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U.S. HIGHWAY CRASHES IN ADVERSE ROAD WEATHER CONDITIONS

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1. INTRODUCTION

Weather-related crashes are those that occur in the presence of rain, sleet, snow, fog, wet pavement, snowy/slushy pavement, and/or icy pavement. Twenty-four percent of all crashes are weather-related. Each year, nearly 7,400 people are killed and over 673,000 people are injured in these crashes. This paper examines driver behavior and crash risk in inclement weather; addresses weather exposure and severity; and presents statistics on weather-related crashes, injuries, and fatalities on U.S. roads from 1995 to 2005. The paper also discusses regional variance in weather-related crash types and rates, fatal weather-related crashes involving commercial vehicles, and the economic impact of weather-related crashes. The paper concludes with a discussion of documented crash mitigation strategies that have safety benefits, as well as research needs to better understand the nature of the problem and explore improved strategies.

2. WEATHER IMPACTS ON DRIVER BEHAVIOR AND CRASH RISK

Weather acts through visibility impairments, precipitation, high winds, and temperature extremes to affect driver capabilities, vehicle performance (i.e., traction, stability and maneuverability), pavement friction, and roadway infrastructure. These impacts can increase crash risk and severity. Several studies have been conducted on driver behavior and crashes during rainfall or snowfall. Examination of free-flow speeds on curved highway sections in rural New York State illustrated that drivers did not reduce speeds sufficiently on curves during wet pavement (Lamm, et al 1990). The investigators concluded that drivers did not recognize that pavement friction is lower on wet pavement as compared with dry pavement. In a survey of over 2,000 Hawaiian drivers, over 62 percent of respondents stated that they drove five percent slower on wet pavement (Zhang, Prevedouros 2004). Nearly one-third of surveyed drivers indicated that they drove at the same speed as on dry roads. Over 87 percent of respondents stated that they reduced speeds by an average of 11 percent during rainfall. Researchers concluded that drivers perceive a higher crash risk when driving in the rain, especially in heavy traffic.

In a study of crashes during and after rain events in Calgary and Edmonton, Canada (Andrey, Yagar 1993); investigators concluded that crash risk during rainfall was 70 percent higher than crash risk under clear, dry conditions. In an assessment of weather and seasonal effects on highway crashes in California (Satterthwaite 1976), weather was found to be a major factor. On very wet days, crash frequency was twice the rate on dry days. Using data from the United States and Israel, researchers analyzed crash risk during rainy weather (Brodsky, Hakkert 1988). They learned that injury crash risk was two to three times higher than in dry conditions. The researchers also reported that crash risk was greater when rain followed a period of dry weather.

By examining Iowa highway data, researchers found that traffic volumes during snow events were 30 percent lower than volumes in clear weather (Khattak, Knapp 2000). An assessment of crash risk on

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Connecticut highways also illustrated that traffic volumes during snow were lower than those during rain or clear weather (ElDessouki, et al 2004). In an examination of winter crashes on Iowa highways (Khattak, Knapp 2000), crash rates were found to be substantially higher during snow events. The study results also indicated that there were fewer injuries in crashes during snow than there were in crashes without snow. When investigators analyzed crash rates in the 48 contiguous states, their findings suggested that drivers adjust their behavior sufficiently (e.g., drive slower) to reduce crash severity during snowfall, but not enough to lower snow crash frequency (Eisenberg, Warner 2005). The fatal crash rate was lower on snow days than on dry days. The study also revealed that substantially more crash fatalities happen on the first snowy day of the winter season. By analyzing 10 years of winter crash data on Iowa interstates (Maze, Hans 2007), researchers concluded that crash risk is 3.5 times higher at the start of a winter season than it is at the end. This finding indicates that more experience driving in snowy conditions reduces crash risk and crash frequency.

The aforementioned studies, and others, were synthesized to compile the reductions shown in Table 1. These studies illustrate that both freeway speed and volume decrease in inclement weather. Wet pavement in the absence of rainfall is not viewed as hazardous, so speed reductions are minimal. Many drivers do not realize that pavement friction is significantly reduced under these conditions, leading to greater stopping distances. On the other hand, drivers reduce speed further and drive a little more cautiously during rainfall. This may be due to lower visibility caused by precipitation and spray from vehicle tires. The fact that volume reductions are relatively low indicates that most drivers do not cancel trips due to rain. The combination of high traffic volumes, relatively high speeds (though still lower than speeds under clear dry conditions), and low traction likely explain why most weather-related crashes occur during rainfall and on wet pavement.

Exposure is also an important factor. Rain and wet pavement occur year-round in every part of the county. People drive in the rain far more frequently than they drive in snow, which is limited to a portion of the country during part of the year. This seasonal exposure to snowy weather impacts driver behavior. At the beginning of the winter season, drivers are faced with atypical conditions that they must adjust to. This may explain why snow crash rates are higher at the start of the winter season than at the end. Most drivers perceive snow as more dangerous than rain. This causes more people to cancel or defer trips resulting in significant volume reductions. This perception also results in significant speed reductions. Travel speeds in snow are low enough to reduce injuries and fatalities when crashes occur.

3. WEATHER-RELATED CRASH STATISTICS

The FHWA Road Weather Management program defines “weather-related” crashes as those that occur in the presence of “adverse weather” and/or “slick pavement”. “Adverse weather” includes rain, sleet, snow, fog, rain/fog, and sleet/fog. “Slick pavement” includes wet, snowy/slushy, and icy pavement. It should be noted that the extent to which these conditions cause crashes is unknown. The crash data cover all types of vehicles including passenger cars, light trucks (e.g., pickups, vans), large trucks (e.g., tractor trailers), motorcycles, buses, and other vehicles (e.g., motorhomes).

