FINAL REPORT

FHWA-WY-10/05F

State of Wyoming
Department of Transportation

U.S. Department of Transportation
Federal Highway Administration

HIGH WIND WARNING SYSTEM FOR BORDEAUX, WYOMING

By:

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1000 E. University Way
Laramie, Wyoming 82071

December 2010

Notice

Quality Assurance Statement

Technical Report Documentation Page

Report No. FHWA-WY-10/05F	Government Accession No.	Recipients Catalog No.

Title and Subtitle HIGH WIND WARNING SYSTEM FOR BORDEAUX, WYOMING	Report Date July 2010 Performing Organization Code
Author(s) Rhonda Young, Edward Offei, and Quiyue Dai,	Performing Organization Report No.
Performing Organization Name and Address Department of Civil and Architectural Engineering University of Wyoming 1000 E. University Way Dept 3295 Laramie, WY 82071	Work Unit No. RS06(207) Contact or Grant No.
Sponsoring Agency Name and Address Wyoming Department of Transportation 5300 Bishop Blvd. Cheyenne, WY 82009-3340 WYDOT Research Center (307) 777-4182	Type of Report and Period Covered August 2007 – July 2010 Sponsoring Agency Code

Supplementary Notes
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Abstract
The state of Wyoming has frequent severe wind conditions, particularly in the southeast corner of the state along Interstate 80 and Interstate 25. The high winds are problematic in many ways including, interfering with the performance of the transportation system, blowing vehicles off the road, or even overturning high profile trucks, which can cause economic losses and safety concerns for road users. The primary objectives of this research involve two parts: First, develop a statistical model that reveals the correlation between likelihood of overturning trucks and the weather conditions. Second, use the result of the statistical model to develop a data driven operation plan for Wyoming Department of Transportation (WYDOT) to use in the winter season at a hazardous high wind corridor to improve truck safety.

Key Words Variable Speed Limit System, Speed Limits, Speed Compliance, Wyoming, WYDOT		Distribution Statement Unlimited	
Security Classif. (of this report) Unclassified	Security Classif. (of this page) Unclassified	No. of Pages 174	Price

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

SI* (Modern Metric) Conversion Factors

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	35.71	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	megagrams	1.103	short tons (2000 lbs)	T
Temperature (exact)				
°C	Centigrade temperature	1.8 C + 32	Fahrenheit temperature	°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	pound-force per square inch	psi

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lbs)	0.907	megagrams	Mg
Temperature (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°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	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

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CHAPTER 1:

INTRODUCTION

1.1 Problem Statement

The state of Wyoming has frequent severe wind conditions, particularly in the southeast corner of the state along Interstate 80 and Interstate 25. During the winter the wind speeds often reach sustained levels of 30 to 40 mph with wind gust speeds of 50 to 60 mph. Wyoming ranks first in the United States with an annual average wind speed of 12.9 mph (Curtis & Grimes, 2004). The high winds are problematic in interfering with the performance of the transportation system, and can blow vehicles off the road or even overturn high profile trucks, which can cause economic losses and safety concerns. .

Interstate 80 and Interstate 25 not only serve as major arterials in the southeast portion of the state, connecting cities in adjacent states, but also play a crucial role as major trans-continental routes across the United States. Large portions of the daily traffic on these roadways are long-distance freight trucks. It is estimated that trucks consist of about 55 percent of the traffic volume on the I-80 and 20 percent on I-25 in 2003, which is amounted to approximately 6,260 and 1,140 trucks running on the Interstates each day, respectively (Young & Liesman, 2007). The high profile vehicles, especially those running empty or lightly loaded, are particularly vulnerable to the high wind. Empty trucks have higher profile-weight ratios and therefore are more likely to be blown off the road or blown over by high winds.

