SHRP2 SOLUTIONS
TOOLS FOR THE ROAD AHEAD

# FINAL REPORT

## FHWA-WY-16/08F

## SHRP2 IMPLEMENTATION ASSISTANCE PROGRAM (IAP)—ROUND 4 CONCEPT TO COUNTERMEASURES—RESEARCH TO DEPLOYMENT USING THE SHRP2 SAFETY DATA

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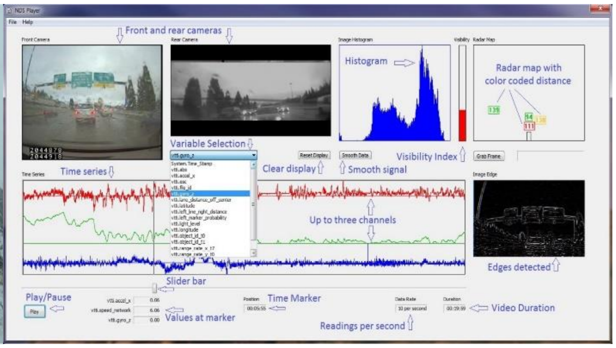

# DRIVER PERFORMANCE AND BEHAVIOR IN ADVERSE WEATHER CONDITIONS: AN INVESTIGATION USING THE SHRP2 NATURALISTIC DRIVING STUDY DATA—PHASE 1

DECEMBER, 2015

A Report from
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American Association of State Highway and Transportation Officials
AASHTO
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# Technical Report Documentation Page

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**16. Abstract**

Inclement weather events such as fog, snow, ground blizzard, slush, rain, and strong wind affect roadways by impacting pavement conditions, vehicle performances, visibility, and drivers' behavior. Road-user characteristics and behavior are among the most important elements influencing the driving task. The ability to see objects that are in motion relative to the eye ("dynamic visual acuity") and the reaction process (e.g., speed choice, lane maintenance, car following, etc.) are of utmost importance for safe driving. Adverse weather conditions can result in a sudden reduction in visibility on roadways, which leads to an increased risk of crashes. The literature shows a variation of crash risk estimates; however, a general trend can be concluded that adverse weather and road conditions can easily elevate the risk of crashes. Drivers' performance and behavior are absent in safety modeling due to lack of driver data. The second Strategic Highway Research Program (SHRP2) has collected the most comprehensive Naturalistic Driving Study (NDS). The unique NDS data will enable researchers to better understand the role of driver performance and behavior under various highway research.

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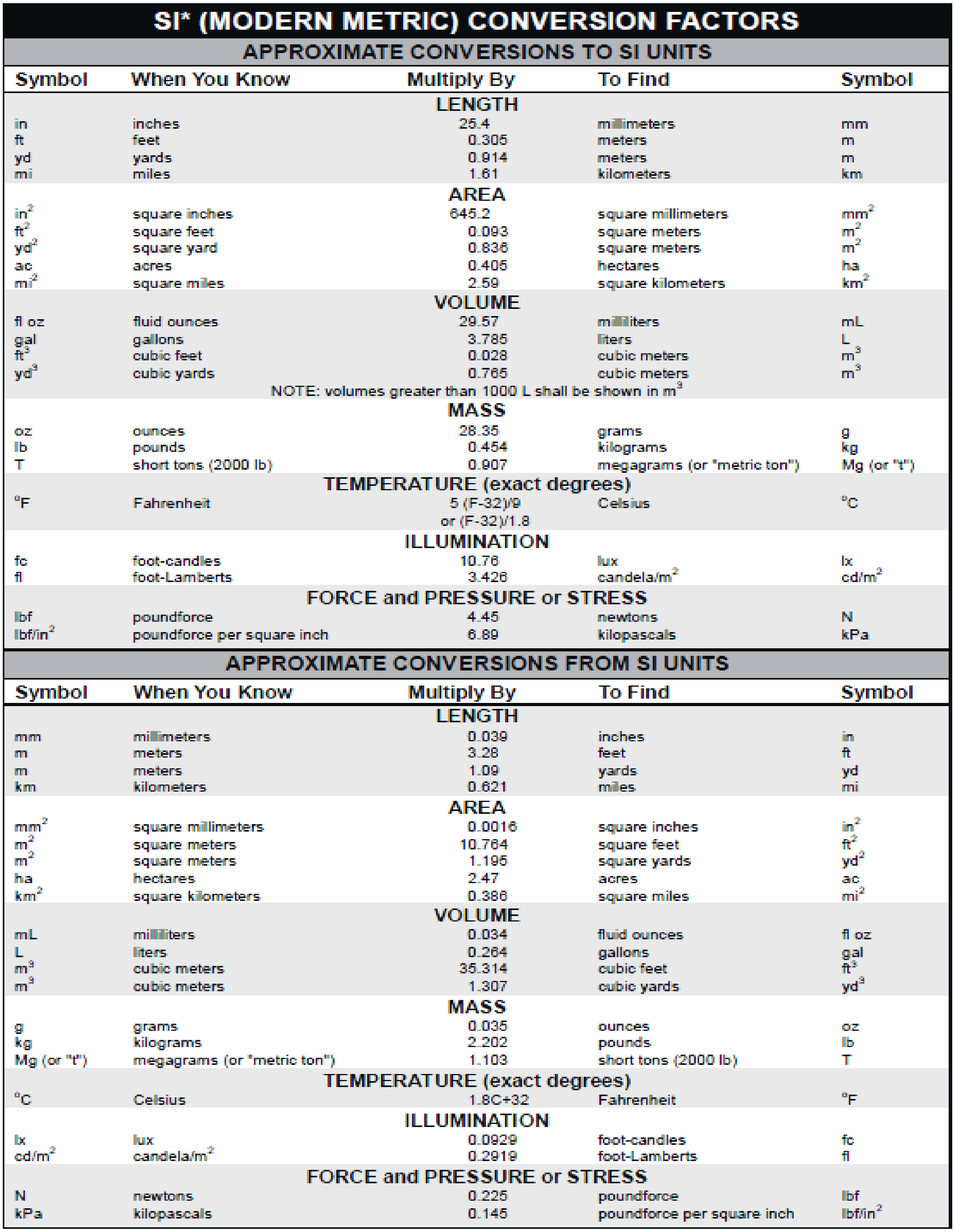
# METRIC CONVERSION FACTORS



## SI* (MODERN METRIC) CONVERSION FACTORS

### 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<br>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$^2$ |

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

# EXECUTIVE SUMMARY

Traffic safety is a top priority of transportation agencies across America – safety for the traveling public using our roadways, safety for transportation agency employees and their contractors working to maintain our streets and highways, and safety for our incident responders. More than 2.36 million people were injured in motor vehicle crashes in 2012. While driver behavior is most often cited as the primary factor in more than 90 percent of these crashes, little is known about how this behavior contributes to crashes.

The second Strategic Highway Research Program (SHRP 2) is conducting the largest and most comprehensive naturalistic driving study (NDS) ever imagined. The study recruited 3147 volunteer drivers, ages 16–94, across six sites: two counties surrounding Tampa, Florida; ten counties in central Indiana containing Indianapolis; Erie County, New York containing Buffalo; four counties in North Carolina containing Raleigh, Durham, and Chapel Hill; ten counties in central Pennsylvania containing State College; and four counties in Washington containing Seattle. Data include vehicle speed, acceleration, and braking; all vehicle controls; lane position; forward radar; and video views forward, to the rear, and on the driver's face and hands. When complete in early 2014, the NDS data set will contain over 33,000,000 travel miles from over 3,800 vehicle-years of driving, totaling over four petabytes of data (Hallmark and Mcgehee, 2013).

This project now supported by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) will enable state transportation agencies and their research partners to use new data developed through the second Strategic Highway Research Program (SHRP2) to develop improved methods for reducing crashes and improving highway safety.

The SHRP2 safety data comprise two large databases: a Naturalistic Driving Study (NDS) database and a Roadway Information Database (RID). The NDS data provide a wealth of information regarding driving behavior, and the RID is a companion database measuring roadway elements and conditions. These two databases can be linked to associate driver behavior with the actual roadway characteristics and driving conditions. The NDS provides objective information on what preceded crash and near-crash events, and identifies what drivers actually are doing during real-world driving conditions. In the SHRP2 study, more than 3,400 volunteer drivers in six locations had their cars outfitted with miniature cameras, radar, and other sensors to capture data as they went about their usual driving tasks. These data are the first opportunity for researchers to study U.S. driving behavior that is as close to “natural” as possible for the purpose of investigating highway safety issues. The RID is a geo-database that contains detailed information about the roadway characteristics in and around the NDS study cities. New roadway data were collected using a mobile van on 12,500 centerline miles across the six NDS sites. Existing roadway and other relevant information were obtained from government, public, and private sources and includes crash histories, traffic, weather, work zones, and safety campaigns. The NDS and RID data sets are linked on December 31, 2014, to provide researchers with a uniquely powerful data source. Both data sets are geo-referenced, allowing for driver behavior to be matched with the roadway environment, as well as to temporal elements of the driving environment, such as work zones and weather.

Through the FHWA/AASHTO IAP, results from the NDS and RID databases are being made available to state DOTs interested in analyzing the data to identify crash causation factors and to develop effective countermeasures, such as road designs or public safety campaigns, which will address their common safety concerns. In August, FHWA and AASHTO announced that 10 states will participate in a “Proof of Concept” effort offered through the SHRP2 program, Concept to Countermeasure – Research to Deployment Using the SHRP2 Safety Databases. Approximately $3 million in financial and technical assistance is being made available to conduct research on 11 topics. IAP recipients have agreed not only to research a topic using the SHRP2 safety data but also to actively pilot and promote any promising countermeasures that are identified by their research. A primary – but not the only – goal is national adoption of new countermeasures. States, partnered with researchers, will manage the research, implement findings, and deliver authorized research results. To simplify the application process and to reduce the risk and uncertainty to applicants, a three-phased process will be used. In Phase 1, participants will use a reduced set of NDS and RID data to demonstrate within nine months that their research concept is viable, and that a full analysis with a larger data set can answer the research question posed by the agency and its research partners. At the end of Phase 1, the work will be presented and reviewed by FHWA and the AASHTO Safety Task Force to determine whether the results are promising enough to move to Phase 2. Those DOTs selected for Phase 2 will have access to the full SHRP2 safety data set. A separate work plan, budget, and schedule will be negotiated for Phase 2. If Phase 2 produces meaningful results that are likely to lead to an implementable countermeasure or a new behavioral strategy, then FHWA could provide additional financial or technical support for Phase 3, which would address implementing the countermeasure. Implementation would not include additional research; instead, implementation in Phase 3 could include engineering or other support to update national manuals or policies, or strategies to incorporate the countermeasure and endorse it for national adoption. Phase 3 might also include pilot testing a developed safety countermeasure in the field, implementing new public outreach efforts, or using other measures to improve highway safety (Florida et al., 2014).

From 30 applications submitted to FHWA/AASHTO, 10 state DOTs were selected to begin research in January 2015 using the two safety databases, with each state receiving approximately $100,000 for each proposal. The DOTs included Florida, Iowa, Michigan, Minnesota, Nevada, New York, North Carolina, Utah, Washington, and Wyoming. Washington State DOT received two awards for separate research topics. The topics include pedestrian–vehicle interaction; roadway departures; speeding; work zones; horizontal and vertical roadway curves; interchange ramps; adverse weather conditions; and roadway lighting (Florida et al., 2014).

**Table 1.** Accepted proposals from different DOTs

| | |
|---|---|
| Pedestrian Safety | Florida DOT<br>Nevada DOT<br>New York State DOT |
| Roadway Departure | Iowa DOT |
| Speeding | Michigan DOT<br>Washington DOT |
| Work Zones | Minnesota DOT |
| Horizontal and Vertical Curves | North Carolina DOT |
| Interchange Ramps | Utah DOT |
| Adverse Conditions | Wyoming DOT |
| Roadway Lighting | Washington DOT |

The Wyoming DOT research is about how drivers respond to adverse weather and road conditions. The study will gain insights into driver dynamics with regard to choosing speeds and headways for different conditions and what cues are the most effective in providing drivers with a more realistic variable speed limit system. This study will also provide valuable information about how drivers behave in various roadway and weather conditions, and how these behaviors impact the effectiveness of safety countermeasures. The unique SHRP2 safety data will enable Wyoming DOT researchers to understand the role of driver performance and behavior in various highway conditions. The data also will allow for a better understanding of how drivers adjust their behaviors to compensate for increased risk due to reductions in visibility. The safety data will help in obtaining objective insights into what drivers are actually doing during adverse weather and road conditions. More discussion is provided below:

Inclement weather events such as fog, snow, ground blizzard, slush, rain, and strong wind affect roadways by impacting pavement conditions, vehicle performances, visibility, and drivers' behavior. Road-user characteristics and behavior are among the most important elements influencing the driving task. The ability to see objects that are in motion relative to the eye ("dynamic visual acuity") and the reaction process (e.g., speed choice, lane maintenance, car following, etc.) are of utmost importance for safe driving. Adverse weather conditions can result in a sudden reduction in visibility on roadways, which leads to an increased risk of crashes. Effects of adverse weather conditions on the operations and safety of transportation is considerably researched; however, the primary elements of driver behavior and performance are absent from these studies. According to the U.S. Department of Transportation's Federal Highway Administration (FHWA), weather contributed to more than 24% of the total crashes between 1995 and 2008, based on National Highway Traffic Safety Administration (NHTSA) data. Several studies concluded that crashes increase by 100% or more due to vision obstruction during rainfall (National Traffic Safety Board, 1980); (Brodsky and Hakkert, 1988), while others found more moderate, but still statistically significant, increases (Andrey and Olley, 1990); (Andreescu and Frost, 1998). Sudden reduction in visibility was found to increase severity level of crashes, and these crashes tend to involve more vehicles compared to other crash types. According to the NHTSA's Fatality Analysis Reporting System (FARS), inclement weather of rain, snow, and fog/smoke resulted in 31,514 fatal crashes between 2000 and 2007. Shankar, Mannering, and Barfield (1995) reported that the crash rates increased for locations with a high number of rainy days per month, maximum rainfall, and maximum snowfall (Shankar et al., 1995). Ahmed et al. (2012) reported that an additional one inch increase in precipitation elevated the risk of a crash by 169% (Ahmed et al., 2012). The literature shows a variation of crash risk estimates; however, a general trend can be concluded that adverse weather and road conditions can easily elevate the risk of crashes. Drivers' performance and behavior are absent in safety modeling due to lack of driver data. The Second Strategic Highway Research Program (SHRP2) has collected the most comprehensive Naturalistic Driving Study (NDS). The unique NDS data will enable researchers to better understand the role of driver performance and behavior under various highway research.

The Wyoming Department of Transportation (WYDOT) and University of Wyoming have completed a proof-of-concept utilizing a sample NDS data set and Roadway Information Database (RID). The NDS and RID data sets were utilized to better understand how drivers adjust their behaviors to compensate for increased risk due to reduction in visibility. The main goal of this study was to enhance the understanding of how drivers respond to adverse weather and road conditions (e.g., speed adaptation, lane maintenance, car following, etc.). This was conducted by compiling a sample data set from DS data, then extracting and reducing the data for inclement weather events (i.e., heavy rain in Phase 1) on freeways to address the following research questions:

1. Can inclement weather trips be identified effectively using NDS and RID data?
2. Can driver responses (i.e., speed and headway adaptation, and lane wandering) during inclement weather (i.e., reduction in visibility due to heavy rain in Phase 1) be characterized efficiently from NDS data?
3. What are the best surrogate measures for weather-related crashes that can be identified using NDS data?
4. What type of analysis can be performed and conclusions be drawn from the resulting data set?

According to the FHWA, Connected Vehicle (CV), Variable Speed Limits (VSL), and Advanced Traveler Information Systems (ATIS) are considered the next step in tackling U.S. freeway congestion and safety problems. VSL systems have been widely implemented in the U.S. and Europe to help mitigate: 1) recurrent congestion; 2) adverse weather impacts on freeways; 3) traffic injuries and fatalities; and 4) pollution. VSL systems will be an integral part of CV technology.

Because selecting the right speed for the condition is considered one of the most important driving tasks on high speed facilities, and the interaction between the driver and weather condition is not well understood, the objective of this research is to assess the relationship between driver behavior (i.e., speed and headway choice), roadway factors, and environmental factors.

The study will gain insights into drivers’ dynamics in regard to choosing speeds and headways for different conditions and what cues are the most effective in providing drivers with a more realistic VSL system. It will also provide valuable information about how drivers interact with changing roadway and weather conditions and the effectiveness of countermeasures. All current VSL systems’ algorithms are based solely on weather and traffic conditions. To the knowledge of the principle investigators, no VSL systems considered driver behavior in their algorithms. Current practices in setting speed limits within VSL systems under different traffic and weather conditions are based on traffic simulation, survey questionnaires, and historical crash data. The NDS data will help provide objective insights into what drivers actually do during adverse weather and road conditions.

Wyoming was selected as one of three sites for the Connected Vehicle Pilot Deployment; the project will be conducted on Interstate 80 (I-80) VSL corridors. The research from this study will aid in supporting CV technology. Continuous data collected in real-time from vehicles will be analyzed to examine the usefulness of the NDS data in providing real-time weather information.

Based on the experiences in Phase 1, we proposed in Phase 2 addressing a 5th research question:

5. Can the NDS data be extrapolated to provide real-time weather information in the context of the Road Weather Connected Vehicle Applications?

The main objective of this research is to examine the feasibility of using NDS and RID data sets to improve our understanding of weather- and visibility-related crashes. The study will help in enhancing suggested speed limits within VSL systems and providing guidance information within ATIS. This study will investigate the applicability of using vehicle time series data to support CV technology during inclement weather. The outcome from this research will help in reducing traffic injuries and fatalities.