Police-reported crash data were obtained from two National Highway Traffic Safety Administration (NHTSA) databases—the Fatality Analysis Reporting System and the General Estimates System. The Fatality Analysis Reporting System contains data on all fatal traffic crashes on U.S. public roads that resulted in death within 30 days of the crash. There is not an equivalent data source for non-fatal injuries. The General Estimates System provides estimates based on a nationally representative sample of police-reported crashes. Various sources suggest that roughly half of all vehicle crashes are not reported to the police. Most unreported crashes involve minor property damage and no significant injuries.

In Table 2; the average number of crashes, injuries, and fatalities are presented for the 11-year period from 1995 to 2005, inclusive. Crashes by weather and pavement condition are shown in Table 3. Injuries and fatalities are summarized by condition in Table 4 and Table 5, respectively. In these tables, “Other/Unknown Weather” includes smog, smoke, blowing sand, blowing snow, blowing dust, and crosswinds.

"Other/Unknown Pavement" includes pavement with sand, dirt, and oil. The NHTSA databases do not include statistics for crashes due to high winds (e.g., tractor trailer blow-overs), nor fatalities caused when motorists drive into high water or flooded areas.

As shown in Table 2, nearly one-quarter of all vehicle crashes occur in adverse road weather conditions. On average, 178 weather-related crashes happen every hour. Over 673,000 people are injured and nearly 7,400 people are killed in these crashes each year. That is, more than 1,800 people receive injuries and 20 people die in weather-related crashes every day. Weather-related crash fatalities account for 17 percent of all traffic fatalities.

Figure 1 depicts annual crash frequency by road weather condition. Figure 2 is normalized to show the number of weather-related crashes per million vehicle miles traveled. The normalized figure illustrates that the weather-related crash rate has generally decreased over the 11-year period from 1995 to 2005. Most of these crashes happen when the pavement is wet and during rainfall. Seventy-five percent of weather-related crashes occur on wet pavement and 47 percent happen during rainfall. Of all vehicle crashes, 18 percent take place on wet pavement and 12 percent occur during rainfall. Twenty-four percent of weather-related crashes take place on snowy, slushy, or icy pavement. Roughly 15 percent of weather-related crashes occur during snowfall and sleet. Fog is present in just two percent of weather-related crashes. Approximately 62 percent of weather-related crashes and 15 percent of all crashes happen during precipitation. Slick pavement conditions are very dangerous, even when there is no precipitation or fog. Over one-third of weather-related crashes occur on slick pavement in the absence of adverse weather.

3.1 *Regional Variance in Weather-Related Crash Rates*

The crash data were examined to identify regional variance in weather-related crash rates, as seen in Figures 3 and 4. The map in Figure 5 shows four regions: Northeast, Midwest, South and West. Most weather-related crashes take place in the South and the Midwest. Nationwide, 47 percent of weather-related crashes happen in the rain. Nearly 64 percent of weather-related crashes occur during rainfall in the South. On average, wet pavement is present in 75 percent of weather-related crashes. In the South, over 90 percent of weather-related crashes happen on wet pavement. The higher frequency of wet weather crashes in the South is due to exposure. The precipitation map shown in Figure 6 indicates that the South receives more precipitation than any other region. The majority of this precipitation is in the form of rain, which can be seen in Figure 7. The South also has the highest population and the most vehicle miles traveled, as shown in Table 6.

In the Midwest, crashes during winter weather occur more frequently than they do nationwide. Nationally, 15 percent of weather-related crashes happen in snow and sleet. In the Midwest, 24 percent of weather-related crashes occur during snow and sleet. On average, 11 percent of weather-related crashes happen on snowy and slushy pavement. Compare this to the Midwest, where over 18 percent of weather-related crashes occur in these conditions. As shown in Figure 7, the Midwest has relatively high snowfall totals. Table 6 indicates that this region has the highest number of weather-related crashes. Although the Midwest has only 22 percent of the population, 40 percent of weather-related crashes occur there.

3.2 *Weather-Related Crashes Involving Commercial Vehicles*

Most freight shipments in the U.S. are carried by commercial vehicles. Commercial vehicles include large trucks with gross vehicle weights over 10,000 pounds, as well as most types of buses. Over eight million registered large trucks operate in the U.S. These account for about 3.5 percent of all vehicles, 7 percent of all vehicle miles traveled, and 11 percent of all fatal crashes. Roughly 16 percent of fatal crashes involving commercial vehicles are weather-related. That is one percent less than fatal weather-related crashes in all vehicle types. Sixty percent of fatal weather-related crashes in commercial vehicles occur in rainy conditions. Thirty-two percent happen in snow or sleet, 12 percent take place in fog, and 7 percent occur in other types of weather (e.g., crosswinds, blowing sand). Figure 8, which is adjusted for vehicle miles traveled, demonstrates that the rate of fatal weather-related crashes involving commercial vehicles has gradually declined over the 11-year period. However, these crashes occur more often than fatal weather-related crashes in all vehicles types. This can be seen in Table 7 and Figure 9.