The project location for an experimental high wind warning system was selected by the Wyoming Department of Transportation on Interstate 25 south of the town of Wheatland, in an area known as Bordeaux. Several specific factors were responsible for the selection of this location:

- High winds are particularly prevalent during the winter months.
- The percent of trucks in the traffic stream is high.
- Because this is a sparsely populated and remote area, it can take considerable time to respond to high-wind crashes, which can create excessive delays and economic losses due to interstate closure.
- The rural nature of the area means that there are few, if any, alternate routes.

1.2 Research Objectives

The primary objective of this research is to develop a system to improve truck safety during high wind conditions. This primary objective can be divided into six parts:

- Find the most hazardous section based on the historical crash data along the Interstate 25 corridor to set the project limits for the high wind warning system.
- Conduct field studies to provide an overview of the study location and chose the suitable locations for installation of the monitoring equipment.

- Confirm the relation between high wind conditions and high risk of truck crashes.
- Review weather and speed data along the corridor to determine appropriate threshold values for the high wind warning system.
- Analyze crash data to create baseline conditions to monitor the future effectiveness of the system.
- Develop final recommendations for the High Wind Warning System.

1.3 Report Format

The first chapter provides a brief description of the problem statement and research objectives. The second chapter presents a literature review of wind effects on vehicles and information concerning the use of ITS equipment in high wind condition areas. Chapter 3 includes an in-depth description of the project location and provides a history of crash data along the corridor. Chapter 4 focuses on the description of equipment used to collect data and the datasets used in the research. Data quality issues are also described in this chapter. Chapter 5 describes the data analysis methodology and results obtained in this research effect. Chapter 6 describes the proposed high wind warning system and makes suggestions for ITS operation. Chapter 7 summarizes the results and provides final conclusions.

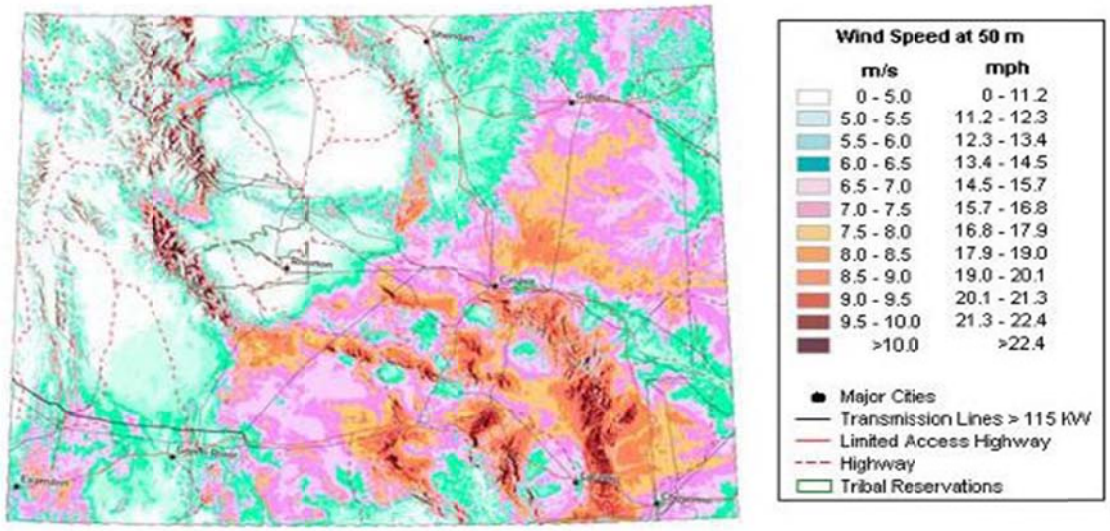
CHAPTER 2:

LITERATURE REVIEW

This literature review gives an overview of the previous research studies done both by University of Wyoming and other agencies. First, the weather conditions in Wyoming, especially in winter, are introduced. Second, the previous research study on truck safety by University of Wyoming is presented and the connection between previous studies and current research is illustrated. Finally, the wind-related crash researches conducted by other agencies are presented and analyzed.