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## LIST OF ACRONYMS/ABBREVIATIONS

| | |
|---|---|
| ABS | Anti-Lock Brake System |
| AVI | Automatic Vehicle Identification |
| CI | Confidence Interval |
| CTRE | Center for Transportation Research and Education |
| CV | Connected Vehicle |
| DAS | Data Acquisition System |
| FARS | Fatality Analysis Reporting System |
| FHWA | Federal Highway Administration |
| FMVSS | Federal Motor Vehicle Safety Standards |
| GES | General Estimates System |
| GIS | Geographic Information Systems |
| ILD | Inductive Loop Detector |
| NDS | Naturalistic Driving Study |
| NHTSA | National Highway Traffic Safety Administration |
| OR | Odds Ratio |
| PDO | Property Damage Only |
| RID | Roadway Information Data |
| RWIS | Road Weather Information System |
| SHRP2 | Second Strategic Highway Research Program |
| TMC | Traffic Management Center |
| VSL | Variable Speed Limit |
| VTTI | Virginia Tech Transportation Institute |
| WYDOT | Wyoming Department of Transportation |

# Chapter 1- Crash severity, Weather related and Drivers information Using Insight website available data

According to the FHWA, 90 percent of crashes are related to driver behavior, and human error is identified as the primary factor contributing to over than 60 percent of crashes. It is expected that the role of driver performance during inclement weather is even more. This study will help to enhance our understanding of weather and visibility related crashes and driver behavior (i.e., speed adaptation and headways) in inclement weather on freeways. This will be achieved by examining the feasibility of effectively extracting adverse weather related trips from the NDS data and investigating driver response during those circumstances. The NDS trips and Roadway Information Data (RID) will be used to explore how the likelihood of crashes and near crashes in inclement weather depends on driver behavior, environmental and roadway factors. The environmental factors such as visibility level can be extracted directly from the in-vehicle cameras and ambient light sensor. The driver behavior and vehicle performance, collected via various NDS sensors, such as speed choice and adaptation, judgment of safe following distance, lane maintenance, wipers use, ABS activation, yaw rate, Electronic Stability Control, driver attention and distraction, and driver characteristics can be modeled for inclement and clear weather conditions. In Phase I, the NDS data from the States of Washington and Florida was acquired to better understand the contributing factors to reduced visibility related crashes due to inclement weather (i.e., rain/ heavy rain) on freeway segments. Dealing with the NDS data could be challenging for various reasons; the size and complexity of the data, the continuous nature of the data, and the difficulty of identifying events of interests, processing and reducing video data, linking NDS data with RID data, identifying surrogates for different crash types, and defining baselines in normal driving conditions. The main focus of this proof-of-concept phase will be directed toward rain and heavy rain conditions only. To address the first research question of identifying appropriate trips in rainy conditions, a preliminary analysis will be conducted using the NDS time-series data. The research approach will include; development of data requests and queries of the NDS and RID data; reducing and extracting relevant information for the study from NDS video data; and conducting a preliminary analysis to demonstrate the techniques that would be used for the full analysis from all NDS data in Phase II. This report is divided into three chapters. Chapter 1 focused on the information provided on Insight Website. In fact, the main purpose of this chapter is assessing the availability of required data to achieve mentioned objective. Table1 shows number of trips in each state.

**Table 2.** Number of trips in each state

| Site name | Total |
|---|---|
| **Florida** | 1224511 |
| **Indiana** | 459849 |
| **New York** | 1312668 |
| **North Carolina** | 905385 |
| **Pennsylvania** | 346293 |
| **Washington** | 1165357 |
| **Total** | 5414063 |

### Type of Vehicles were Used

Table 3 and Figure 1 show the vehicle type distribution that was instrumented for data collection in the SHRP 2 NDS study. Information about integrated technologies on the vehicle is also provided on the website. It should be noted that individual vehicle records may be linked to multiple participants if more than one member of a household participated in the program.

**Table 3.** Type of vehicles were installed with data collection equipment

| Vehicle type | Florida | Washington | Florida + Washington | All six states |
|---|---|---|---|---|
| **Car** | 573 | 547 | 1120 | 2405 |
| **Pickup-Truck** | 35 | 34 | 69 | 169 |
| **SUV-Crossover** | 148 | 132 | 280 | 660 |
| **VAN-Minivan** | 25 | 28 | 53 | 136 |
| **Total** | 781 | 741 | 1522 | 3370 |

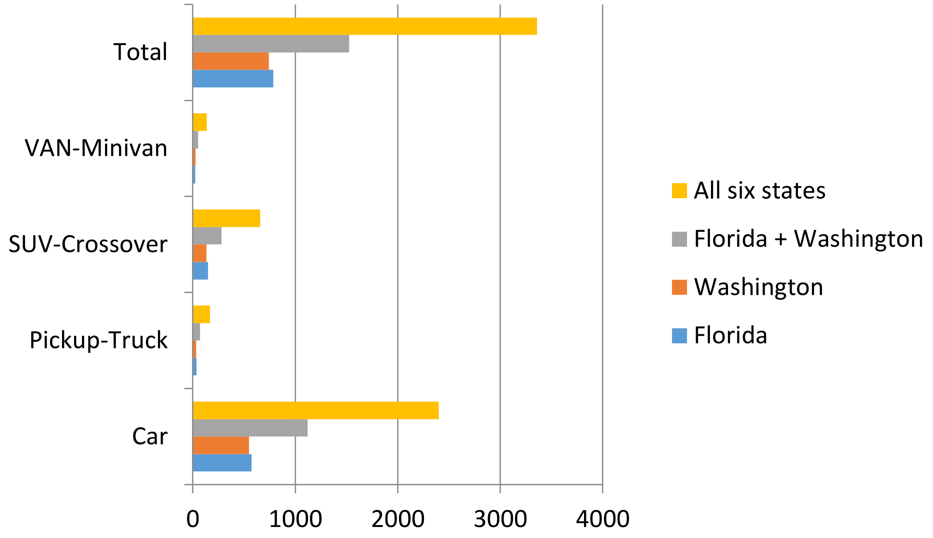


**Figure 1.**Type of vehicles were installed with data collection equipment

### Trips, Participants, Vehicles and Events

In this section trips with high number of minutes (longer than 10 minutes) of wipers used considered as trips in rainy conditions. Table 4 and Table 5 show the available trips by time wiper used and site name.

**Table 4.** Trips, participants, vehicles and events by time wipers used less than 10 minutes and site name

| | Florida | Washington | total |
|---|---|---|---|
| **Trips** | 243512 | 201302 | 444814 |
| **Participants** | 717 | 710 | 1427 |
| **Vehicles** | 681 | 577 | 1258 |
| **Events** | 1657 | 1386 | 3043 |

As can be seen from Table 4, in case of time wipers used less than 10 minutes in Florida there are 243512 trips related to 717 participants, 681 vehicles and 1657 events. 201302 trips with time wipers used less than 10 minutes related to 710 participants, 577 vehicles and 1386 events are available in Washington as well.

As mentioned before, Trips with high number of minutes (longer than 10 minutes) of wipers used considered as trips in rainy conditions (Using wipers less than 10 minutes may have other reasons such as cleaning the windshield). Table 5 shows Trips, participants, vehicles and events by time wipers used greater than 10 minutes and site name. As can be seen from Table 5, trips according to characteristic mentioned before in Florida and Washington are 943 and 4070 respectively. 70 participants in Florida and 73 participants in Washington, 68 vehicles in Florida and 58 vehicles in Washington and 22 events in Florida and 63 events in Washington were matched with the criteria mentioned above.

**Table 5.** Trips, participants, vehicles and events by time wipers used greater than 10 minutes and site name

| | Florida | Washington | total |
|---|---|---|---|
| **Trips** | 943 | 4070 | 5013 |
| **Participants** | 70 | 73 | 143 |
| **Vehicles** | 68 | 58 | 126 |
| **Events** | 22 | 63 | 85 |

In order to analyze the effects of rainy conditions on drivers' behavior and performance those trips that origin distance to destination are greater than 10 miles will be considered in this chapter. Table 6 shows number of trips that origin to destination distance is greater than 10 miles.

**Table 6.** Trips origin to distance greater than 10 minutes summary

| | Florida | Washington | total |
|---|---|---|---|
| **Trip: Distance Origin to Destination greater than 10 miles** | 126962 | 118254 | 245216 |
| **Trip: Distance Origin to Destination greater than 10 miles and time wipers used greater than 10 minutes** | 435 | 1218 | 1653 |

## Site Selection

Shrp2 technical group used a two stage process for selecting study sites:

1. Two requests for qualification were released. This stage produced 11 qualified sites.
2. A request for proposal was send to those contractors who responded to and passed the initial qualification stage.

After that, technical group faced with the responsibility of narrowing down the request for proposal respondents to the final six organizations and their respective sites determined to be best suited for the study. The key factor for selecting these sites was maximal geographical and environmental diversity. The request for the proposal stage lead to final selection of the six SHRP2 NDS sites (Antin et al., 2011).

In terms of number of data acquisition system (DAS) kits (and thus, roughly, number of participants) managed, the three largest sites were associated with Buffalo, New York; Seattle, Washington; and Tampa, Florida. Durham, North Carolina, housed the moderately sized site, and the smallest two sites were located in Bloomington, Indiana, and State College, Pennsylvania. Figure 2 shows the selected six data collection sites and nominal distribution of DAS kits in all six states.

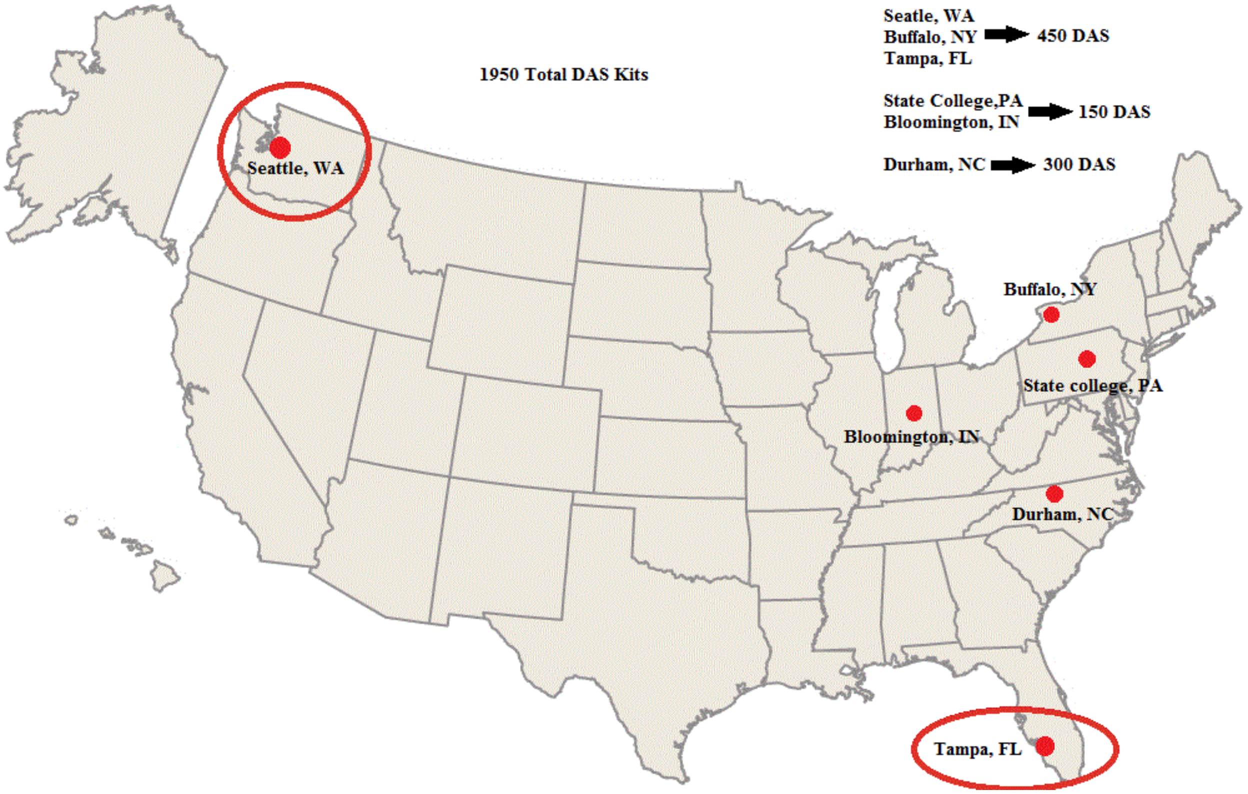


**Figure 2.** Six data collection sites and nominal distribution of the DAS kits

### Mobile Data Collection Project

The mobile data collection project covered about 12,500 centerline miles in the six NDS sites. Because data were collected in both directions of travel, a total of approximately 25,000 miles was provided. Table 7 is mobile data collected during this project provided by Center for Transportation Research and Education (CTRE). These data were collected consistently and within project specifications across the six NDS sites. Figure 3 shows Florida and Washington data collection plan.

**Table 7.** Miles collected in the mobile data collection project

| **NDS site** | Miles collected |
|---|---|
| Florida | 4366 miles |
| Washington | 4277 miles |
| Indiana | 4635 miles |
| New York | 3570 miles |
| Pennsylvania | 4277 miles |

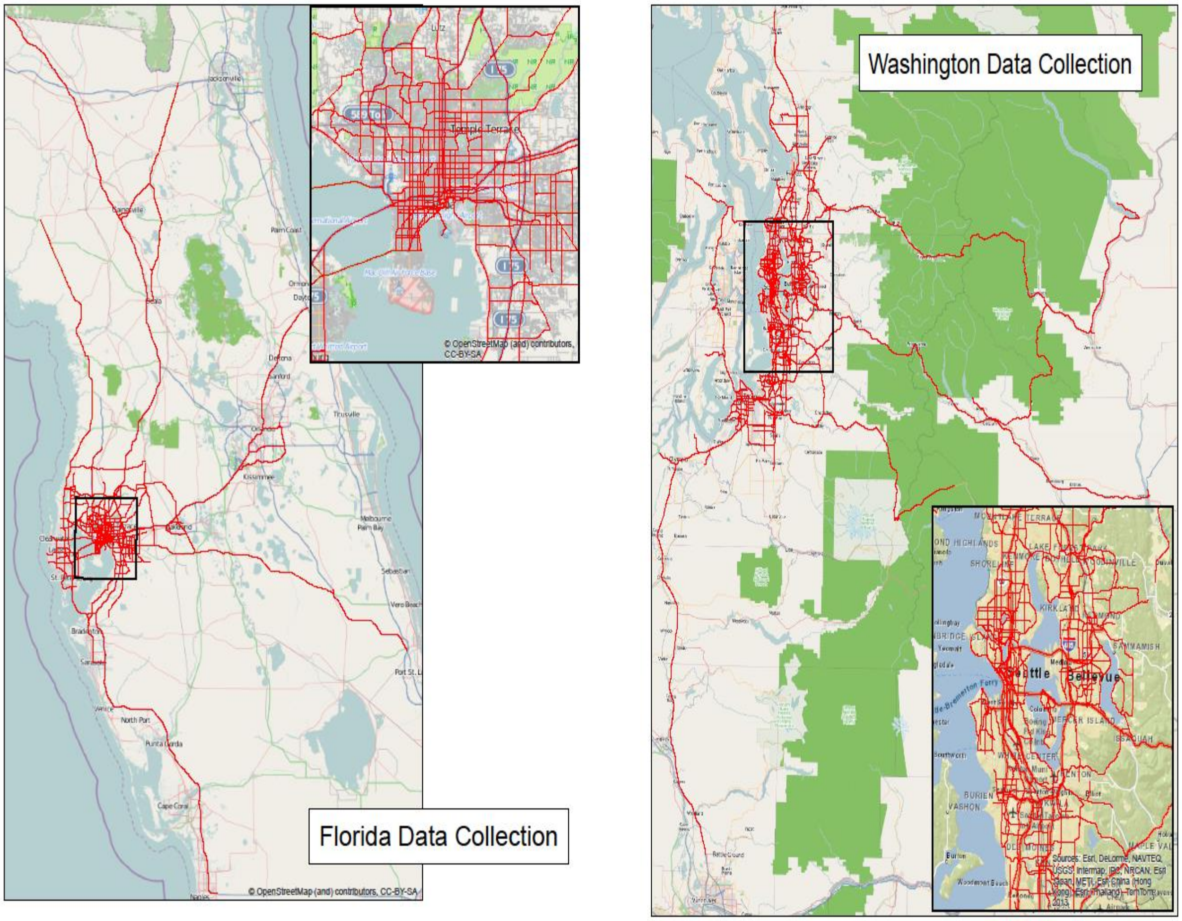
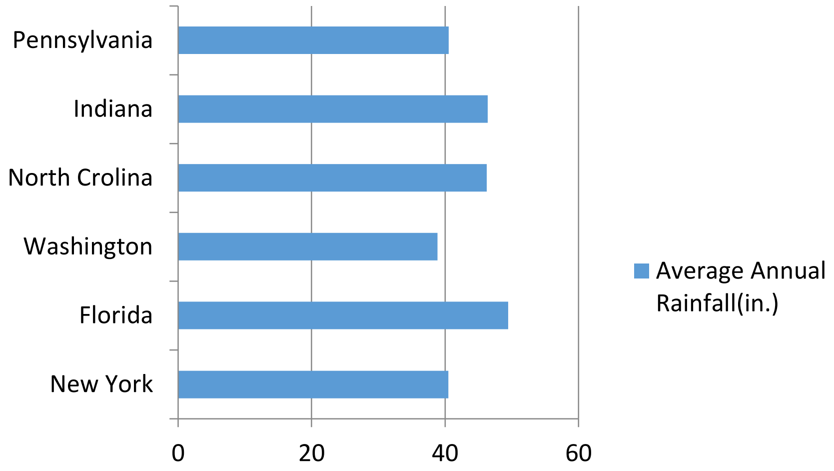


**Figure 3.** Florida and Washington Data Collection Plan

(Source: CTRE website)

## Weather Conditions

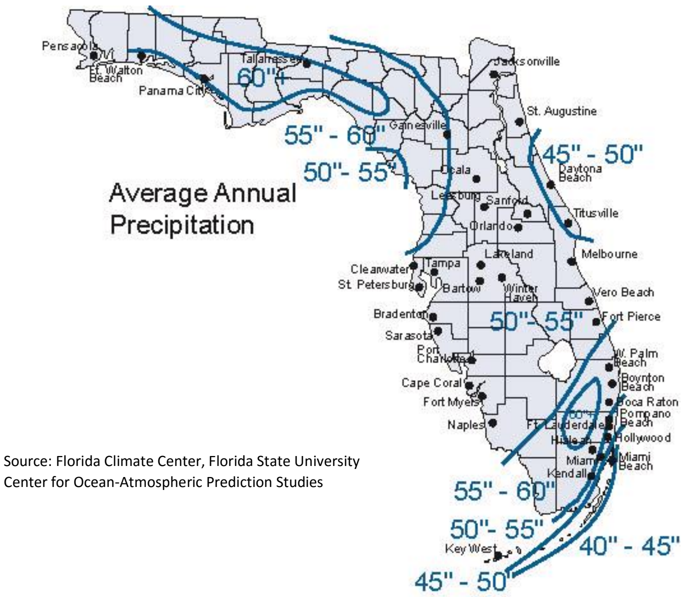
For the first time in early 1950's Tanner noticed that weather conditions affect drivers' performance and behavior. These effects could be seen in different factors such as speeds, headways and in general, drivers reactions to overall system (Tanner, 1952). Visibility plays an important role in understanding driver behavior during inclement weather conditions. Figure 4 shows the average annual rainfall for recruitment site counties. As can be seen average annual rainfall in Indiana, North Carolina and Florida are more than 40 inches. This figure shows that on average Washington to some extent receiving less amounts of rainfall than other recruitment sites. Figure 5 shows average annual precipitation map in Florida.