Rainfall hazards cause freight delays and increased risk of truck collisions with other vehicles and highway structures. Rain reduces braking performance, resulting in increased stopping distances and more frequent skidding. Snow and ice conditions produce additional hazards to freight transportation including delays, road closures, reduced visibility, loss of traction, and loss of vehicle performance. Commercial vehicles also have significant vulnerability to fog and low visibility. These conditions may increase the stopping distances required to avoid a crash. If a crash occurs, the larger mass of a commercial vehicle and greater release of kinetic energy produces a more severe impact. Accordingly, fog and other visibility impairments may result in more fatal crashes for commercial vehicle than for motor vehicles as a whole. Strong winds can disrupt high-profile trucks in exposed areas such as interstate highways, valleys, and open prairies. Lightly loaded semi-trailers are particularly vulnerable to blow-overs. Cargo can also be sensitive to temperature extremes.

The higher rate of fatal weather-related commercial vehicle crashes may be due to trip characteristics. Commercial vehicle operators typically have longer trip lengths than passenger car drivers. Commercial vehicle trips are business related and therefore less discretionary than trips by private automobile owners. These longer and less-discretionary trips may expose commercial vehicles to a variety of mesoscale weather effects. Commercial vehicles engaged in local trucking operations make more frequent stops for pickups and deliveries as part of a given trip. Similar to long distance trucking, local trips may also be less discretionary than personal travel, increasing the likelihood of exposure to adverse weather impacts.

4. ECONOMIC IMPACTS OF WEATHER-RELATED CRASHES

The National Highway Traffic Safety Administration published a report that estimated the economic impact of motor vehicle crashes in 2000 (Blincoe, et al; 2002). The estimated cost included travel delay, emergency services (e.g., medical, police, fire services), property damage, medical costs, rehabilitation costs, productivity losses, insurance administration costs, legal and court costs, and the costs to employers. Data from this report were used to estimate that the average cost per crash in 2000 was $14,100. Using this value, the costs of weather-related crashes were calculated. On average, there are 1,561,430 police-reported, weather-related crashes. The annual cost of these crashes is estimated to be $22 billion. The NHTSA report indicated that 57 percent of all crashes are not reported to police. If unreported crashes are included, the cost of all weather-related crashes reaches $51 billion each year. This may be a conservative estimate if drivers are less likely to report minor crashes during inclement weather.

Eleven percent of crash costs are attributable to travel time delay caused by traffic congestion at crash sites. Property-damage-only (PDO) crashes result in 49 hours of delay. Injury and fatal crashes cause roughly 86 and 232 hours of delay, respectively. These statistics indicate that police-reported, weather-related crashes cause over 94 million hours of delay annually. Unreported crashes typically involve only minor property damage. If unreported weather-related crashes are taken into account, annual delay exceeds 272 million hours.

5. CRASH MITIGATION STRATEGIES

There are three types of road weather management strategies that can be used to reduce weather-related crash risk and rates: advisory, control and treatment. Advisory strategies provide motorists with information on weather and pavement conditions. Control strategies alter the state of roadway devices to permit or restrict traffic flow. Treatment strategies supply resources to roadways to minimize or eliminate weather impacts.

Advisory strategies include the dissemination of road weather information via 511 interactive telephone services and transportation agency web sites, as well as the operation of motorist warning systems. During severe weather, 511 call volumes can increase by four to five times and road weather web sites experience significant spikes. State and local agencies can provide route-specific information on National Weather Service forecasts, atmospheric observations, pavement conditions, pavement temperatures, winter road maintenance activities, and weather-related travel restrictions. These types of road weather information allow the public to make more informed travel decisions and avoid hazardous roads.

Motorist warning systems can be deployed on ramps, bridges, or road segments to alert drivers to dangerous conditions such as wet pavement, low visibility, and high winds. These systems typically correlate weather, pavement, and traffic data collected from field sensors with pre-determined response plans. In some cases, these systems provide decision support to traffic managers who decide which pre-programmed messages to disseminate. Many motorist warning systems automatically activate flashing beacons on static signs, display warnings on dynamic message signs, or issue advisories via highway advisory radio. Motorist warning systems improve safety by decreasing average speed and promoting uniform traffic flow, which reduces crash risk.

There are three control strategies that can improve roadway safety: access control, speed management, and weather-related signal timing. Access control involves closing bridges or road segments, or restricting the access of certain vehicles. For example, high-profile vehicles may not be allowed to travel through a valley when crosswind speeds are high. On mountain passes, winter travel may be limited to vehicles with snow tires or tire chains. By controlling access, agencies prevent drivers from encountering dangerous road conditions. Speed management systems typically collect weather, pavement, and traffic data to provide decision support to managers. Based upon prevailing conditions, speed limits are reduced using highway advisory radio, dynamic message signs, and/or variable speed limit signs. By reducing average speed, these systems can decrease crash frequency and crash severity. Weather-related signal timing also reduces the frequency and severity of crashes. Signal timing plans for heavy rain, snowy, or icy conditions increase cycle lengths and reduce progression speeds.

Treatment strategies include fixed anti-icing/deicing systems and mobile anti-icing/deicing operations. Fixed systems can be installed on bridges and elevated ramps that are prone to slick pavement. These systems collect weather and pavement condition data to predict or detect slick pavement. When such conditions are present, chemical spray sequences can be activated automatically or by maintenance managers. Mobile anti-icing/deicing operations entail the use of maintenance vehicles to apply materials (i.e., sand or chemicals) onto the pavement before, during, and after snowfall or frost formation. Treatment strategies can significantly reduce winter crash rates and associated delay.

