for a more detailed investigation of how the impacts of weather on freight vary by weather event, highway type, time of day, and region size. The key takeaways from the regional analysis are listed below, followed by a discussion of important considerations and limitations of the analysis and directions for further research. All key takeaways are overall findings from the analysis of all 13 regional study areas.

- Weather events that fall into the categories of Ice and Snow, Fog, Flood, Wind, Rain, and Extreme Temperature were, together, associated with the vast majority of traffic speed decreases during weather events, as well as costs to the freight industry from weather-related delay.
- Ice and Snow events were associated with over half of all lost time due to decreased traffic speeds during weather events and are the most costly for the freight industry (costing over 25 dollars per segment hour and over 25 cents per truck per segment).
- Weather events exert the largest negative impacts on traffic speeds between hour 0 and hour 1. However, small decreases in speed are also seen in the hours leading up to a weather event, and moderate decreases in speed are still seen up to four hours after the event.
- Throughout the day, irregular flow highways (highways that experience morning and evening rush hours) suffer more than even flow highways in terms of loss of speed during weather events.
- Time of day matters—all highway types suffer more in terms of loss of speed during weather events that occur during morning and evening rush hour periods.
- Highways in smaller regions (where region size is based on population size and economic intensity) suffer less than highways in medium and large regions in terms of loss of speed during weather events.

While the analysis was able to detect these trends looking across the 13 regions, it is important to understand the limitations of the methodology employed and the data used. The association of weather events with traffic speeds based on county means that it is not certain that traffic speeds on a given roadway were always directly impacted by the associated weather event. The eight-hour timeframe applied to each weather event (four hours before and after hour 0) also limits the analysis as storms vary in length, but it was necessary to establish a common timeframe in order to have consistency in the analysis. Ideally, the analysis would track each storm individually for the time that it occurred, but the resources required for such a detailed analysis were not adequate for this effort. Nonetheless, given the sample size amassed using these assumptions, the research team was able to determine the significant trends listed above.

The analysis was based upon weather events reported in the National Storm Events Database. These are storms that are significant by several criteria, including having an impact on the State's commerce. While these are low-frequency, high-impact events, there are many smaller events that are not part of this analysis. These smaller events may not generate significant delays individually but are far more numerous in total and may account for a significant amount of delay. It should also be noted that catastrophic events that shut down roads entirely are not included in the analysis since no traffic was flowing. While events that close highways altogether are very rare, the amount of delay they incur for the freight industry could be significant.

It appears on the surface that this analysis would lead to a somewhat lower estimate of national weather-related freight delay than the $8-9 billion estimated in the previous study. However, some of the caveats noted above, including the limited sample of events and the use of average hourly traffic speeds, probably bias the analysis toward a lower estimate. Significant variability in freight flow estimates is another factor that introduces uncertainty, although the direction of this bias is not known. In summary is not possible to scale the regional delay estimate in this study up to a national estimate. However, the research in this study could be used to develop a national estimate with greater confidence than that of the previous study. A next step would be to match the delay factors by type of event and match them with the weather exposure factors developed in Task 8 of this study. A set of national weather zones could be developed and the delay and exposure factors applied to highways within that zone. A reasonable approach would be to start with the Interstate system and eventually expand to the National Highway System.

Additional future research could try to hone in on smaller geographic areas. This would allow for the use of radar data to precisely track the time and locations of weather events. Additionally, the lack of robust data on trucking volumes and the value of cargo presented challenges in crafting the methodology for this analysis. While research will have to rely on models and gross estimates for the foreseeable future, the further development of trucking data will greatly aid future efforts to continue this research.

U.S. Department of Transportation
Federal Highway Administration
Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590

http://www.ops.fhwa.dot.gov

February 2016
FHWA-HOP-16-044

*This material is based upon work supported by the FHWA
under contract number DTFH61-12-D-00048-T-13005.*