Average Annual Rainfall for Recruitment Site Counties,
1981–2010

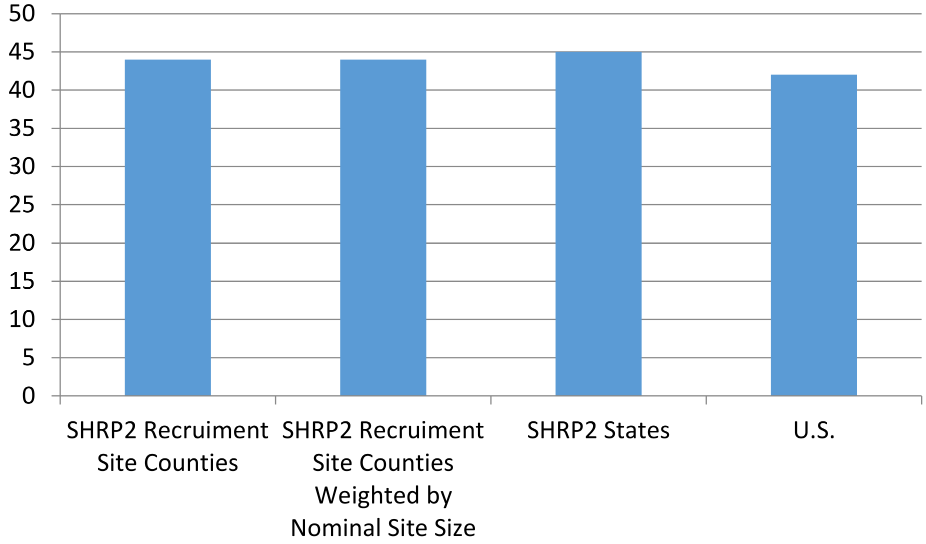
Source: National Oceanic and Atmospheric Administration 2014

**Figure 4.** Average annual rainfall for six data collection site



Source: Florida Climate Center, Florida State University
Center for Ocean-Atmospheric Prediction Studies

**Figure 5.** Florida average annual precipitation map

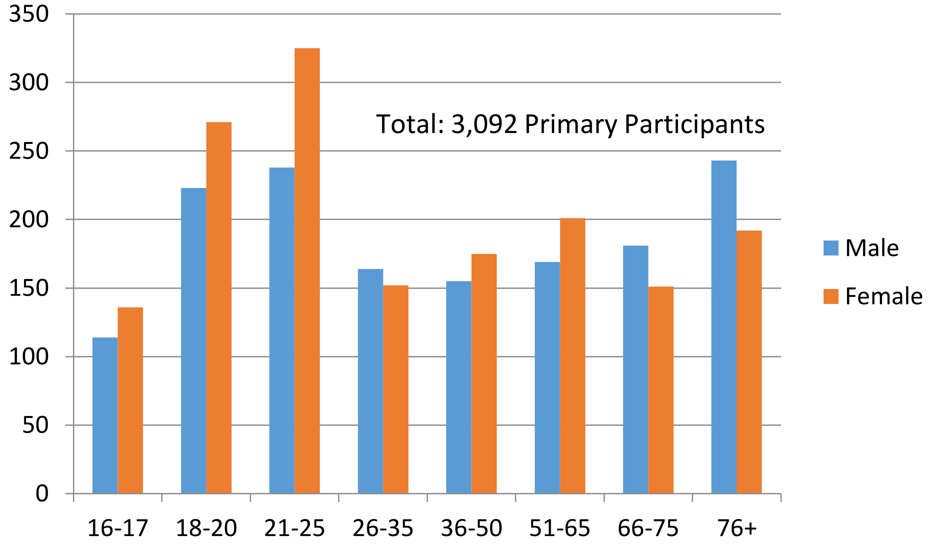


Source: National Oceanic and Atmospheric Administration 2014

**Figure 6.** Average annual rainfall (in.)

Figure 6 shows average rainfall across study sites, SHRP2 states and all states in the U.S. from 1981 through 2010. This figure shows that SHRP2 states receiving greater amounts of rainfall on average than other states.

## Gender



Source: Dingus et al. 2014.

**Figure 7.** Primary participants in different age groups

Figure 7 shows primary participants enrolled in NDS for at least four months relative to original sample design goals in different age groups. As can be seen from the figure, in most of the age groups females are more than male participants. This issue is completely considerable in participants younger than 25 years old.

**Age Groups**

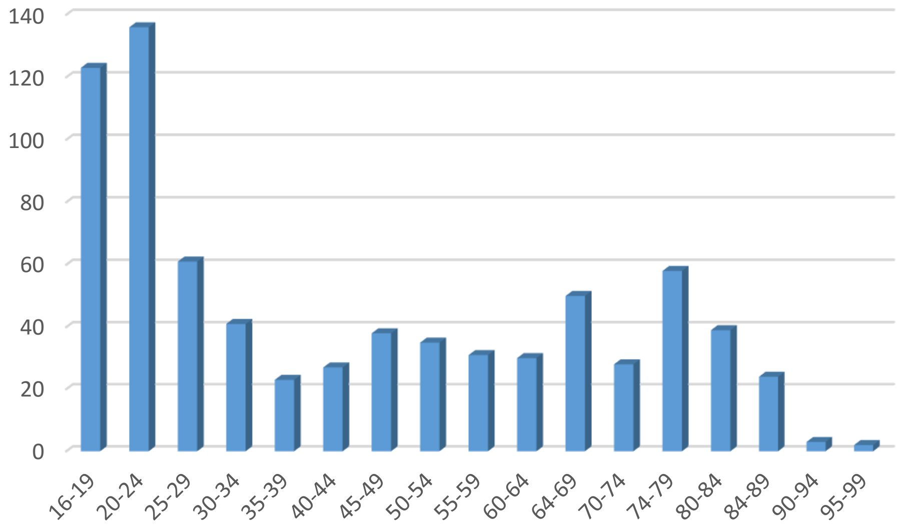


**Figure 8.** Number of drivers in Washington in different age groups

Figure 8 shows number of drivers in different age groups in Washington. This figure shows that drivers younger than 30 years old play an important role in SHRP2 NDS in Washington and the same trend can be seen for Florida in Figure 9.

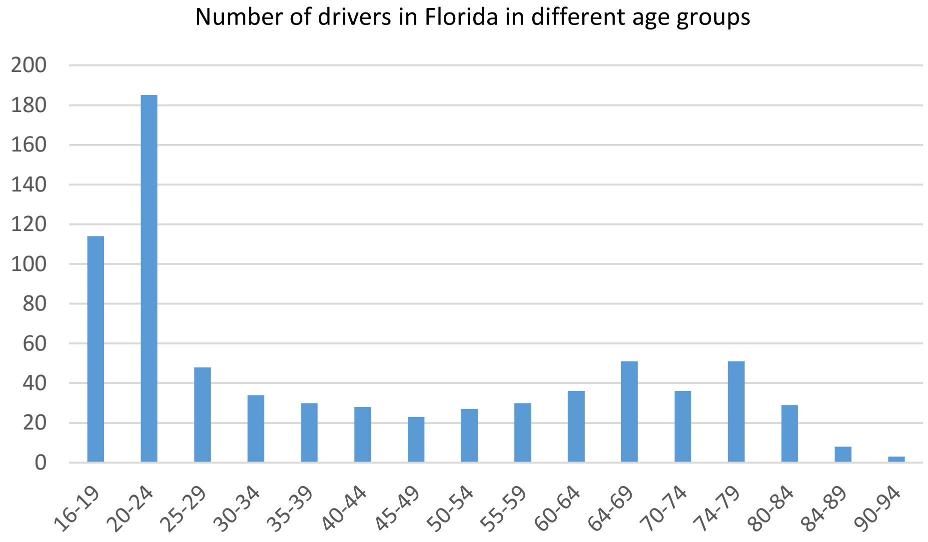


**Figure 9.** Number of drivers in Florida in different age groups

## Crash Severity

Crashes in the SHRP2 NDS were classified based on level of severity in 4 groups as follows:

Level I: airbag deployment, injury, rollover, high delta-V crashes (virtually all Level I crashes would be police-reported [PR] crashes);
Level II: police-reportable crashes (including PR crashes, as well as other crashes of similar severity that were not reported);
Level III: crashes involving physical contact with another object; and
Level IV: tire strike; low-risk crashes.

The nature of the NDS data collection methods meant that crashes were not always immediately identified by the research team. In fact, a few crashes may continue to be identified during subsequent data reduction and analysis activities months, and sometimes even years, after data collection (Smith et al., 2015). Figure 10 illustrates the number of crashes observed in the SHRP 2 NDS by severity level.

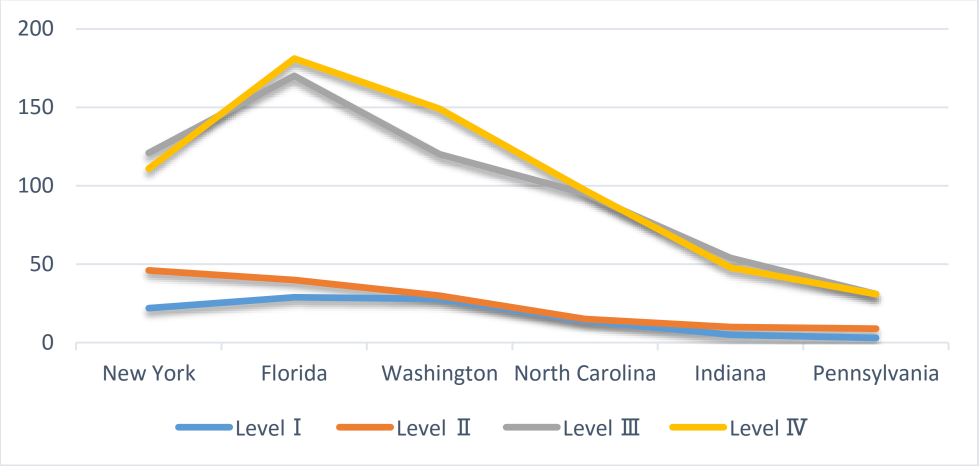


**Figure 10.** SHRP 2 crashes by severity level (confirmed crash evaluations as of June 30, 2014).

**Table 8.** Basic Crash Severity Level Data across Sites (as of Dec 17, 2015)

| Basic Crash Severity Level Data across sites | | | | | | | |
|---|---|---|---|---|---|---|---|
| | New York | Florida | Washington | North Carolina | Indiana | Pennsylvania | Total |
| **Level Ⅰ** | 22 | 29 | 28 | 14 | 5 | 3 | 101 |
| **Level Ⅱ** | 46 | 40 | 30 | 15 | 10 | 9 | 150 |
| **Level Ⅲ** | 121 | 170 | 120 | 95 | 54 | 31 | 591 |
| **Level Ⅳ** | 111 | 181 | 149 | 97 | 48 | 31 | 617 |

Information provided in Table 8 obtained from the Insight Website. More discussions about different levels are provided below:

Level I - Most Severe: Severe Crash. Any crash that includes an airbag deployment; any injury of driver, pedal cyclist, or pedestrian; a vehicle roll over; a high Delta V; or that requires vehicle towing. Injury if present should be sufficient to require a doctor's visit, including those self-reported and those apparent from video. A high Delta V is defined as a change in speed of the subject vehicle in any direction during impact greater than 20mph (excluding curb strikes) or acceleration on any axis greater than +/-2g (excluding curb strikes).

Level II - Police-reportable Crash: Police-Reportable Crash. A police-reportable crash that does not meet the requirements for a Level I crash. Includes sufficient property damage that it is police reportable (minimum of ~$1500 worth of damage, as estimated from video). Also includes crashes that reach an acceleration on any axis greater than +/-1.3g (excluding curb strikes). If there is a police report this will be noted. Most large animal strikes and sign strikes are included here.

Level III - Minor Crash: Physical Contact with another Object. Most crashes not included above are Level III crashes. Includes physical contact with another object but with minimal damage. Includes most road departures (unless criteria for a more severe crash are met), small animal strikes, all curb and tires strikes potentially in conflict with oncoming traffic, and other curb strikes with an increased risk element (e.g., would have resulted in worse had curb not been there, usually related to some kind of driver behavior or state).

Level IV - Low-risk Tire Strike: Tire Strike, Low Risk. Tire strike only with little/no risk element (e.g., clipping a curb during a tight turn).

Not a Crash: Includes all Event Severity (V14, 20) levels except for Crash. Includes Near Crashes and Baselines.

**Table 9.** 2010 Crash Data by SHRP2 states

| State | No. of Crashes | Licensed Drivers(1,000s) | Crash Rate (per 1,000 Licensed Drivers) |
|---|---|---|---|
| **Florida** | 236,528 | 13,950 | 16.96 |
| **Indiana** | 193,323 | 5,550 | 34.83 |
| **New York** | 315377 | 11286 | 27.96 |
| **North Carolina** | Not available | 6,537 | Not available |
| **Pennsylvania** | 121,101 | 8,737 | 13.86 |
| **Washington** | Not available | 6,537 | Not available |
| **All 50 states; Washington, D.C.; and Puerto Rico** | 5,419,000 | 210,115 | 25.79 |

Source: Federal Highway Adinistration2014; Volpe National Transportation System Center, U.S.DOT, personal communication 2014, "(Naturalistic Driving Study : Descriptive Comparison of the Study Sample with National Data, n.d.)"

In order to compare crashes in different states, raw crash numbers must be changed to rate. Table 9 shows that after expressing number of crashes as rates Indiana has the greater crash rate than U.S. crash rate and Florida shows lower crash rate in comparison with all states crash rate. New York shows slightly greater crash rate in comparison with all states. Finally, Pennsylvania shows the lowest crash rate among recruitment sites.

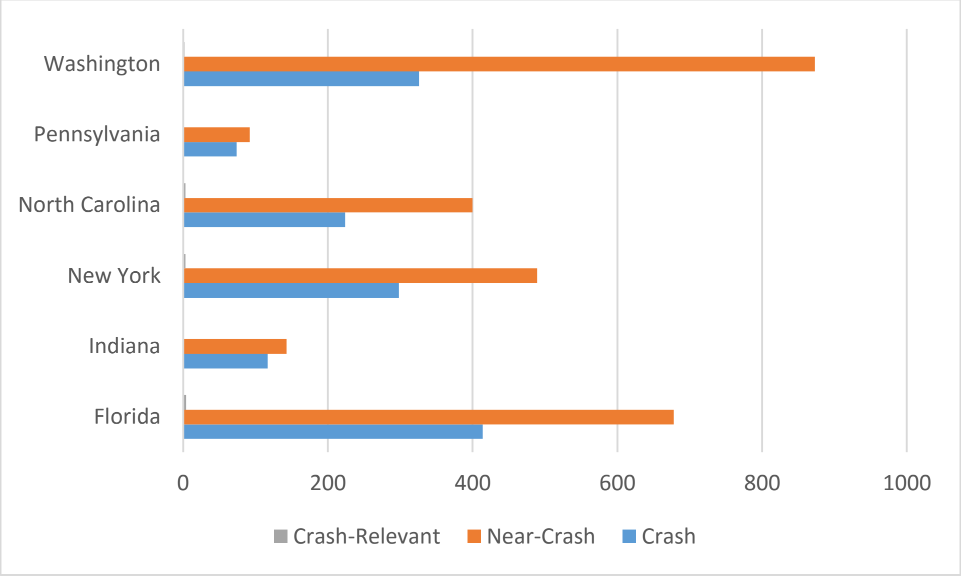


**Figure 11.** Event Severity and Site Name

Figure 11 shows crashes and near crashes in all six states as of Dec, 2015 extracted from the insight website. Crashes provided in the last update of the Insight Website is around twice the previous update of Insight Website. Table 10 shows the event severity in SHRP2 states in detail. As can be seen Florida and Washington have more crashes and near crashes than other SHRP2 study sites. Figure 12 compares crash severities between Washington and Florida. As can be seen, in case of Not a Crash Washington has greater portion. However, in other crash severity levels, Florida has more severe crashes in comparison with Washington.

**Table 10.** Event severity and site name

| | Florida | Indiana | New York | North Carolina | Pennsylvania | Washington | Total |
|---|---|---|---|---|---|---|---|
| **Crash** | 414 | 117 | 298 | 224 | 74 | 326 | 1453 |
| **Near-Crash** | 678 | 143 | 489 | 400 | 92 | 873 | 2675 |
| **Crash-Relevant** | 4 | 1 | 3 | 3 | 1 | 2 | 14 |
| **Total** | 1096 | 261 | 790 | 627 | 167 | 1201 | 4142 |

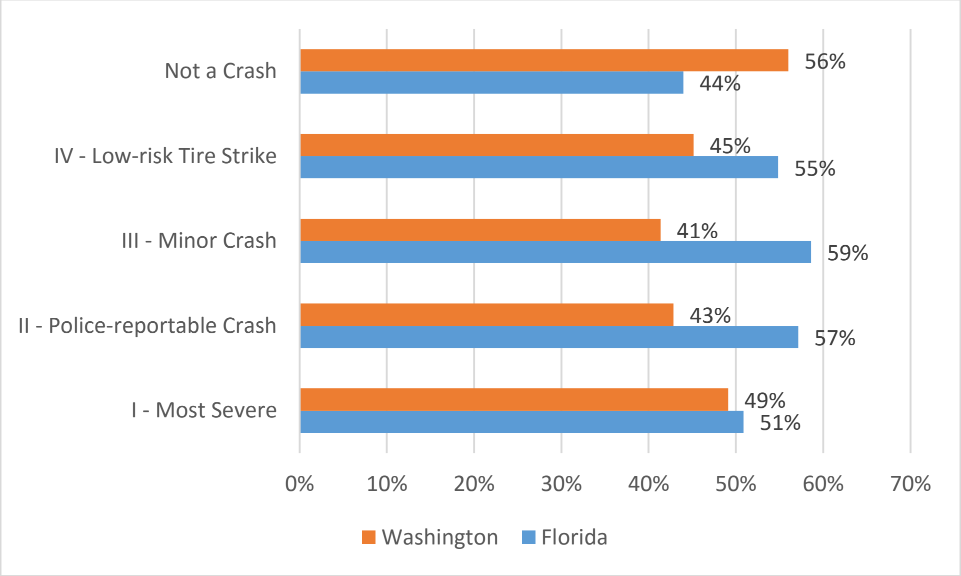


**Figure 12.** Comparison between Crash Severities in Florida and Washington

## Speed: Evaluation of the Role of Speeding in Crashes and Safety Critical Events in severe weather conditions using the SHRP2 data

One of the most predominant factors contributing to crashes is speed. The economic cost to society of speeding-related crashes is estimated by NHTSA to be $40.4 billion per year. In 2007, speeding was a contributing factor in 31 percent of all fatal crashes, and 13,040 lives were lost in speeding-related crashes (NHTSA, 2009).