6. CONCLUSION

Weather has significant impacts on road safety. One quarter of all crashes on U.S. public roads are weather-related. Over 1,561,000 weather-related crashes occur annually. More than 673,000 people are hurt and nearly 7,400 die in these crashes each year. In terms of crash frequency, rate, and severity; wet weather is far more dangerous than winter weather. Most weather-related crashes happen during rainfall and on wet pavement. This may be explained by exposure and driver behavior. Rain occurs year-round in every part of the country, while snow and ice are limited to one season and a portion of the country. Drivers reduce speed slightly on wet pavement. During rainfall, people drive more cautiously and reduce speed further. Drivers travel much slower when faced with winter weather, and many cancel trips resulting in lower traffic volumes. Weather-related crashes have significant impacts on roadway mobility and the economy. It was estimated that weather-related crashes cause between 94 million and 272 million hours of delay each year. The annual cost of weather-related crashes is estimated to be between $22 billion and $51 billion.

To minimize weather impacts on road safety; more research on weather-related crashes is needed. Additional research will help transportation agencies better understand whether the overall decline in weather-related crashes is due to exposure and severity, advances in road weather observing and forecasting, better traveler information, successful mitigation strategies, or other factors.

Research needs fall into four general categories: weather exposure, human factors, education and training, and mitigation strategies. Regarding exposure, we need to investigate the relationships between weather severity, weather exposure on road networks, and crashes. We need to determine why there are more crashes during the first snow event of the season. We should examine the trip characteristics of commercial vehicles to understand why fatal weather-related crashes occur more often than such crashes in other types of vehicles.

In the human factors area, we need to know how drivers make travel decisions (e.g., mode, departure time, trip deferral) and how to influence such decisions. We need to learn how to best influence driver behavior (e.g., speed, following distance) in adverse weather. We also need to determine the most useful types of pre-trip and en-route road weather information. What are the most effective delivery methods and formats for road weather information? Are targeted, route-specific messages more or less effective than generic warnings broadcast for county-wide areas?

In the area of training, we must increase driver education and awareness of weather impacts in order to influence driver decisions. Do drivers understand the dangers of rain and wet pavement? Should tailored education programs be developed for different types of drivers (e.g., passenger vehicle owners, commercial vehicle operators, motorcyclists)?

We must know which road weather management strategies are most effective at reducing speeds, crash rates, and crash fatalities. Are site-specific mitigation strategies more or less effective than strategies applied to corridors or road networks? Should targeted strategies be developed for each region based on climatologic, traffic, and population characteristics?

The FHWA Road Weather Management program (www.fhwa.dot.gov/weather) is involved in projects on macroscopic and microscopic traffic flow analyses in inclement weather, human factors studies to investigate driver behavior and the effectiveness of road weather information, documentation of proven advisory and control strategies, as well as outreach and education. Although the FHWA is sponsoring research to address many of the questions above, more research must be conducted.

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Weather Conditions	Freeway Traffic Flow Reductions	
	Average Speed	Volume
Light Rain/Snow	3% - 13%	5% - 10%
Heavy Rain	3% - 16%	14%
Heavy Snow	5% - 40%	30% - 44%
Low Visibility	10% - 12%	--

Table 1 – Weather Impacts on Freeway Traffic Flow

	Vehicle Crashes		Persons Injured		Persons Killed	
Total	6,400,607		3,113,447		42,262	
Non-Adverse Conditions	4,839,176	76%	2,440,233	78%	34,900	83%
Adverse Road Weather Conditions	1,561,430	24%	673,214	22%	7,362	17%
Slick Pavement & Clear Weather	539,711	35%	219,607	33%	2,381	32%
Slick Pavement & Other/Unknown Weather	14,131	1%	5,961	1%	65	1%
Slick Pavement & Adverse Weather	981,889	63%	435,942	65%	4,555	62%
Dry Pavement & Adverse Weather	23,902	2%	10,751	2%	351	5%
Other/Unknown Pavement & Adverse Weather	1,797	0%	953	0%	10	0%

Table 2 – Average Crashes, Injuries, and Fatalities in Adverse Road Weather Conditions

		Weather Conditions								
		Clear	Rain	Sleet	Snow	Fog	Rain, Fog	Sleet, Fog	Other, Unknown	Total
Pavement Conditions	Dry	4,802,260	6,925	157	2,170	14,643	0	7	14,054	**4,840,216**
	Wet	394,138	715,549	4,715	29,578	17,786	1,731	145	6,318	**1,169,961**
	Snow, Slush	51,674	3,341	4,532	105,488	507	81	146	2,647	**168,416**
	Ice	93,899	10,298	11,198	73,617	2,342	149	685	5,166	**197,355**
	Sand, Dirt, Oil	11,094	198	0	0	205	0	0	188	**11,684**
	Other, Unkn	10,951	915	33	151	295	0	0	423	**12,975**
	Total	**5,364,016**	**737,226**	**20,635**	**211,004**	**35,778**	**1,962**	**983**	**29,003**	**6,400,607**

Table 3 – Average Crashes by Weather and Pavement Condition

		Weather Conditions								
		Clear	Rain	Sleet	Snow	Fog	Rain, Fog	Sleet, Fog	Other, Unknown	Total
Pavement Conditions	Dry	2,421,904	3,170	44	627	6,800	103	7	6,821	**2,439,477**
	Wet	172,809	347,122	2,211	11,715	6,652	1,047	111	3,061	**544,727**
	Snow, Slush	14,386	1,210	1,595	30,996	217	19	45	1,013	**49,462**
	Ice	32,412	4,008	4,437	23,364	838	25	330	1,887	**67,301**
	Sand, Dirt, Oil	5,366	139	0	0	71	0	0	154	**5,730**
	Other, Unkn	5,724	469	28	146	100	0	0	283	**6,750**
	Total	**2,652,601**	**356,118**	**8,315**	**66,849**	**14,657**	**1,195**	**492**	**13,220**	**3,113,447**