On the other hand, there are over 5,870,000 vehicle crashes each year. Twenty-three percent (23%) of these crashes—nearly 1,312,000—are weather-related. Weather-related crashes are defined as those crashes that occur in adverse weather (i.e., rain, sleet, snow, fog, severe crosswinds, or blowing snow/sand/debris) or on slick pavement (i.e., wet pavement, snowy/slushy pavement, or icy pavement). On average, 6,250 people are killed and over 480,000 people are injured in weather-related crashes each year (Booz Allen, 2013).

The combination of these two prevalent may increase the severity of crashes. This section focused on using the available NDS data provided in SHRP2 Insight Data Access Website to better understand drivers speed behavior in Florida and Washington. It is worth to mention that little information is available on the Insight Data Access Website about where the event actually occurred.

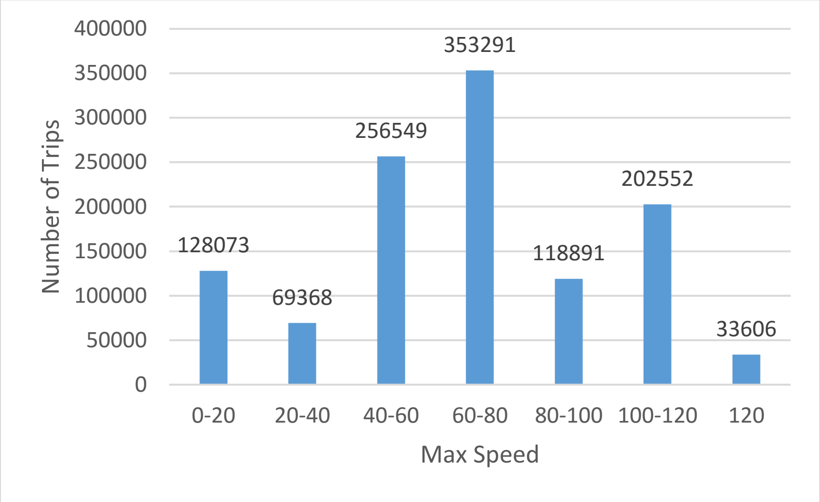


**Figure 13.** Maximum speed in Washington

Figure 13 shows the average speed for NDS trips collected in SHRP2 project in Washington. As, shown in the Figure 13 more than 353000 collected trips with maximum speed of 60 to 80 were collected in Washington and also more than 33000 trips with speed higher than 120 kph were collected during the project time. It should be mentioned that each trip evaluated to determine the maximum speed, then placed within the appropriate category.

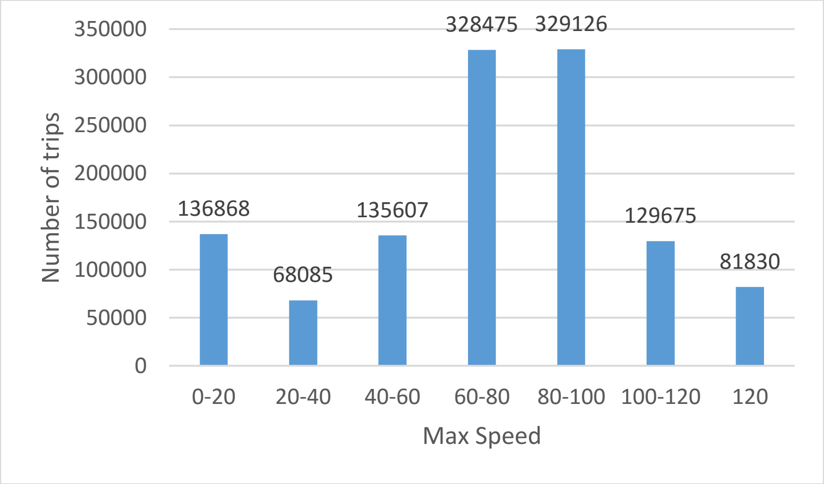


**Figure 14.** Maximum speed in Florida

Figure 14 shows that more than 320000 trips with 60-80 speed range were collected during the project and also approximately 33000 trips were collected with 80-100 kph speed range. Comparing figure 1 and 2 shows people in Florida are more likely to drive with higher speed. More than 81000 trips with speed higher than 120 kph were recorded in Florida during the project which is significantly higher than trips with speed higher than 120 kph in Washington (more than 1.4 trips with speed higher than 120 kph in Washington).

**Table 11.** Trips by site name and mean speed (as of Dec 17, 2015)

| | 0.0 - 15.0 | 15.0 - 30.0 | 30.0 - 45.0 | 45.0 - 60.0 | 60.0 - 75.0 | 75.0 - 90.0 | 90.0 - 105.0 | 105.0 - 120.0 | >= 120.0 | NULL (no value) | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Florida** | 151587 | 161977 | 339686 | 352132 | 140668 | 51780 | 17596 | 5786 | 507 | 2792 | 1224511 |
| **Washington** | 144623 | 181060 | 427651 | 239619 | 109364 | 48442 | 10501 | 2172 | 106 | 1819 | 1165357 |
| **Total** | 296210 | 343037 | 767337 | 591751 | 250032 | 100222 | 28097 | 7958 | 613 | 4611 | 2389868 |

Table ***11*** shows the Trips by site name and mean speed. As can be seen more trips were collected in Florida in comparison with Washington (1224511 in Florida versus 1165357 in Washington). By comparing the provided data in

Table ***11***, for speed greater than 120 kph, more data was recorded for Florida (more than 4.7 times higher). By comparing the 105-120 kph speed range in Washington and Florida, again recorded data shows higher portion of speeding in Florida.

Since the posted or advisory speed is not provided for each event in Insight Data Access Website, it is not possible to extract mentioned data from the website. As a result, based on the definitions provided for driver behavior by VTTI, **exceeded speed limit** and **exceeded safe speed but not speed limit** were used in this report. The definition of abovementioned terms are provided below:

**Exceeded speed limit**: Subject vehicle traveling at a speed greater than the posted speed limit (not in a work zone). In Variable Speed Zones, this is relative to the speed limit in effect at the time of the event. Coded when more than 10 mph above posted speed limit.

**Exceeded safe speed but not speed limit**: Subject vehicle traveling at a speed close to or under the posted speed limit, but still too fast to maintain a safe driving environment given current environmental conditions (e.g., weather, traffic, lighting). Ex. during conditions that may require slower speeds such as weather, traffic situation, etc.

**Table 12.** Trips by site name and driver behavior (Exceeded safe speed but not speed limit and exceeded speed limit data) (as of Dec 17, 2015)

| | Exceeded speed limit | Exceeded safe speed but not speed limit | Total |
|---|---|---|---|
| Florida | 263 | 53 | 316 |
| Washington | 117 | 67 | 184 |
| Total | 380 | 120 | 500 |

Table 12 comparing Washington and Florida, people are more likely to exceed speed limit in Florida (Exceeded speed limit in Florida is higher than Washington); however, in unsafe situations such as severe weather conditions they are more conservative (Exceeded safe speed but not speed limit in Washington is higher than Florida). This could be due to the fact that drivers in Florida are more adapted to adverse weather conditions such as heavy rain.

**Table 13.** Events by site name and driver behavior (Exceeded safe speed but not speed limit and exceeded speed limit data) (as of Dec 17, 2015)

| | Exceeded speed limit | Exceeded safe speed but not speed limit | Total |
|---|---|---|---|
| Florida | 265 | 53 | 318 |
| Washington | 118 | 67 | 184 |
| Total | 383 | 120 | 500 |

Table 13 shows the provided events by site name and driver behavior. As shown, in Florida there are more events recorded due to exceeded speed limit. On the other hand, in case of Exceeded safe speed but not speed limit, Washington has the higher proportion. It is worth to mention that both of exceeding speed limit and exceeding safe speed limit are considered as events. Hence, provided data in both

Table ***11*** and Table 12 are similar.

**Table 14.** Speeding VS no-speeding by roadway type and in severe weather conditions

| | Baseline | crash- near crash-crash relevant | Odds (CI) |
|---|---|---|---|
| **Interstate/Bypass/Divided Highway with no traffic signals** | | | |
| Not speeding | 507 | 65 | 9.75 (2.983567,1.570968) |
| Speeding | 16(3%) | 20(23%) | |
| **Other roadways** | | | |
| Not speeding | 1299 | 343 | 12.39438 (3.009311,2.025175) |
| Speeding | 22 (1.6%) | 72 (17%) | |

Table 14 shows speeding versus not speeding by two roadway categories and in adverse weather conditions. Due to low sample size roadway categories divided by two groups. The first group is Interstate/Bypass/Divided Highway with no traffic signals and other roadway categories considered as one group. The odds of a driver having “exceeded the speed limit” for safety critical events compared to baselines events for the same roadway type were compared. The 95% confidence interval (CI) for the odds are also provided. When the confidence interval contains 1.0, the odds are not statistically significant.

Based on provided data in Table 14 safety critical events were more likely to be speeding related than for corresponding baseline events. For instance, safety critical events in general which occurred on Interstate/Bypass/Divided Highway with no traffic signals were 9.7 times more likely to be speeding related than for baseline events on similar roadway. Around 23% of safety critical events were speeding related while 3% of baseline events were speeding related.

# Chapter2- Analyzing weather related crashes in Florida and Washington using SHRP2 Roadway information database (RID)

The goal of SHRP 2 Project S04A was to design, build, and populate a Roadway Information Database (RID) with data from the SHRP 2 mobile data collection project (S04B); existing roadway data from government, public, and private sources; and supplemental data that further characterize traffic operations. The RID will in essence provide the road element for safety research on the more than 5 million trips taken by the NDS participants. The data will support a comprehensive safety assessment of driver behavior and crash risk, especially the risk of lane departure and intersection collisions. The RID will enable safety researchers to look at data sets of selected road characteristics and study matching NDS trips to explore the relationships between driver, vehicle, and roadway. This capability of the RID makes it a very useful tool for NDS users interested in roadway characteristics and features because it allows researchers to focus on only those NDS trips that traversed road segments containing the items of interest (Omar Smadi, Neal Hawkins, Zachary Hans, Basak Aldemir Bektas and Inya Nlenanya, Reginald Souleyrette, 2015). (CTRE, n.d.). This chapter focuses on analyzing Washington and Florida weather related crashes provided in RID using three years of data. Since provided crash data for different states are different in RID, crash data from 2011 to 2013 for Washington and 2008 to 2010 for Florida was selected for more analysis in this chapter.

## Washington Weather-related Crash Analysis using RID

Table 15 shows the summary of crashes in Washington from 2011 to 2013 in severe weather conditions. As can be seen the number of total crashes has increased from 104603 in 2011 to 107635 in 2013. Crashes in severe weather conditions increased from 23225 in 2011 to 27893 in 2012 and then reduced to 22331 in 2013. The weather-related crash distribution for different years from 2011 to 2013 is shown in Figure 15.

**Table 15.** crash summary from 2011to 2013 in Washington

| | 2011 | 2012 | 2013 |
|---|---|---|---|
| **Total crashes** | 104603 | 106996 | 107635 |
| **Adverse weather** | 23225 | 27893 | 22331 |

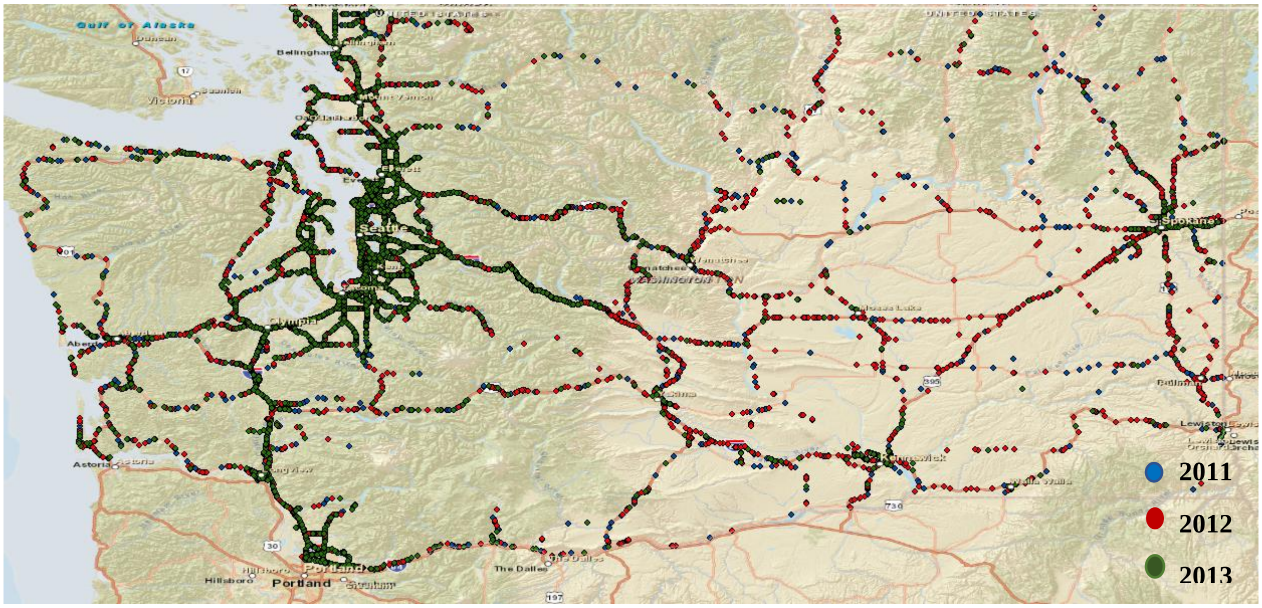


**Figure 15.** Washington crash frequency in adverse weather conditions from 2011 to 2013(GIS map)

## Weather-Related Crashes in Different Years

Figure 16 shows that 22% of crashes in 2011were weather-related crashes. In 2012 number of weather-related crashes increased to 26% and finally in 2013 it reduced to 21% of total crashes.

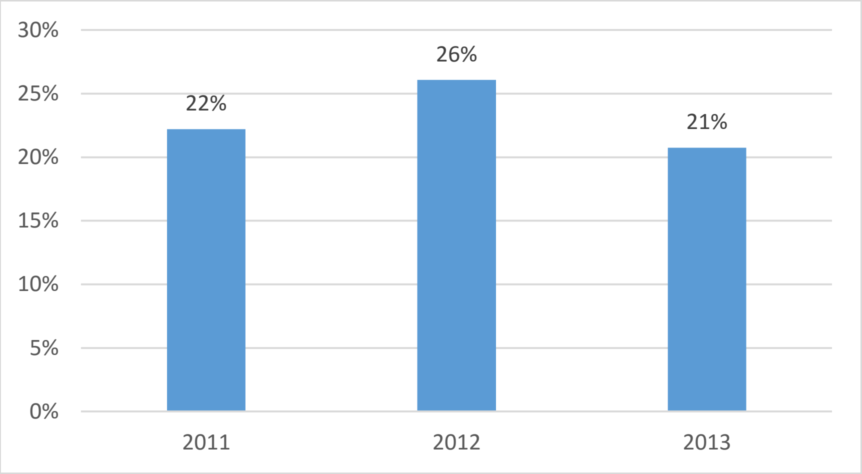


**Figure 16.** Washington weather-related crashes from 2011 to 2013

### Crash Severities

Figure 17 shows the distribution of crash severities in adverse weather conditions. As can be seen 65.56% of crashes during adverse weather conditions were Property Damage Only (PDO), 34.08% injury and 0.36% of crashes were fatal crashes.

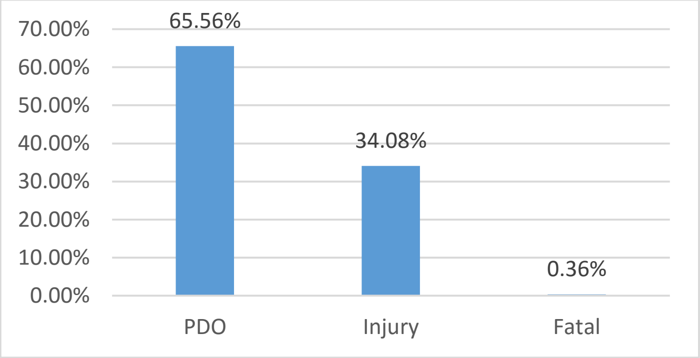


**Figure 17.** Crash severity during adverse weather conditions in Washington from 2011 to 2013

### Age

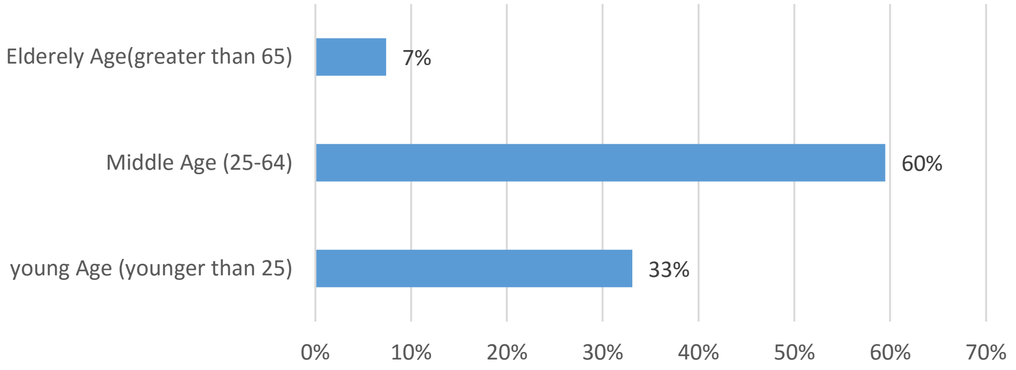


**Figure 18.** Distribution of crashes by drivers' age in adverse weather conditions in Washington from 2011 to 2013

Drivers are divided into three age groups: Young Age (less than 25), Middle Age (25 – 64) and Elderly Age (greater than 65). Considering severe weather related crashes, the middle age drivers cause the highest proportion during the study period (60%) and elderly age (greater than 65) made up the lowest portion during the mentioned period (7%).