Table 4 – Average Injuries by Weather and Pavement Condition

		Weather Conditions								
		Clear	Rain	Sleet	Snow	Fog	Rain, Fog	Sleet, Fog	Other, Unknown	Total
Pavement Conditions	Dry	34,328	6	1	7	338	0	0	154	**34,834**
	Wet	1,876	3,341	39	116	203	46	2	42	**5,666**
	Snow, Slush	175	12	27	405	4	1	1	8	**635**
	Ice	329	39	87	203	22	1	5	15	**701**
	Sand, Dirt, Oil	42	1	0	0	0	0	0	2	**45**
	Other, Unkn	126	2	0	2	6	0	0	3	**382**
	Total	**36,877**	**3,401**	**154**	**733**	**573**	**48**	**8**	**468**	**42,262**

Table 5 – Average Fatalities by Weather and Pavement Condition

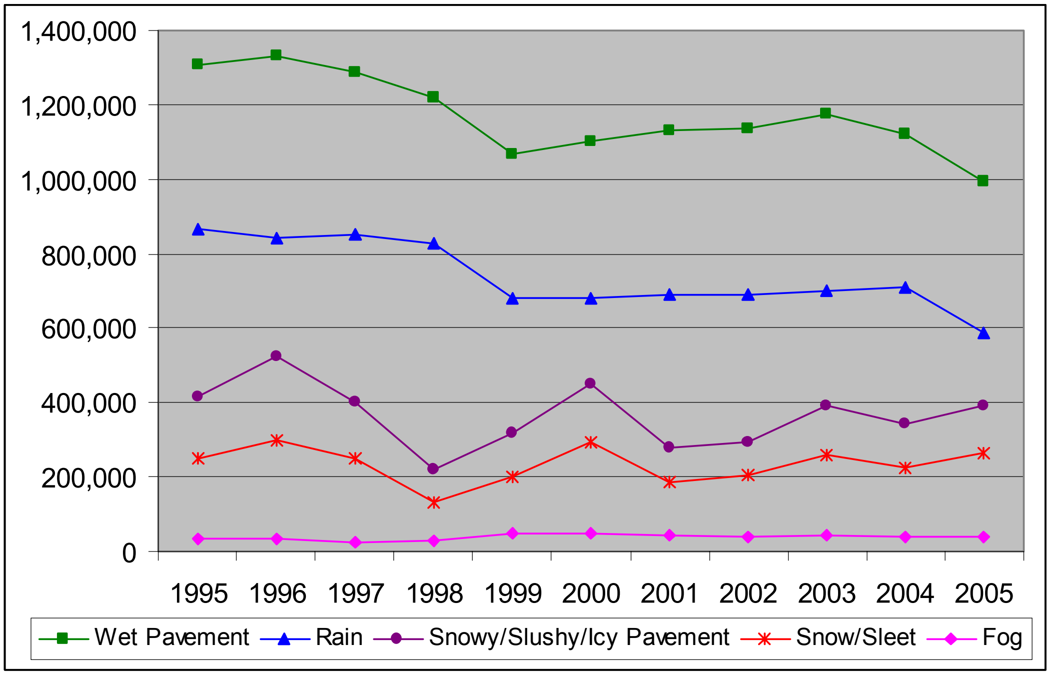

Figure 1 – Weather-Related Crash Frequency by Condition

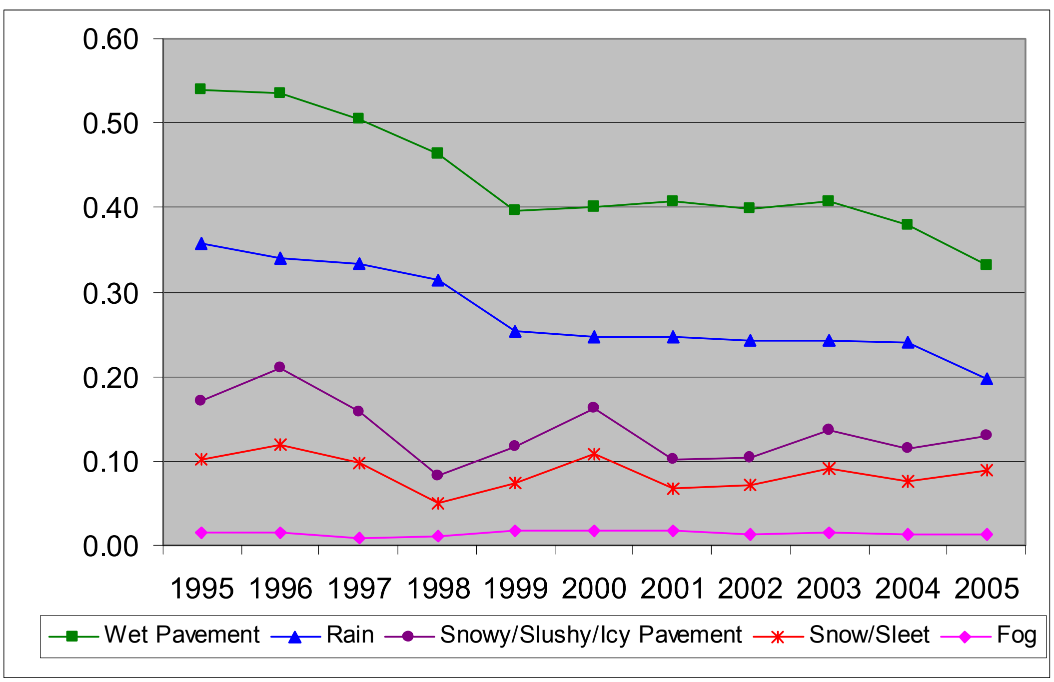

Figure 2 – Weather-Related Crash Rates per Million Vehicle Miles Traveled (VMT)