### Weather Conditions

Figure 19 shows the crashes in different weather conditions. As can be seen from the below pie chart, more than 80 percent of weather related crashes occurred in raining condition, snowing with more than 10 present is in the second place. Fog with 4.12 percent of weather related crashes is in the third place. The pie chart below shows the significance of considering adverse weather conditions such as rainy, snowy and foggy conditions in different crash studies.

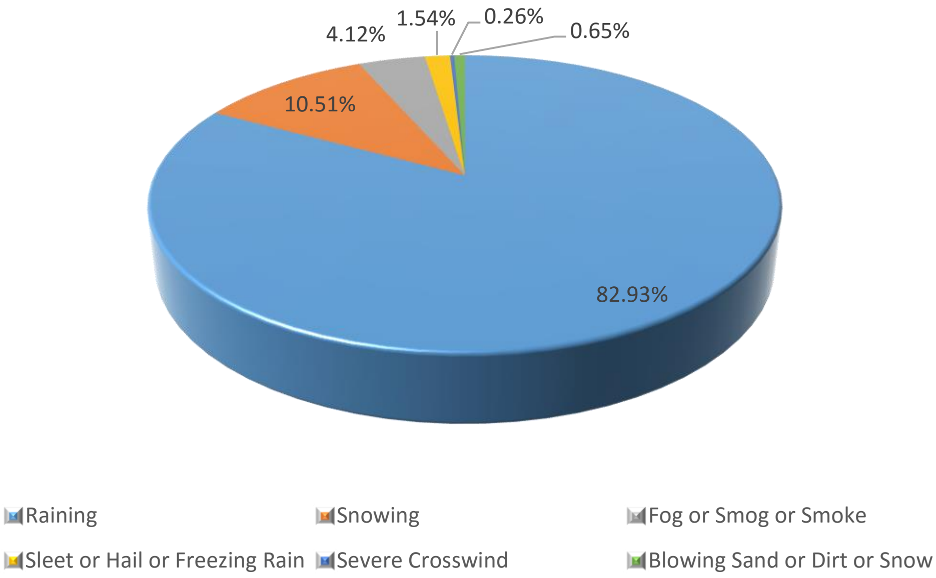


**Figure 19.** Distribution of crashes in different weather conditions in Washington from 2011 to 2013

## Lighting Conditions

Lighting conditions play an important role in crashes. Figure 20 shows more than 58 present of weather related crashes occurred during the daylight. Dark streets lights on, with near 25 percent is in the second place and dark-no street lights with more than 10 percent is in the third place of weather related crashes.

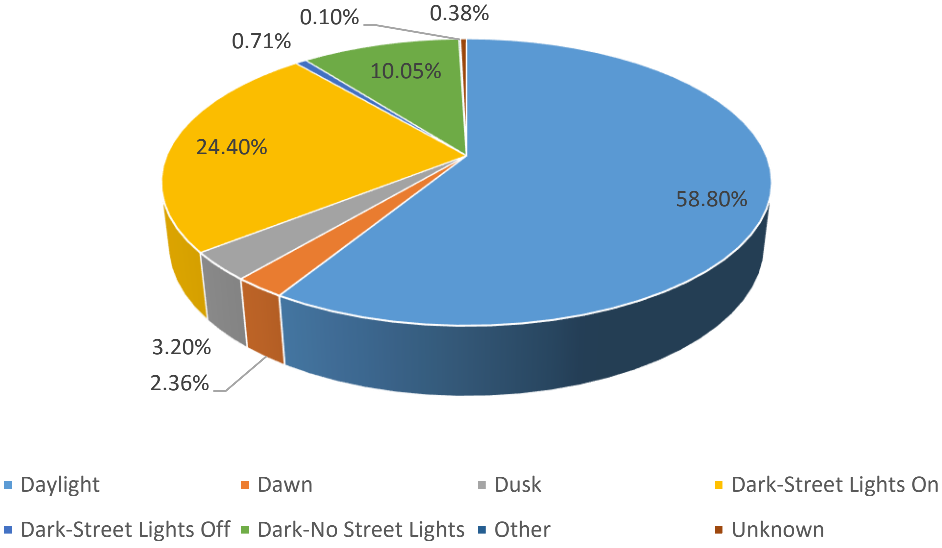


**Figure 20.** Washington weather-related crashes by time of day from 2011 to 2013

### Gender

Figure 21 shows the distribution of weather related crashes by gender in Washington from 2011 to 2013. As shown 54% of crashes occurred by males and 42% of weather related crashes occurred by females.

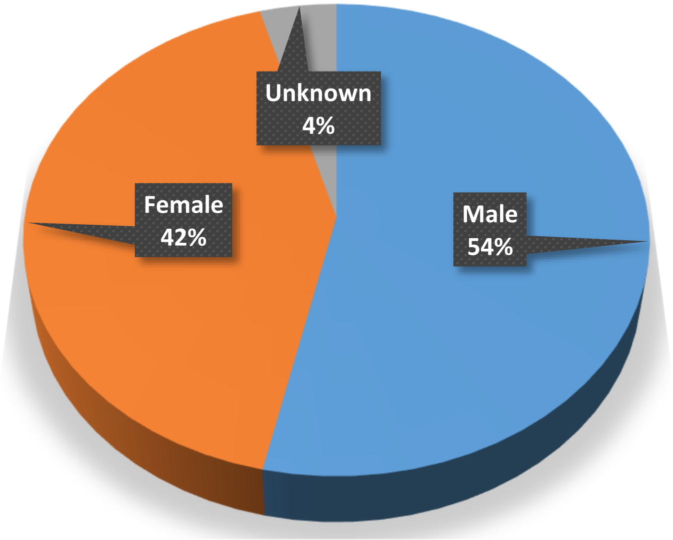


**Figure 21.** Washington distribution of weather related crashes by gender from 2011 to 2013

### Speed Limit

Figure 22 shows the percentage of vehicles involved in weather related crashes by speed limit of the corresponding roadway. Almost 38% of vehicles involved in crashes on roadways posted at 60 mph. Only 29 % of crashes in adverse weather conditions occurred in posted 35 mph or lower. Correspondingly, more than 70 percent of crashes occurred on roadway posted 40 or higher.

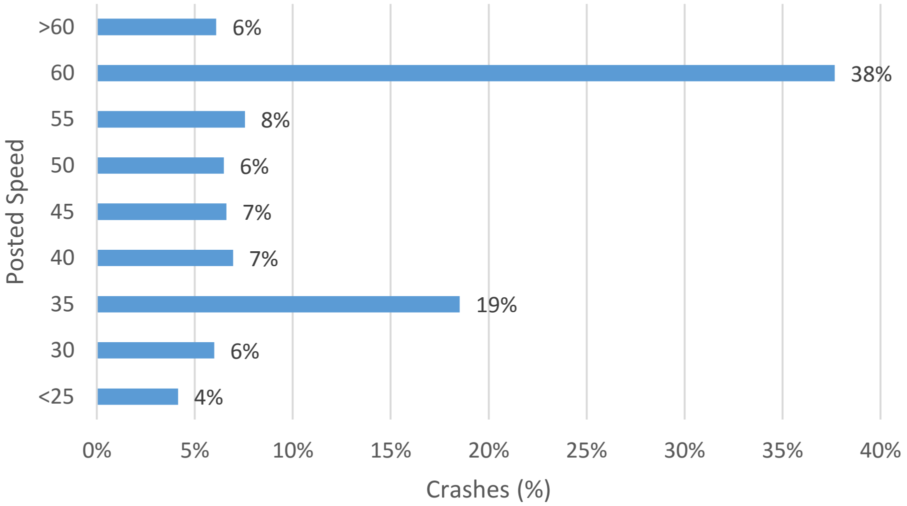


**Figure 22.** Washington weather related crashes by posted speed from 2011 to 2013

### Florida Weather-Related Crash Analysis using RID

This section provide descriptive analysis for obtained crash data using RID for Florida between 2008 and 2010. RID layers used in this section are “on 2008”, “on 2009” and “on 2010”. It should be mentioned that, some information such as age, gender and posted speed are the missing parts in these layers.

Table 16 shows summary of total and weather related crashes in Florida from 2008 to 2010. As shown, total crashes reduced from 151327 in 2008 to 150009 in 2009 and then increased to 154849 in 2010. In contrast, weather related crashes increased from 15837 in 2008 to 17011 in 2009 and then reduced to 16349 in 2010. Figure 23 shows distribution of weather-related crashes in Florida using GIS map from 2008 to 2010.

**Table 16.** crash summary from 2008 to 2010 in Florida

| | 2008 | 2009 | 2010 |
|---|---|---|---|
| **Total crashes** | 151327 | 150009 | 154849 |
| **severe weather** | 15837 | 17011 | 16349 |

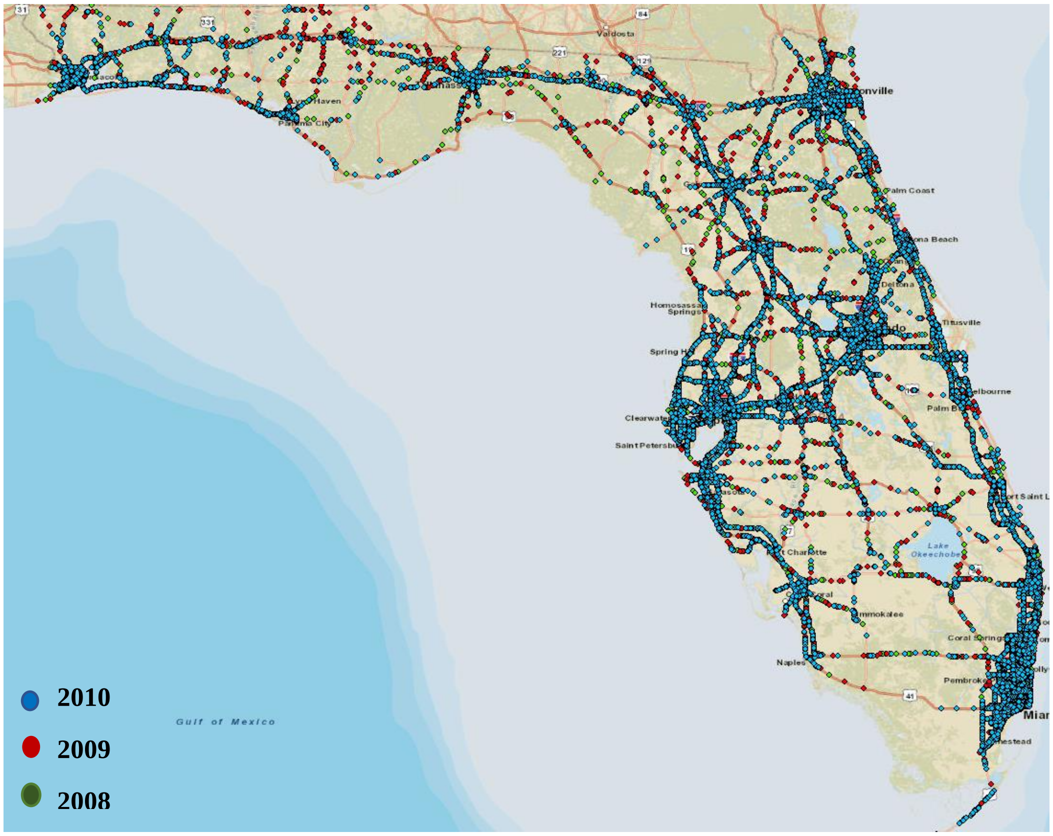


**Figure 23.** Distribution of weather-related crashes in Florida between 2008 and 2010

As mentioned before weather related crashes increased from 10.47% in 2008 to 11.34% in 2009 and then reduced to 10.56% in 2010. Figure 24 shows the percentage of weather related crashes between 2008 and 2010.

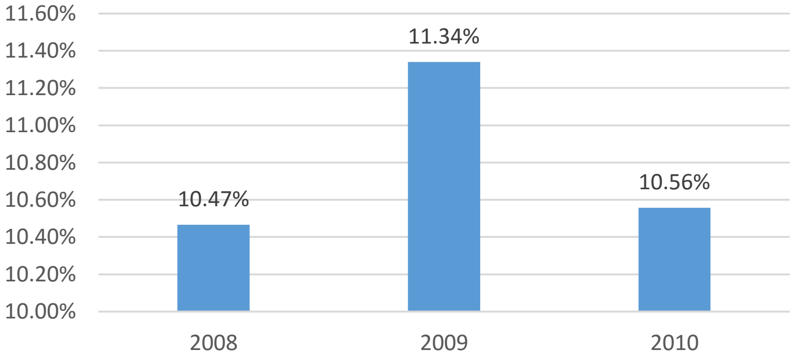


**Figure 24.** Florida weather related crashes (2008-2010)

## Crash Severities

Crash severities defined as HIGHESTINJ in these layers. Based on the definition this information is initially converted from the incoming report data, but may be changed during the Safety Office's crash location processing. The provided information coded as single-digit code which indicates highest injury severity that has occurred because of the crash, listed in order of severity from least to most (Source: FDOT Safety Office). As shown in Figure 25 fatalities made up 0.03% and no injury crashes made up 52.08% of weather related crashes.

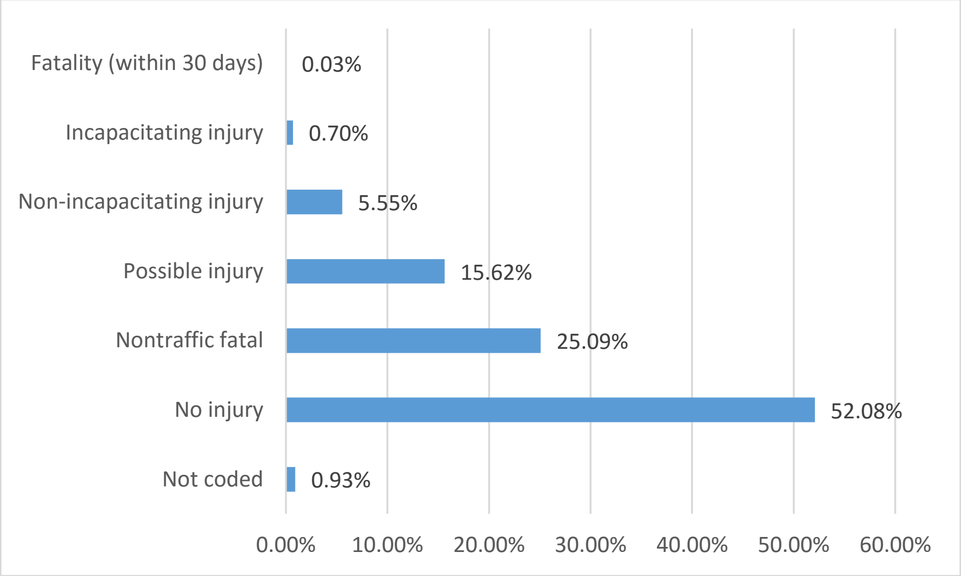


**Figure 25.** Weather-related crash severities in Florida from 2008 to 2010

## Weather Conditions

Weather code from the crash report form, as entered by the officer shows in the **Figure 26**. As can be seen more than 96% of Weather-related crashes occurred during the rainy condition and less than 4% occurred during the foggy condition.

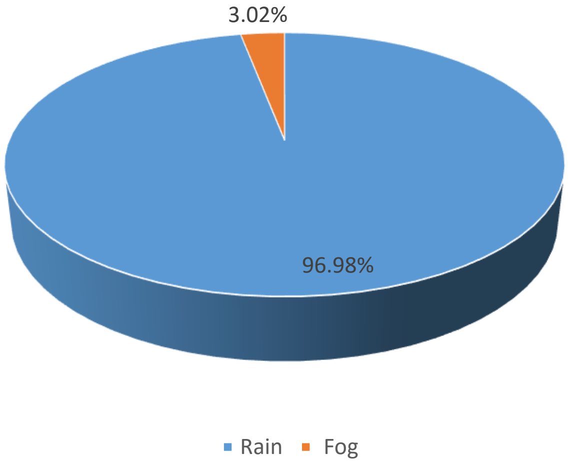


**Figure 26.** Distribution of weather-related crashes by weather conditions in Florida from 2008 to 2010

## Lighting Condition

Figure 27 illustrates the distribution of weather related crashes by lighting conditions. As noted approximately 66% of weather-related crashes occurred during the daylight with 6.8% occurring during the night time with no lights. More than 21% of crashes occurred during the night time with street light and the remains happened during dawn and dusk.

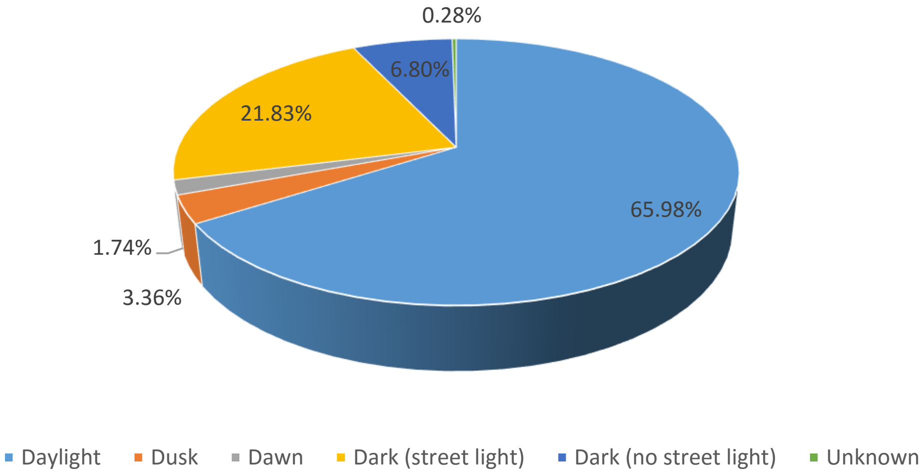


**Figure 27.** Distribution of weather-related crashes by lighting condition in Florida from 2008 to 2010

## Cause of Crashes

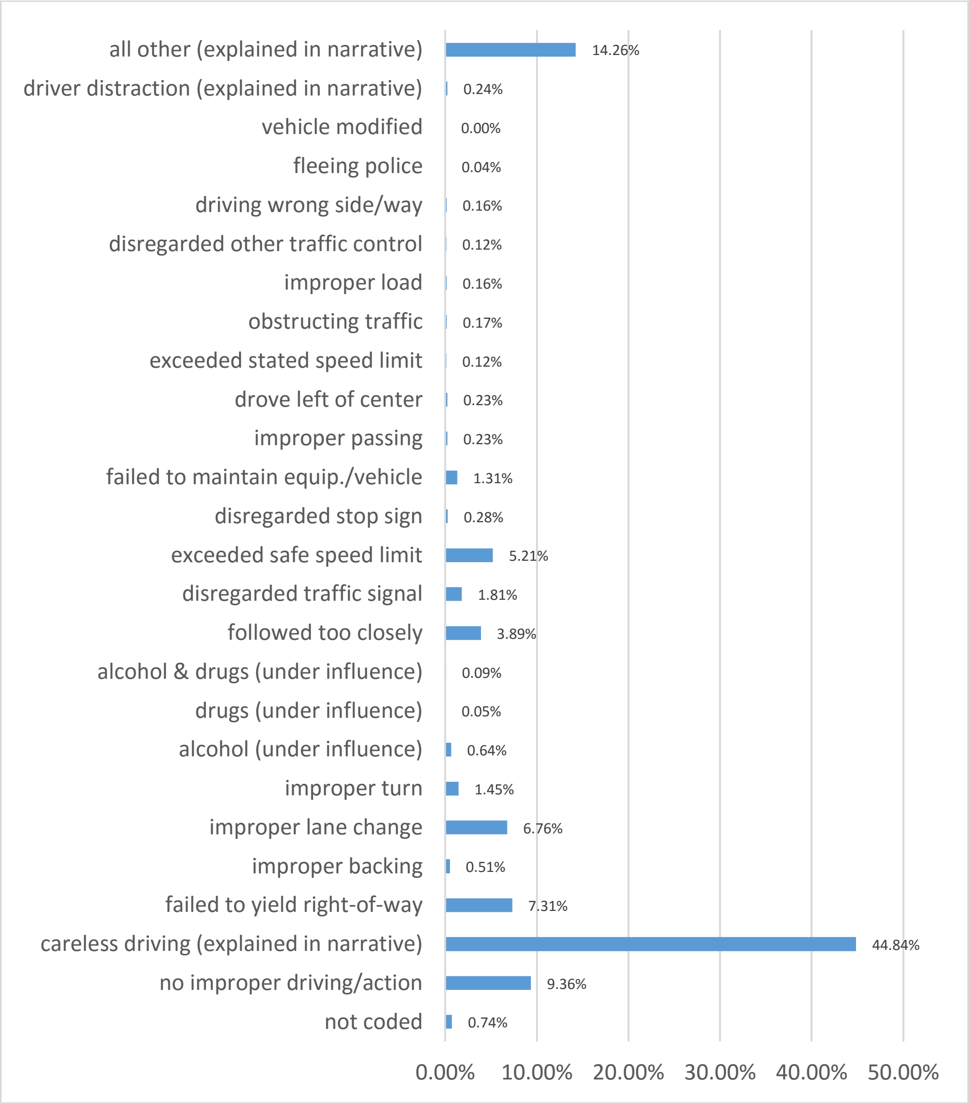


**Figure 28.** Distribution of weather-related crashes by crash cause in Florida from 2008 to 2010

Distribution of weather related crashes by crash cause in Florida illustrated in Figure 28. As can be seen careless driving made up more than 44% of weather related crashes during the mentioned time period. No improper action, failed to yield right of way and improper lane change are another important factors that have high percentage of weather related crashes with 9.36%, 7.31% and 6.76% respectively. Exceeded safe speed limit made up 5.21% of weather related crashes.

## Visibility Impairment

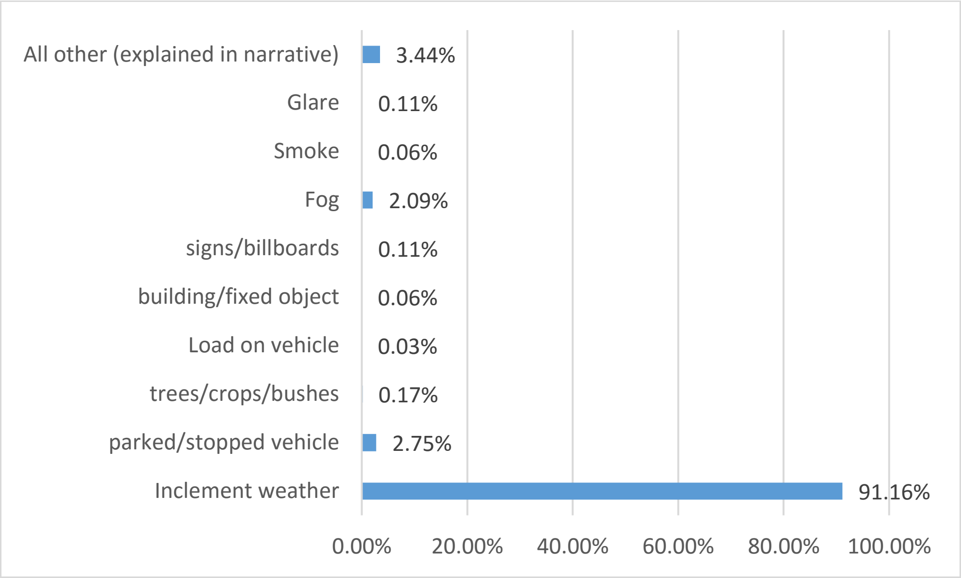


**Figure 29.** Distribution of weather-related crashes by visibility in Florida from 2008 to 2010

Visibility play an important role in car crashes. As shown in figure above visibility impairment due to inclement weather made up more than 91% of crashes occurred during adverse weather conditions. Fog which is another important visibility problem in Florida made up 2.09% of weather related crashes due to visibility impairment.

# Chapter 3- NDS Analysis

The main objective of this chapter is to examine the feasibility of using NDS and RID data sets to improve our understanding of weather- and visibility-related crashes. The study will help in enhancing suggested speed limits within VSL systems and providing guidance information within ATIS. This study will investigate the applicability of using vehicle time series data to support CV technology during inclement weather. The outcome from this research will help in reducing traffic injuries and fatalities.

## Data Acquisition and Preparation

Data acquisition and reduction are crucial steps in this study. In Phase 1, NDS data were requested to examine driver response in rain/heavy rain in the states of Florida and Washington. Roadway Information Database (RID) as well as visual inspection of aerial and street view images from Google maps were also utilized. The provided NDS data included forward-facing and rear-facing videos, basic trip characteristics, and selected vehicle time series data. To address the first research question of identifying appropriate trips in rainy conditions, a preliminary criterion for data extraction was identified by the University of Wyoming (UW) research team. To accomplish the study objectives, 50 ND S trips during rain/heavy rain on freeway segments from Florida and Washington States were requested. Identifying and extracting requested data was a challenging task in this project. The criterion for NDS data extraction is unique for various reasons. Weather information is not readily available in NDS and RID. Although wiper setting could give an indication about rain intensity, wiper setting is not consistent across different vehicles. Wiper setting in NDS data indicates the position of the wiper switch rather than wiper swipe rate; moreover, different drivers have different tolerances to rain/visibility, and splashes from other vehicles may affect driver choice of the appropriate wiper speed. There was another issue encountered during the preliminary investigation on five sample traces provided by VTTI to fine tune the extraction process: the wiper blades of Honda Civic vehicles did not cover the whole windshield in front of the camera. The UW research team had to come up with a strategy to effectively identify NDS trips in rain/heavy rain without introducing biasness to the sample data used in Phase 1. The final NDS extraction steps for trips in rain/heavy rain were as follows:

1) Only trips with multiple wiper settings were targeted; vehicles that did not include the full spectrum of values for the wiper status (0, 1, 2, and 3) were filtered out. Vehicles with on/off wiper settings only would not provide an indication of rain intensity.
2) Months with high rain precipitation in the states of Washington and Florida were used for this task.
3) Only NDS daytime trips in rain on freeways would be used. Nighttime trips were eliminated in Phase 1 due to the low resolution of provided sample video data.
4) Honda Civics were eliminated from the data set because of the lack of wiper blade coverage of the windshield surface in front of the camera.
5) Potential events were tagged with the duration of the trip that different wiper settings of 0, 1, 2, and 3 were active to facilitate data extraction for light/heavy rain conditions.
6) Each identified trip in rain was matched with two trips in clear weather conditions for the same route and subject as much as possible.

An additional 100 matching NDS trips during clear weather on the same segments and subjects in Florida and Washington States were requested. About 147 useful traces with requested characteristics in rain/heavy rain, and their matching clear weather traces, were provided. Some of the provided trips in rain did not have matching trips in clear weather and thus were excluded from the analysis. Although most of the trips in inclement weather conditions were matched with two trips in clear weather conditions, only a matching rate of 1:1 was achieved in Phase 1 due to data limitation. Matching is important to control for sundry factors such as driver population, roadway geometry, etc. It is worth mentioning that real-time traffic data are not available in the NDS data. To isolate the impact of adverse weather conditions on driver behavior, trips in free-flow traffic were identified. Classifying the NDS data into two different traffic states (free-flow and mixed traffic) resulted in a total of 56 trips that were considered for further analysis. Travel times were used to broadly identify trips in free-flow/light traffic; the presence and distance to other vehicles identified by the front radar and the estimated headway times were also a good indicators of traffic conditions. NDS video data were manually analyzed to verify and validate results. Table 1 shows summary statistics for the number of trips, route names and length of routes, total travel times, and percentages of wiper use at different settings along with their matching clear weather trips. After screening provided data for surrogates for crashes/near crashes, only three trips were identified as events, two of which occurred in rain. All corresponding RID data were identified and linked to the provided NDS data. The 56 NDS trips constituted a total of about 1,775 interstate kilometers traveled over 21.94 hours on six interstate routes in Florida and Washington States. These trips occurred mostly on I-4, I-75, and I-275 in Florida, and on I-5, I-90, and I-405 in Washington.

**Table 17:** Summary Statistics of NDS Trips Considered in Phase 1

| **Traffic Condition** | **Weather Condition** | | **Heavy Rain** | **Matched Clear** | **Light Rain** | **Matched Clear** | **Total** |
|---|---|---|---|---|---|---|---|
| **Free-Flow Condition** | **Number of Trips** | | **7** | **7** | **9** | **9** | **32 trips** |
| | **% Wiper Setting** | 0 | 6.1% | 99.5% | 0.0% | 96.6% | |
| | | 1 | 0.0% | 0.0% | 60% | 3.4% | |
| | | 2 | 0.0% | 0.0% | 22% | 0.0% | |
| | | 3 | 93.9% | 0.5% | 18% | 0.0% | |
| | **Total Duration (hr)** | | 3.26 | 2.80 | 1.42 | 1.37 | **8.85 hr** |
| | **Total Length (km)** | | 308.67 | 308.67 | 172.76 | 172.76 | **962.86 km** |
| **Heavy/ Mixed Traffic** | **Number of Trips** | | **3** | **3** | **9** | **9** | **24 trips** |
| | **% Wiper Setting** | 0 | 0.0% | 99.9% | 6% | 91.2% | |
| | | 1 | 10% | 0.0% | 50% | 8.8% | |
| | | 2 | 14% | 0.0% | 26% | 0.0% | |
| | | 3 | 75.2% | 0.1% | 18% | 0.0% | |
| | **Total Duration (hr)** | | 1.34 | 1.64 | 5.44 | 4.67 | **13.09 hr** |
| | **Total Length (km)** | | 95.3 | 95.3 | 309.64 | 312.05 | **812.29 km** |
| **Total Number of Trips** | | | **10** | **10** | **18** | **18** | **56** |

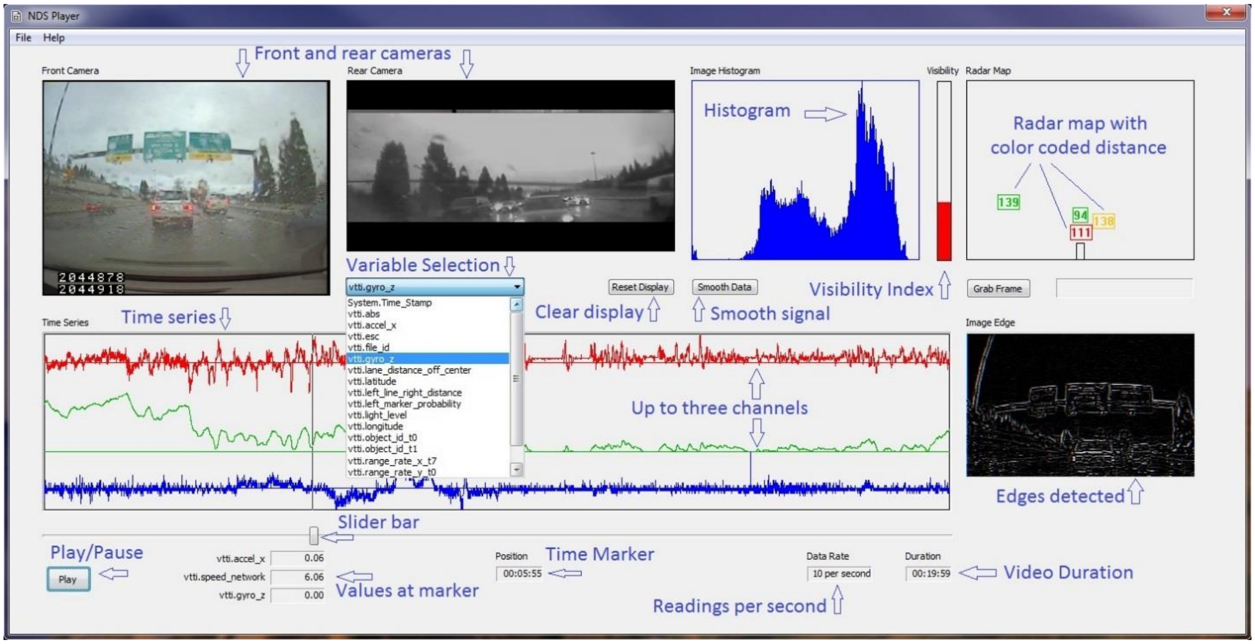
## Data Visualization and Reduction

Dealing with the NDS data could be challenging for various reasons: the size and complexity of the data, the continuous nature of the data, the difficulty of identifying events of interests, processing and reducing video data, identifying weather conditions and visibility limits, linking NDS data with RID data, identifying surrogates for different crash types, and defining baselines in normal driving conditions.

To efficiently characterize driver responses (i.e., speed and headway adaptation, and lane wandering) during inclement weather (i.e., reduction in visibility due to rain/heavy rain in Phase 1), an interactive visualization and reduction software was developed. The software is developed in C++ under the Microsoft Visual Studio 2013 environment. It runs on Windows workstations and uses multimedia libraries that allow the playback and manipulation of video files. The software synchronizes the two video files for the front and rear NDS cameras, as well as the time series data file. This allows users to relate various time series variables to the front and rear videos. In addition, time series could be smoothed using a moving average technique and extracted for further analysis.

## Machine Vision Visibility Estimation

The software is also under development to provide the level of visibility exhibited during driving conditions as recorded in the video. The UW research team is investigating various image processing techniques. One approach to gauge the level of visibility is by measuring the amount of blur in the image. If an image is sharp, one can assume that the visibility is rather high. Conversely, a low visibility level would cause the image to loose sharpness and become blurred. The problem of determining the visibility level is heuristic. In other words, it requires computational algorithms that may not guarantee a correct solution for every case. They can have a good level of accuracy, but they are not 100% foolproof.



vtti.accel_x 0.06
vtti.speed_network 6.06
vtti.gyro_z 0.00
Position 00:05:55
Data Rate 10 per second
Duration 00:19:59

**Figure 30:** NDS Visualization and Reduction Software

Current challenges with the NDS videos include the fact that they span a wide range of driving and weather conditions. These conditions, among others, include varying levels of brightness and ambient light, sceneries, distances to other vehicles and obstacles, headlights and/or taillights of cars ahead, reflections from the road and other objects, street lights, and rain. These conditions, when aggregated together in different combinations, can trick the algorithm into making inaccurate assumptions, and eventually providing less than optimal results.

The algorithm may work with a certain level of confidence on some images, but behaves poorly on others. It is also difficult to teach the algorithm to know when it is providing inaccurate results. This is typically the nature of the heuristic algorithm development cycle where calibration is applied to pertinent factors and conditions to improve the performance. The algorithm is then retested, and the cycle is repeated in an iterative manner. The effort is currently focused on improving the accuracy and performance of the visibility algorithm. The goal is to maximize the detection accuracy by minimizing false positives and false negatives. The research team is attempting other image processing techniques. One of the techniques aims at detecting lane markings and other objects, such as road signs and light poles, to estimate the visibility level. It also takes into account an estimate of the object distance from the camera as correlated with the object location in the video frame. The visibility index is estimated based on the object clarity and its estimated distance from the camera. It should be noted that the NDS utilizes a single camera, though a stereo camera system usually provides a higher accuracy for distance estimation.

## Preliminary Analysis and Descriptive Statistics

As mentioned earlier, trips in rainy conditions were identified by extracting trips with a high number of minutes of wipers used at different speed settings. NDS video data were manually analyzed for 14 randomly selected trips to verify and validate results. The verification and validation process revealed that some trips had mixed light rain and heavy rain, and clear weather conditions. Also, traffic conditions were characterized using presence and distance to other vehicles, and average headway times. Trips were classified into six categories based on visibility and traffic condition: light rain, heavy rain, and clear weather in free-flow and heavy traffic.

For automatic identification of trips in rain, other basic trip characteristics such as number of brake activations, high variability in headway times and distances, electronic stability control, roadway departures, low coefficient-of-friction, number of Anti-Lock Braking System (ABS) activations, and number of traction control activations were examined in Phase 1. A preliminary analysis on trips in rain/heavy rain indicated that there were no ABS, traction control, or electronic stability control activations in any of the trips. This could be explained due to the fact that these variables are not available in NDS data for all vehicles; moreover, the activation of these safety features is not common in rain on freeway segments. As mentioned earlier, 147 NDS total trips were acquired, but only 56 were considered for further analysis when matching is needed. The total 147 acquired trips were utilized in the Ordered Probit model. Results from the preliminary analysis and descriptive statistics were as expected in most of the cases. The following sections provide discussions about speed, acceleration, lane maintenance (yaw rate), lane change, and headway during heavy rain contrasted to clear weather condition in free-flow and heavy traffic. Table 2 shows descriptive statistics and various statistical tests for the main time series variables of interest for heavy rain/clear weather in free-flow and heavy traffic. Also, descriptive statistics are shown for trips that included heavy rain and clear weather conditions within the same trips.