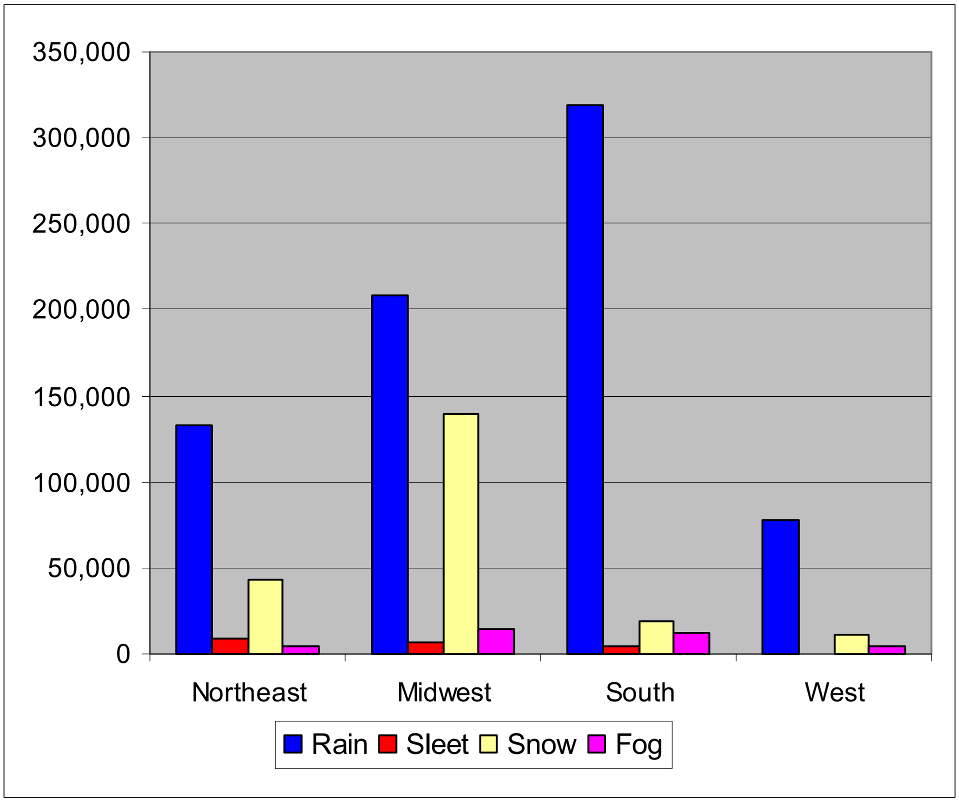

Figure 3 – Adverse Weather Crashes by Region

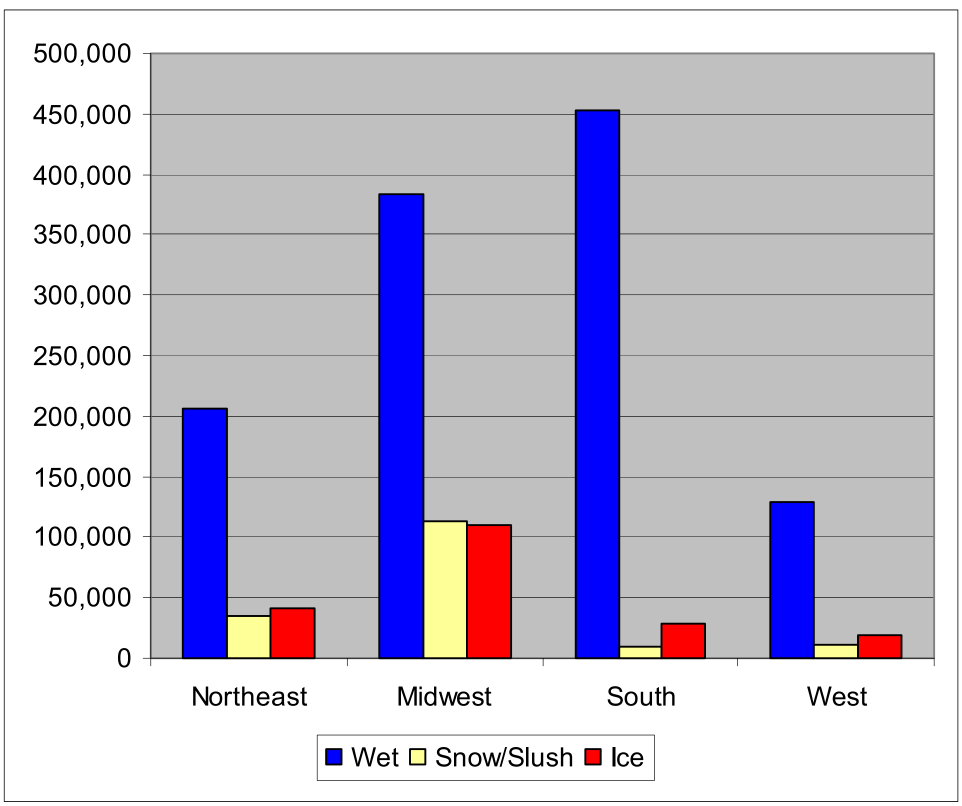

Figure 4 – Slick Pavement Crashes by Region

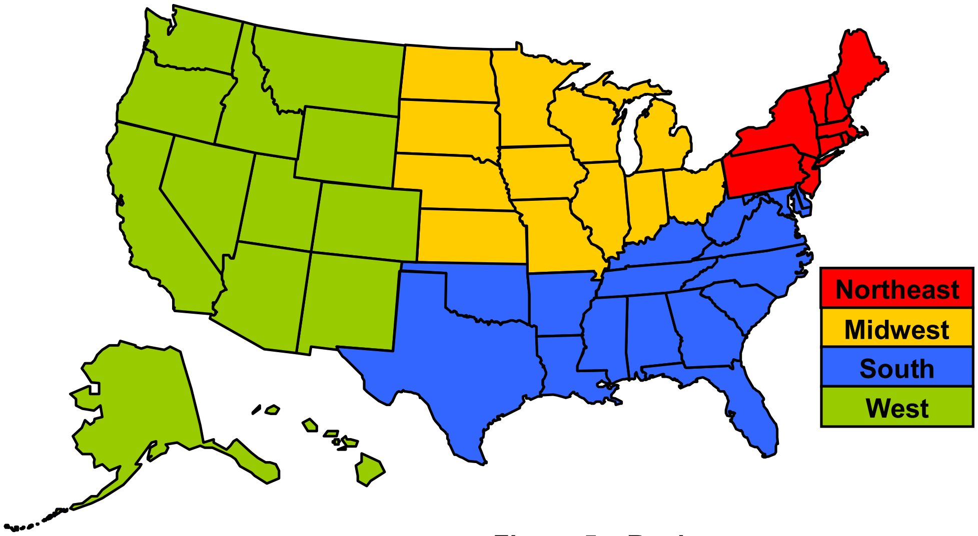

Figure 5 – Regions

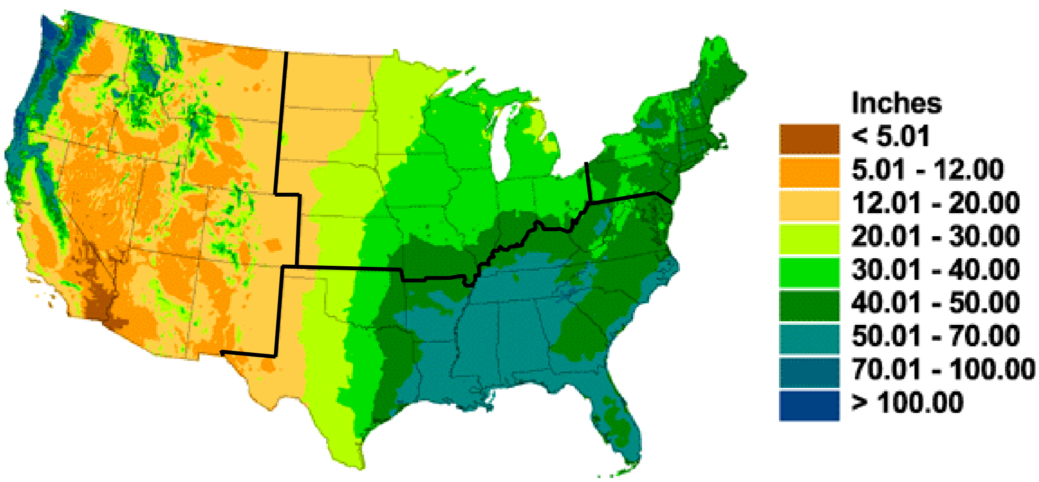

Figure 6 – Mean Total Precipitation