### Driver Behavior (Speed, Acceleration, Lane Maintenance/Change, and Headway)

This proof-of-concept phase investigated the distribution and variation of speeds between clear and adverse weather conditions in various traffic conditions. Six possible scenarios were considered and compared: light rain, heavy rain, and clear weather in light and heavy traffic. Characterization of traffic flow became very important for various reasons: realistic traffic conditions and the appropriate distributions are needed for the calibration of the simulation models, and predictability of traffic conditions in various weather conditions is needed for an effective and realistic VSL system. Characterization of traffic conditions and speed in different weather conditions, moreover, will help in applications such as CV technology. If unusual traffic patterns are detected, these geospatial locations could be flagged for a possible and timely mitigation strategy. From the NDS sample data, it was concluded that speeds have a Weibull distribution in heavy rain under free-flow condition while the speeds were normally distributed in clear weather for the matching data set as shown in Figure 2. Speed in free-flow condition is important for VSL application because the speed choice here is not affected by the interaction with traffic. A t-test indicated that the average speed in heavy rain under free-flow traffic condition was significantly (16.32km/hr) lower than in clear condition and free-flow traffic. It was also found that speeds have higher variability during heavy rain compared to clear condition under free-flow traffic.

Other speed distributions for other scenarios were examined, but they were not included in this report for brevity. Examining drivers’ selection of speed during traffic congestion is also important. This could help determine whether drivers take higher risks during adverse weather conditions to make up for delays encountered because of congestion. Speed distribution during heavy rain in congestion (mixed/heavy traffic) did not fit a specific distribution, which may indicate higher speed variability. The speeds during clear weather conditions in mixed/heavy traffic volumes on the same routes and subjects fitted two normal distributions, which is common during congestion on freeways. There was no significant difference in the distribution of speeds during light rain.

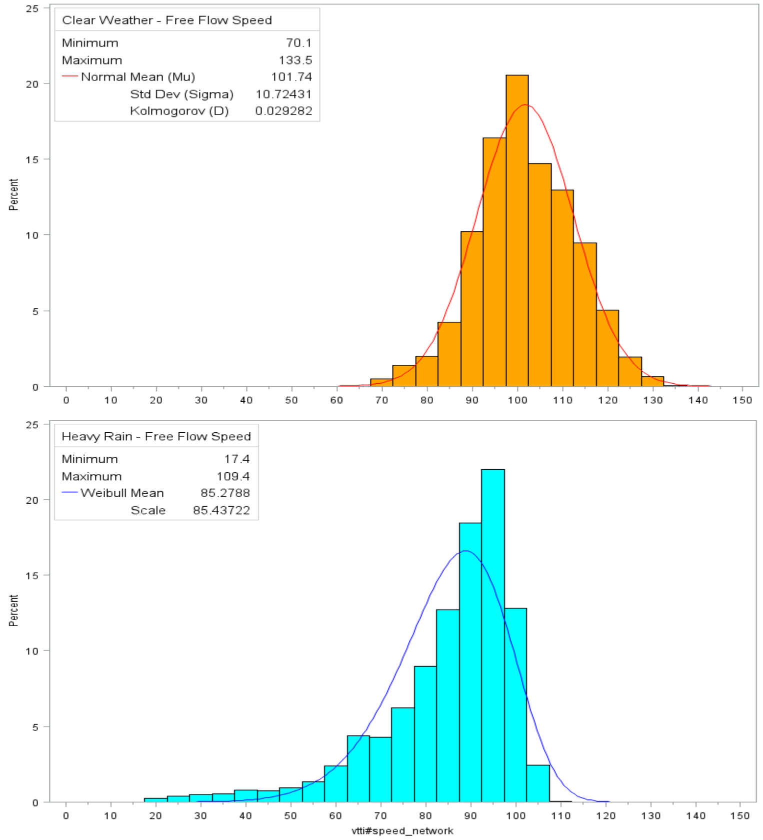


**Figure 31:** Observed and Fitted Distributions for Speeds during Heavy Rain and Clear Weather under Free-Flow Traffic

Although matching technique may control for sundry factors (among them roadway geometry, traffic condition, and driver population) supplementary traffic-flow parameters may be needed to fully isolate driver behavior of speed selection due to the environment. Loop detector and Automatic Vehicle Identification (AVI) traffic-flow data will be collected on the NDS routes during the same time duration from local agencies in Phase 2.

The acceleration/deceleration variable was examined, and ±0.3g acceleration/deceleration rates were set as a threshold to identify aggressive braking/acceleration events. The preliminary analysis showed that while heavy rain has a wider range of acceleration and statistically has a higher average, the average deceleration was found to be statistically higher in the matching clear weather conditions. The variability of acceleration and deceleration and the proportions of deceleration lower than -0.3g were found to be greater in clear weather conditions. These findings coupled with the observed reduction in speed during heavy rain indicate that drivers compensate for the slippery surface conditions by not decelerating by rates greater than -0.3g.

The lane offset variable in the NDS data is estimated using machine vision techniques. Lane offset is an indication of either a lane change or a deviation from the lane. Lane change is defined as an intended and substantial lateral shift of a vehicle (Chovan et al., 1994). Lane change could be modeled using multiple variables: turn signal, steering angle, yaw rate, and machine vision lane offset. Although lane change is not the main focus of this study, distinguishing lane change from lane wandering is important to understand driver behavior in adverse weather conditions. Utilizing time series and video data, lane changes were separated from lane wandering.

**Table 18:** Descriptive Statistics for the NDS Instrumented Vehicles

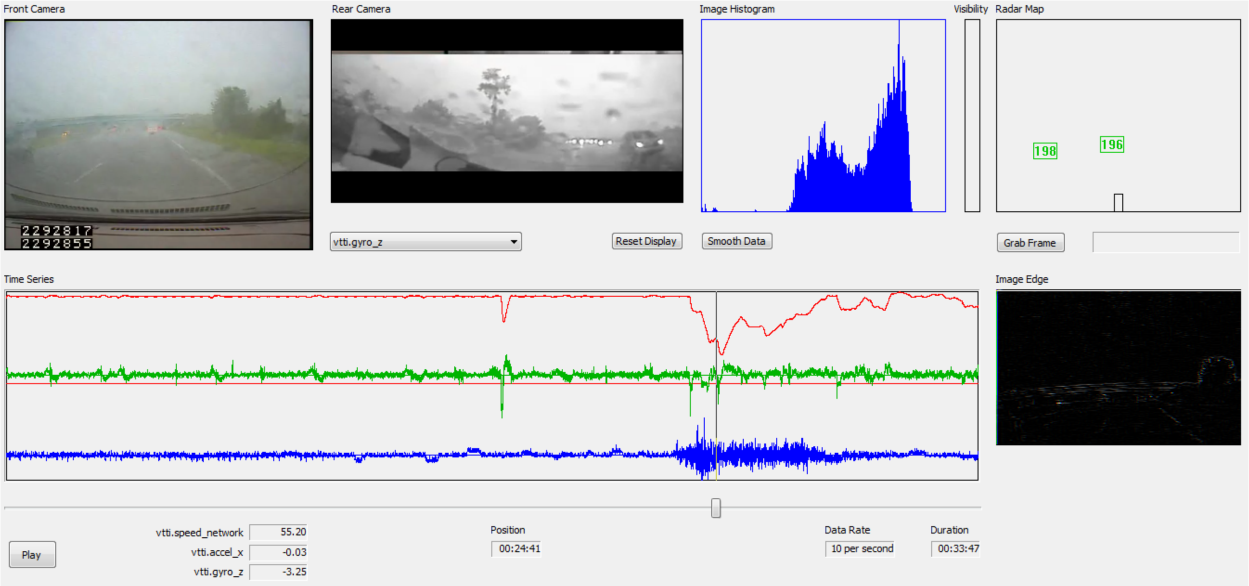
| | Statistical Tests | Free-Flow Traffic (Matched Trips) | | | | Comparison within Trips | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Heavy Rain | | Matched Clear | | Heavy Rain | | Clear Weather | |
| Speed (kph) | Average | 85.07 | | 101.39 | | 91.8 | | 106.36 | |
| | SD | 14.69 | | 11.25 | | 14.65 | | 6.53 | |
| | Min. | 17.4 | | 70.4 | | 35.09 | | 53 | |
| | Max. | 109.4 | | 133.5 | | 125.5 | | 125.9 | |
| | Median | 87.5 | | 101 | | 94.19 | | 106 | |
| | t-Test | Avg. Speed is significantly lower in Heavy Rain | | | | Avg. Speed is significantly lower in Heavy Rain | | | |
| | F-Test | Speed variability is higher in Heavy Rain | | | | Speed variability is higher in Heavy Rain | | | |
| | Z-Test | Proportion of violation ≥ 10 km/h above the speed limit is significantly higher in Clear Weather | | | | Proportion of violation ≥ 10 km/h above the speed limit is significantly higher in Clear Weather | | | |
| Acceleration/ Deceleration (g) (Positive columns= Acceleration) | Average | 0.0263 | -0.0266 | 0.0253 | -0.0276 | 0.0213 | -0.0282 | 0.0158 | -0.0162 |
| | SD | 0.0181 | 0.0214 | 0.0184 | 0.0225 | 0.0157 | 0.0245 | 0.0160 | 0.0185 |
| | Min. | 0.0029 | -0.3132 | 0.0015 | -0.4321 | 0.0015 | -0.2842 | 0.0029 | -0.2610 |
| | Max. | 0.2059 | -0.0029 | 0.1769 | -0.0015 | 0.1769 | -0.0015 | 0.1624 | -0.0029 |
| | Median | 0.0232 | -0.0232 | 0.0203 | -0.0232 | 0.0174 | -0.0218 | 0.0116 | -0.0087 |
| | t-Test | Average Acc. is significantly higher in Heavy Rain and avg. Dec. is higher in Clear Weather | | | | Average Acc./Dec. is significantly higher in Heavy Rain | | | |
| | F-Test | Acc./Dec. variability is higher in Clear Weather | | | | Acc./Dec. variability is higher in Clear Weather | | | |
| | Z-Test | Proportions of Dec. lower than -0.3g is significantly greater in Clear Weather. No Acc. were found higher than +0.3g | | | | No Acc./ Dec. were found higher/lower than ±0.3g | | | |
| Yaw Rate (deg/s) (negative sign=left rotation) | Average | 0.84 | -0.97 | 0.89 | -0.8 | 1.01 | -0.97 | 0.64 | -0.61 |
| | SD | 0.73 | 0.65 | 0.71 | 0.59 | 0.88 | 0.86 | 0.41 | 0.46 |
| | Min. | 0.33 | -8.78 | 0.33 | -3.9 | 0.16 | -8.78 | 0.16 | -4.55 |
| | Max. | 6.83 | -0.33 | 5.85 | -0.33 | 10.08 | -0.16 | 3.25 | -0.16 |
| | Median | 0.65 | -0.65 | 0.65 | -0.65 | 0.65 | -0.65 | 0.49 | -0.33 |
| | t-Test | Yaw rate (right rotation) is significantly higher in Clear Weather—no significant difference in left rotation | | | | Yaw rate is significantly higher in Heavy Rain | | | |
| | F-Test | Yaw rate variability is higher in Heavy Rain | | | | Yaw rate variability is higher in Heavy Rain | | | |
| Lane Offset (cm) | Average | 24.4 | -23.04 | 62.26 | -71.92 | 39.55 | -45.99 | 34.56 | -43.39 |
| | SD | 22.55 | 26.87 | 130.79 | 135.39 | 76.44 | 83.33 | 65.58 | 75.06 |
| | Max | 964.95 | 0 | 999.86 | -0.01 | 838.83 | -0.01 | 955.04 | -999.59 |
| | Min | 0 | -590.8 | 0.05 | -999.12 | 0.05 | -998.61 | 0.05 | -0.04 |
| | Median | 20.32 | -17.02 | 18.66 | -29.08 | 16.85 | -26.94 | 15.54 | -26.88 |
| | t-Test | Avg. lane offset to the right and left from the lane center is significantly higher in Clear Weather | | | | Avg. lane offset to the right and left from the lane center is significantly higher in Heavy Rain | | | |
| | F-Test | Lane offset to the right and left variability is higher in Clear Weather | | | | Lane offset variability is higher in Heavy Rain | | | |
| Headway(sec) | Average | 2.17 | | 2.01 | | 1.98 | | 2.02 | |
| | SD | 1.00 | | 1.12 | | 1.16 | | 1.14 | |
| | Max | 7.84 | | 6.65 | | 7.58 | | 6.68 | |
| | Min | 0.16 | | 0.08 | | 0.12 | | 0.15 | |
| | Median | 2.10 | | 1.99 | | 1.83 | | 1.81 | |
| | t-Test | Headway is significantly higher in Heavy Rain | | | | No significant difference | | | |
| | F-Test | Headway variability is higher in Clear Weather | | | | No significant difference | | | |

A criterion for lane offset values within ±0.3 meters was set to flag lane wandering events, especially when these events vary to the right and left over a short duration of time. Continuous and steady lane offset within a threshold greater than ±0.3 meters to ±9.5 meters in one direction was considered as a full lane change. A past NDS study indicated that using a threshold of ±0.1 meters resulted in a higher than expected number of lane departures (Hallmark et al., 2015). Preliminary analysis indicated that the number of lane changes is higher in clear weather conditions while lane wandering was found to be significantly higher in adverse weather conditions (heavy rain). Analyzing the NDS time series data in conjunction with video data revealed that the estimated NDS machine vision lane offset is too noisy in adverse weather conditions and where there are multiple marking lines near merge and diverge sections. The min/max values for the lane offset also revealed a very interesting finding: drivers tend to change multiple lanes (2–3 lanes) during clear weather conditions versus a single lane change in heavy rain conditions. Controlling for entry and exit of the freeway maneuvers, lane changes occurred in heavy rain were mostly evasive maneuvers to mitigate an increased risk. From video observations, it was found that drivers opted out of speed reduction behind a slower vehicle more often than changing lanes. Yaw rate and steering angle are additional variables that could be used to analyze lane maintenance. Unfortunately, steering wheel position was only available for a fraction of vehicles (only two trips included steering angle data). Yaw rates were analyzed for events with lane offset within ±0.3 meters where there were no lane changes. Yaw rates were significantly higher in heavy rain, which, as mentioned earlier, might indicate frequent evasive maneuvers to mitigate an increased risk.

On the one hand, average headways were found to be significantly higher in heavy rain compared to clear weather condition under free-flow traffic. On the other hand, the variability of headways was found to be significantly higher in clear conditions. This could be explained by the fact that drivers tend to compensate for the increased risk due to the limitation in visibility by maintaining longer headway times.

Additional analyses were conducted on an individual (no matching) seven NDS traces that were identified to have both clear and heavy rain conditions within the same trip. All seven trips were in free-flow traffic condition. There was an agreement across the seven trips that speeds were reduced significantly with a higher standard deviation in heavy rain than in clear condition. Also, the acceleration/deceleration and lane change/maintenance were affected. Number of braking, decelerations, and accelerations were significantly higher in heavy rain than in the clear portion of the trips. There were 44 and 22 braking events in heavy rain and clear weather conditions, respectively. High variability in yaw rate might indicate either too many lane changes or poor lane maintenance. Although the number of lane changes was very limited in heavy rain compared to clear conditions, the high variability in yaw rate during heavy rain suggested worse lane maintenance capabilities than in the clear condition.

Figure 3 shows a continuous speed profile, yaw rate, and acceleration data for one of the seven trips with both clear and adverse weather conditions in free-flow condition. The driver reduced the speed by more than 20 km/hr at the onset of the heavy rain; speed varied significantly afterword. It was also noted that a higher yaw rate and acceleration/deceleration rates were encountered during the heavy rain duration. It is worth mentioning that the results from trips that included clear and heavy rain were not consistent with the matched trips for obvious reasons. Number of accelerations, decelerations, and lane changes due to exit, entry, and weaving maneuvers, among other variables, are controlled for in the matching approach.



vtti.speed_network 55.20
vtti.accel_x -0.03
vtti.gyro_z -3.25
Position 00:24:41
Data Rate 10 per second
Duration 00:33:47

**Figure 32:** Illustration of Sudden Reduction in Visibility Impact on Driver's Performance

### Speed Selection: GIS Analysis and Odds Ratios

Table 3 and Figure 4 show speed behavior in clear and adverse weather conditions. Twelve NDS trips were linked to the RID via ArcGIS software. The main objectives of linking the NDS continuous data and RID were to: 1) compare the NDS speed to the speed limit along a defined route, and 2) provide a visual representation of speed selection in ArcGIS environment. Three sets of trips in heavy rain, light rain, and clear weather conditions were identified on the same 18.19-km route (Interstate 405) in Washington. A new layer was added in the ArcGIS to indicate the speed selection in both clear and rainy traces along the same route. Odds ratios were used to examine the impact of rain on speed behavior. A Z-test was utilized to test the statistical significance of the difference between the proportion of speeds in clear and adverse weather conditions. Table 3 shows that speed reduction was more likely to occur in heavy rain than the corresponding matched trip in clear weather condition. For instance, the NDS drivers drove below the speed limit in approximately 37% of their trips in clear weather. In comparison, about 85% of the trips in heavy rain were driven with speeds less than the limit. Table 3 indicates that speed reduction was more likely to be in light and heavy rain conditions in comparison with the matched trips in clear weather condition. The odds ratios of driving below the speed limit, in general, were 10 and 3 times more likely to be in heavy and light rain, respectively, than matching trips in clear weather conditions. On the same I-405 route in Washington, 37% of the speeds were under the posted speed limit. This was reduced to more than 85% during heavy rain events.