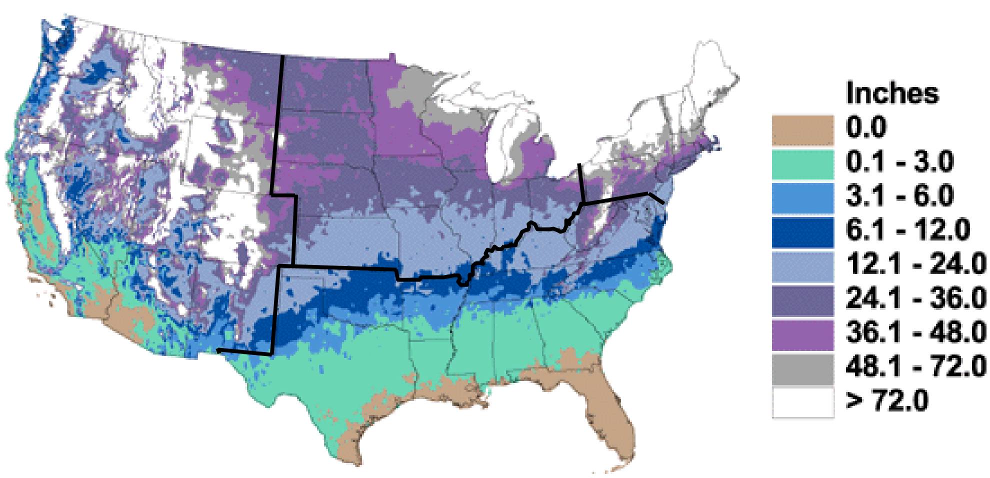

Figure 7 – Mean Total Snowfall

	Average Weather-Related Crashes				2005 Population	2005 Vehicle Miles Traveled
	Fatal Crashes	Injury Crashes	PDO Crashes	Total		
Northeast	16%	21%	17%	18%	19%	15%
Midwest	27%	31%	43%	40%	22%	22%
South	41%	37%	30%	32%	36%	41%
West	16%	11%	10%	10%	23%	22%