**Table 19:** Odds Ratios for Speed Behavior on I-405 (Heavy/Light Rain vs. Clear)

| | Driving below Speed Limit | Driving above Speed Limit | Odds ratio | Confidence Intervals | Z-statistic | Significance level |
|---|---|---|---|---|---|---|
| **Light Rain** | 1,797 | 958 | 9.85 | 8.67 to 11.18 | 35.19 | P < 0.0001 |
| **Clear Weather** | 968 | 1,651 | | | | |
| **Heavy Rain** | 2,621 | 454 | 3.19 | 2.86 to 3.57 | 20.43 | P < 0.0001 |

<table>
<tr><th colspan="4">Heavy Rain</th><th colspan="4">Rain</th><th colspan="4">Clear</th></tr>
<tr><td colspan="4"><b>Trip ID:643,653,657, and 672</b></td><td colspan="4">Trip ID: 646,656,660, and 667</td><td colspan="4">Trip ID:642,654,652, and 669</td></tr>
<tr><td colspan="4"><b>Total trips duration: 52:36</b></td><td colspan="4">Total trips duration: 46:13</td><td colspan="4">Total trips duration: 44:30</td></tr>
<tr><td colspan="4"><b>Speed Groups</b></td><td colspan="4">Speed Groups</td><td colspan="4">Speed Groups</td></tr>
<tr><td><b>>5 Below SL</b></td><td>(0-5) Below SL</td><td>(0-5) Above SL</td><td>>5 Above SL</td><td>>5 Below SL</td><td>(0-5) Below SL</td><td>(0-5) Above SL</td><td>>5 Above SL</td><td>>5 Below SL</td><td>(0-5) Below SL</td><td>(0-5) Above SL</td><td>>5 Above SL</td></tr>
<tr><td><b>64%</b></td><td>21%</td><td>13%</td><td>2%</td><td>38%</td><td>27%</td><td>22%</td><td>13%</td><td>19%</td><td>18%</td><td>31%</td><td>32%</td></tr>
<tr><td colspan="4"></td><td colspan="4"></td><td colspan="4"></td></tr>
<tr><td colspan="12"><b>Route: Interstate 405,Washington, Length: 11.3 miles (18.19 km), Start: Mile Marker 27</b><br><b>Speed limit source: Roadway Information Database (RID) and Street View in Google Map</b></td></tr>
<tr><td colspan="12">🟩 <b>>5 km/hr below the speed limit</b><br>🟨 <b>0-5 km/hr below the speed limit</b><br>🟧 <b>0-5 km/hr above the speed limit</b><br>🟥 <b>>5 km/hr above the speed limit</b></td></tr>
</table>

**Figure 33:** Speed Behavior in Clear, Light-Rain, and Heavy-Rain on I-405, Washington (Mile-Marker 27 to Mile-Marker 38.3)

### Modeling Speed Selection: Ordered Probit Model

To model speed selection, an ordered probit model was calibrated utilizing all the 147 trips occurring in various weather and traffic conditions (matching is not required). The model was developed for four speed intervals: more than 5 kph below the speed limit (base case), 0–5 kph below the speed limit, 0–5 kph above the speed limit, and more than 5 kph above the speed limit. Table 4 shows the selected variables for developing the "speed behavior" model in weather conditions. The dependent variable is speed selection behavior considering four levels. Generally, explanatory variables can be considered as driver's demographics, vehicle characteristics, roadway factors, and traffic and environmental conditions. Due to the lack of drivers' and vehicle characteristics data in Phase 1, only environmental and traffic variables were considered. This analysis will be extended with more driver demographics, vehicle characteristics, roadway geometry, and test data variables in Phase 2.

**Table 20:** Data Description

| Variable | Description | Type | Levels |
|---|---|---|---|
| **Response Variable** | | | |
| **Speed Behavior** | Speed selection in various weather conditions | Ordinal | More than 5 kph below the speed limit |
| | | | 0–5 kph below the speed limit |
| | | | 0–5 kph above the speed limit |
| | | | More than 5 kph above the speed limit |
| **Explanatory Variables** | | | |
| **Traffic** | Traffic Condition | Binary | 0= Free-flow |
| | | | 1= Traffic |
| **Speed Limit** | Posted Speed Limit | Categorical | 0= below 90 kph |
| | | | 1= above 90 kph |
| **Surface Condition** | Road surface condition extracted from video data | Binary | Dry |
| | | | Wet |
| **Weather** | Type of severe weather condition | Categorical | Clear |
| | | | Light Rain |
| | | | Heavy Rain |

### Model Evaluation and Results

To confirm the suitability and fitness of the model, the log likelihood ratio and the pseudo $R^2$ were used. Table 5 shows the results of the model; the Likelihood Ratio (LR) test statistic falls into the rejection area ($p$-value $< 0.05$), which means that the overall explanatory variables of the model have significant influence on the response at a statistical significance level of 95%. Only statistically significant variables were retained in the final models.

Three factors were found to be significant: weather, speed limit, and traffic condition. Among these, weather and traffic have the highest effect on speed behavior. This indicates that reduction in visibility significantly impacts drivers' behavior of selecting speed when compared to light rain or clear weather conditions. Drivers are likely to select significantly lower speed during heavy rain. Traffic has a negative coefficient as expected. Controlling for all other variables, drivers are limited to lower speeds in poorer levels of service. Interestingly, speed limit was significant with a negative coefficient, which might imply that NDS drivers tend to comply more to the speed limits on freeway segments with higher speed limits. Headway was also used as a crash surrogate under various weather and traffic conditions. The results from the headway model yielded expected outcomes and were consistent with the preliminary analysis. Drivers tend to have higher average headway times during heavy rain compared to light rain and clear weather conditions. More driver demographics such as age, gender, taking risks, etc., and vehicle characteristics might be needed to fully reveal driver behavior with respect to speed and headway selection. It is worth mentioning that for VSL application in the U.S., speed levels should be modeled within 5 mph intervals. In this analysis, there were no trips with 10 mph (16 km/hr) higher than the speed limit, and hence speed in km/hr was used.

**Table 21:** Ordered Probit Model for Speed Behavior in Different Weather Conditions

| **Analysis of Maximum Likelihood Estimates** | | | | | | |
|---|---|---|---|---|---|---|
| **Parameter** | | **DF** | **Estimate** | **Standard Error** | **Wald Chi-Square** | **Pr > ChiSq** |
| **Intercept** | **4** | 1 | 9.5048 | 3.8032 | 6.2458 | 0.0124 |
| **Intercept** | **3** | 1 | 10.7118 | 3.8058 | 7.9219 | 0.0049 |
| **Intercept** | **2** | 1 | 12.5218 | 3.8504 | 10.5760 | 0.0011 |
| **Weather** | **Clear** | 1 | - | - | - | - |
| | **Light Rain** | 1 | -1.1883 | 0.6594 | 3.2476 | 0.0715 |
| | **Heavy Rain** | 1 | -1.6786 | 0.6414 | 6.8492 | 0.0089 |
| **Speed Limit** | **Below 90kph** | 1 | - | - | - | - |
| | **Above 90kph** | 1 | -0.1204 | 0.0391 | 9.5040 | 0.0021 |
| **Traffic** | **Free-Flow** | 1 | - | - | - | - |
| | **Traffic** | 1 | -2.5873 | 0.4704 | 30.2481 | <.0001 |

## Naturalistic Driving Study Events Analysis

Although crashes and near crashes are available now for various weather conditions in the NDS database, no crashes or near crashes were provided in the sample NDS data received in Phase 1. Analysis of crash surrogates is important for various reasons; among them is the fact that the Connected Vehicle Initiative proposed using vehicles to communicate roadway conditions in inclement weather conditions. The objective of analyzing crash surrogates is to provide insights into CV weather applications. Real time vehicle dynamics could indicate adverse weather conditions. An increased risk because of adverse weather condition could be flagged in real-time for a mitigation strategy via VSL systems and CV technologies.  Manual observations of the forward-facing video and time series data indicated that there are only three trips with events. Two events were a rear-end conflict, while one event involved swerving to the shoulder in a slippery-surface condition. All events were analyzed as a learning sample to investigate different screening procedures to automate the identification of weather-related crash surrogates. The swerving event is explained in detail in this report.

The swerving incident occurred within 30 seconds due to an abrupt change in speed of downstream traffic (the leading vehicle had to reduce its speed rapidly). Examining the video reveals no obvious reason for the abrupt speed reduction (it seemed like a phantom shockwave phenomena). Due to the slippery surface, the following vehicle could not stop on time behind the leading vehicle in the same lane. The following vehicle swerved to the right shoulder to avoid a collision with the leading vehicle. Figure 5 shows a time line for the event video as sequential snapshots (headway distance extracted from the forward radar is indicated). To address question 3, driver behavior of the instrumented vehicle (i.e., the following vehicle), the leading vehicle, and the surrounding vehicles were characterized before and during the swerving event. The analysis was conducted through detailed modeling of the trajectories of the following, leading, and surrounding vehicles utilizing the forward radar, speed, headway, yaw rate, and acceleration time series NDS data.

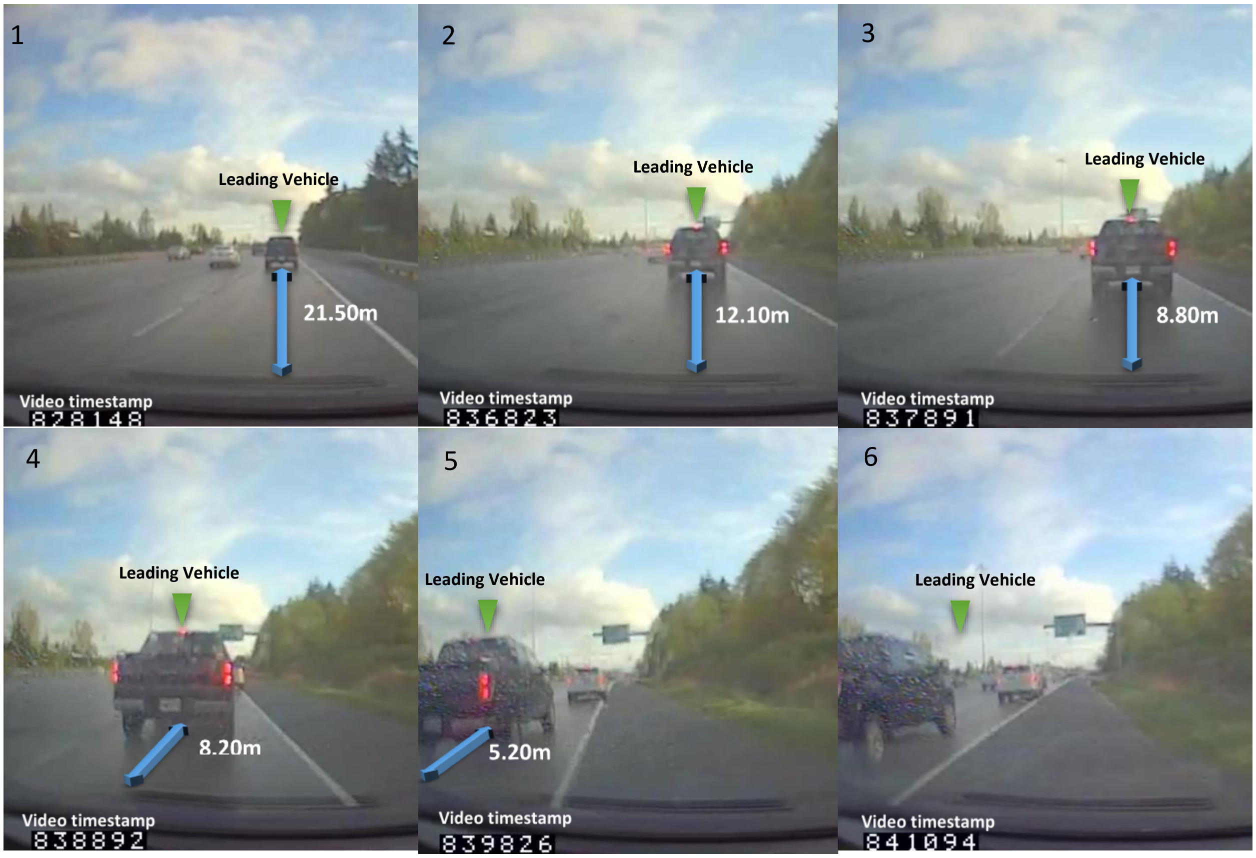


**Figure 34.**Timeline Snapshots for Incident in Third Case

Figure 34 illustrates the acceleration and yaw rate for following vehicle synchronized with the trajectories of the following, leading, and surrounding vehicles for the swerving event in Figure 5. For the first 12 seconds, the acceleration and the yaw rate were nearly constant. Also, the leading and following vehicles had a constant headway distance as shown in the trajectory part. Starting from the 12th second, an increase in the deceleration was associated with an increase in the yaw rate. The deceleration reached -0.66 m/s$^2$, and the yaw rate reached 12.7 deg/s. Additionally, the trajectories of the two vehicles intersected, which indicates a near crash if the following vehicle continued in the same path/ lane. That event is a clear example of having a near crash that could be geospatially flagged in real-time for a proper intervention. The vehicle trajectories show that if the driver in the following vehicle continued in the same lane without turning to the right shoulder, a crash would have taken place. Acceleration and the yaw rate indicated that the driver made a hard brake in combination with a sudden right turn to avoid hitting the leading vehicle.

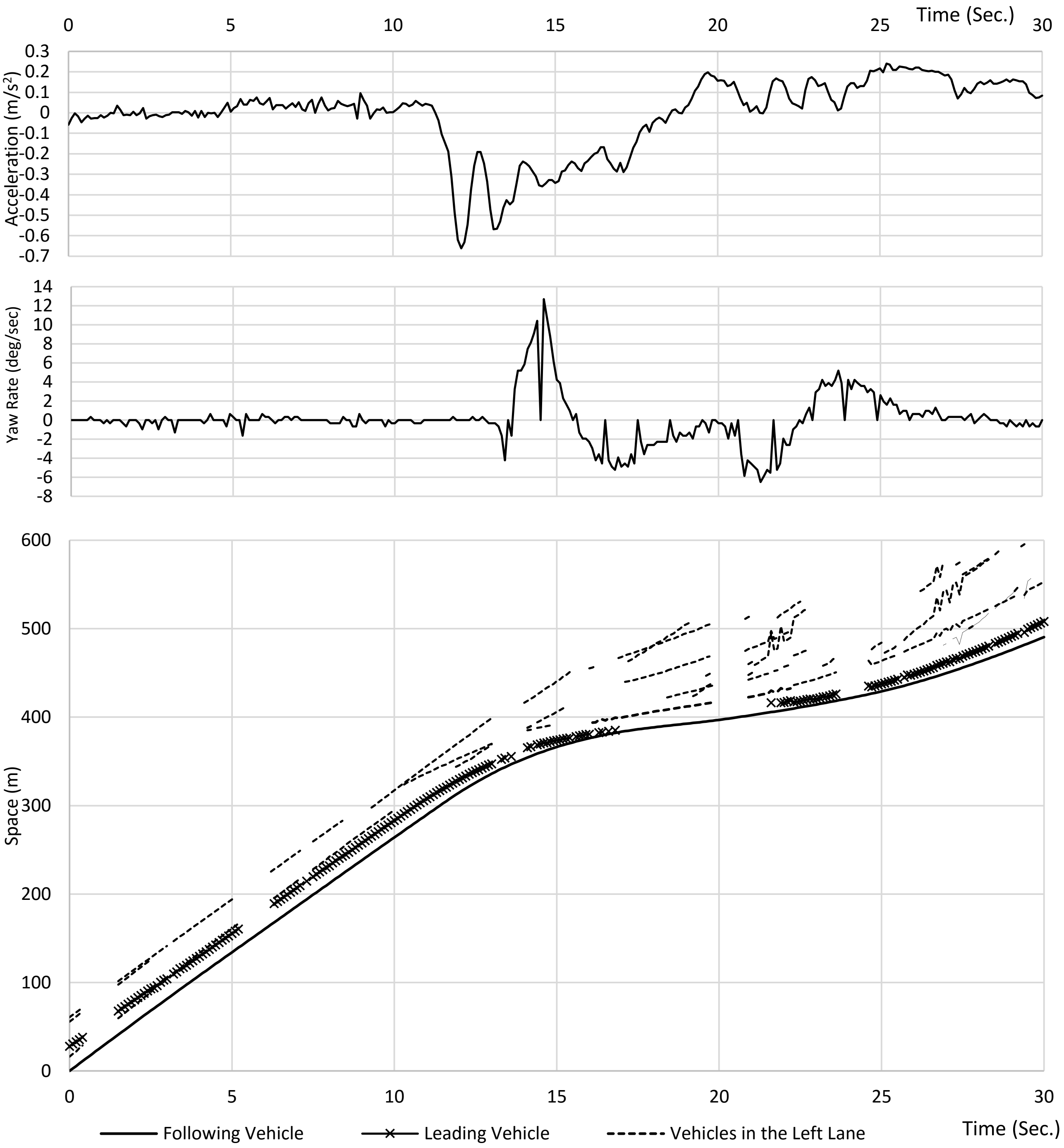


**Figure 35.** Acceleration and Yaw Rate for Following Vehicle Synchronized with Trajectories of Following, Leading, and Surrounding Vehicles for Swerving Event

Although an automated process of weather-related events could be constructed, three events (two of which are rear-end conflict) might not be enough to verify the result. More events will be investigated in Phase 2 for various adverse weather conditions. About 500 crashes, near crashes, and conflict events that occurred in rain, fog/smoke, snow, sleet, and hail as well as an additional 1,844 balanced-sampled baseline events will be acquired in Phase 2. Analysis of crash precursors is also important to understand the different contributing factors to weather-related crashes.

### Conclusions from Phase1

Behavior and road-user characteristics are among the very important elements influencing the driving task. A driver's reaction process to speed choice, lane maintenance, and car following, etc., along with his or her ability to see objects that are in motion relative to the eye ("dynamic visual acuity") are critically important factors for safe driving. Though much research has focused on highway safety in relation to adverse weather and road conditions, driver behavior and performance are absent from these studies. The NDS and RID datasets utilized in Phase 1 revealed that modeling drivers' behavior in adverse weather conditions using vehicle time series data is realizable. All research questions proposed in Phase 1 were adequately addressed. Heavy and light rain trips were identified effectively using the NDS data. A visualization and reduction software was developed; the driving variables such as speed selection, acceleration/deceleration, lane change/keeping, and headway were efficiently characterized. The preliminary analysis showed significant behavior and performance differences between driving in adverse (i.e., heavy rain) and clear weather conditions under free-flow and heavy traffic conditions. An analysis for the trajectories and time series vehicle data indicated that surrogate measures for weather-related crashes could be identified using the NDS data. Preliminary analysis and ordered probit logistic regression models were useful to help in understanding driver behavior under various rain and traffic conditions. Phase 2 is aiming at using a larger NDS data set from the six locations and analyzing various adverse weather conditions.

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