Table 6 – Percentage of Weather-Related Crashes, Population, and VMT by Region

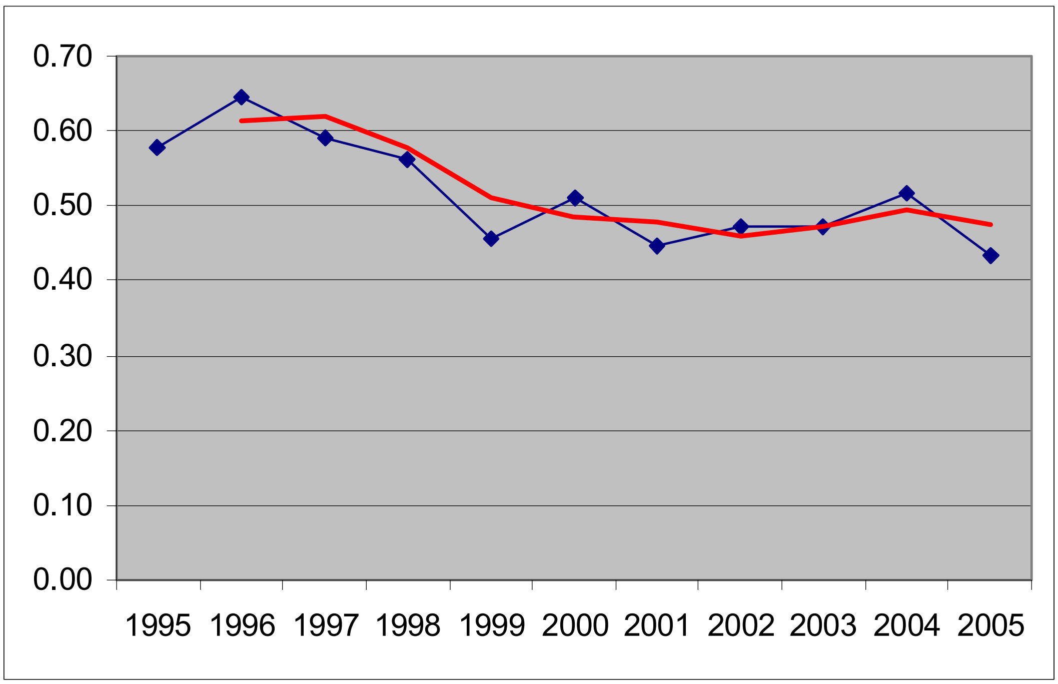

Figure 8 – Fatal Weather-Related Commercial Vehicle Crashes per 100 Million VMT, with 2-year moving average

Weather Conditions	Fatal Weather-Related Crashes	
	Commercial Vehicles	All Vehicles
Rain	60%	46%
Snow/Sleet	32%	12%
Fog	12%	8%

Table 7 – Fatal Weather-Related Crashes in Commercial Vehicles and All Vehicles

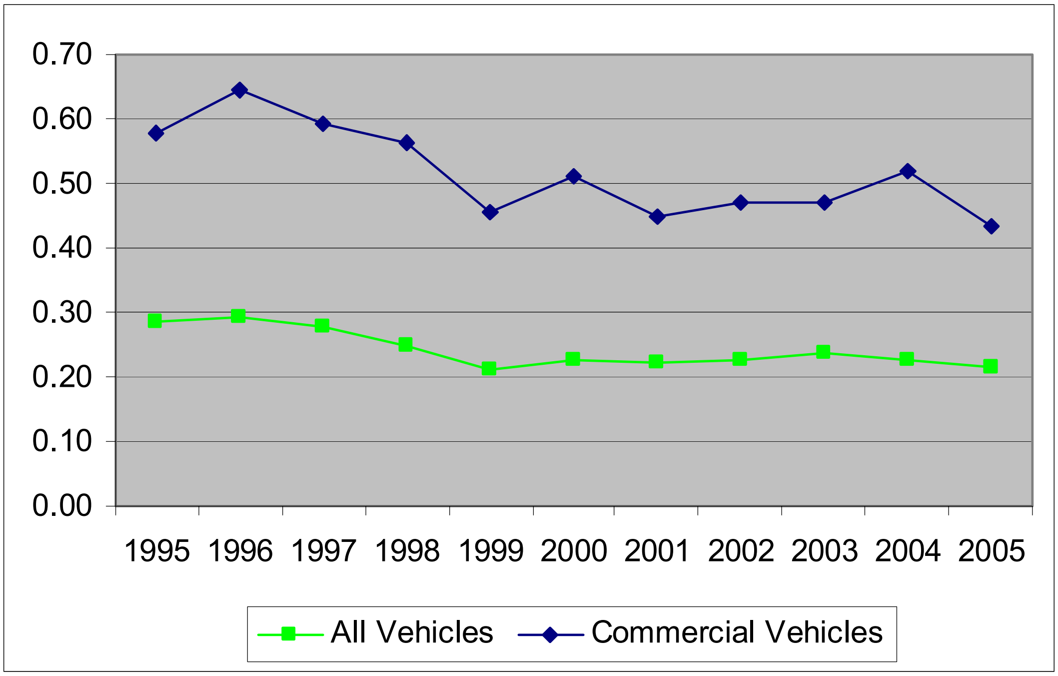

Figure 9 – Fatal Weather-Related Crashes in Commercial Vehicles and All Vehicles per 100 Million VMT