2.1 Wind Conditions in Wyoming

The state of Wyoming is often windy and during the winter month there are frequent periods when the wind speeds reach 30 to 40 mph with wind gust speeds of 50 or 60 mph (Curtis & Grimes, 2004). Many wind farms have been established in southeastern Wyoming as an indication of the high wind conditions. In Figure 2.1, the average annual wind speed at 50 meters above the ground is shown at 400 meters resolution. It can be seen from this figure that the high wind area is in the southeastern part of the state.

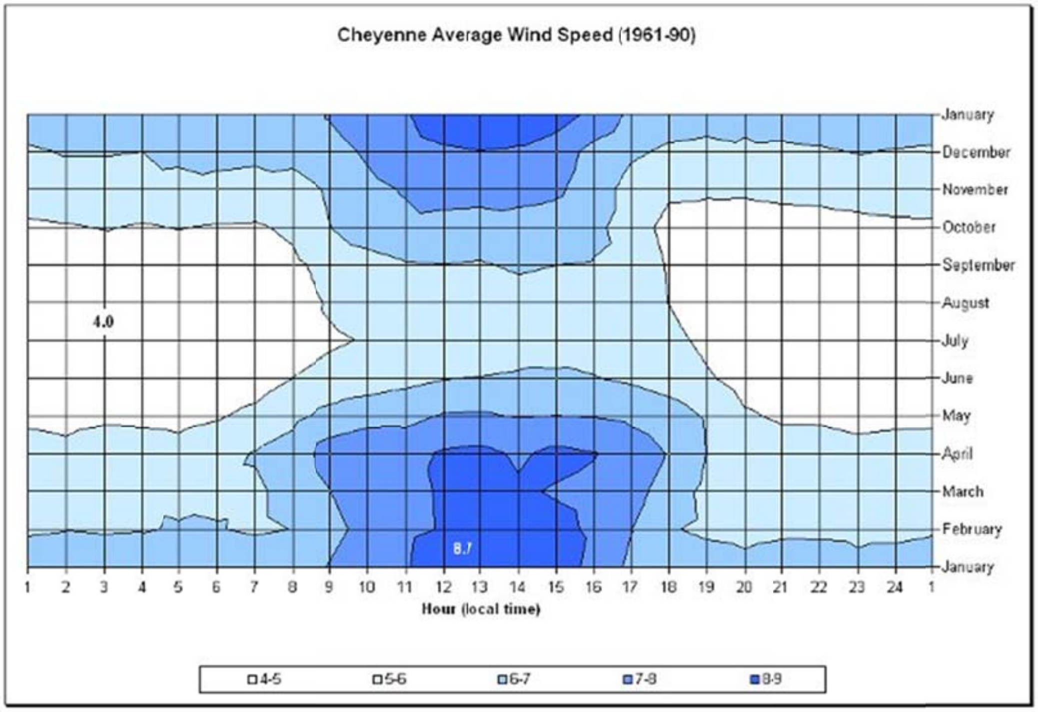


Source: Wyoming Climate Atlas (Curtis and Grimes, 2004)

Figure 2.1: Modeled Wind Speed at 50 m above the Ground

2.1.1 Seasonal and Daily Variations in Wind Speed

Based on analysis of historical wind variation records within the state from1961 to 1990, the seasonal variations of wind speed for the Cheyenne area are depicted in Figure 2.2 (Curtis and Grimes, 2004). The seasonal change is obvious from the figure. During winter months from December to April, the average wind speed reaches the highest average wind speed category of 8 to 9 mph; whereas in the summer time from June to September, the average wind speed is in the lowest range of 4 to 5 mph.



Source: Wyoming Climate Atlas (Curtis and Grimes, 2004)

Figure 2.2: Cheyenne Mean Hourly Wind Speed (mph) Observations from 1961 to 1990

To illustrate the seasonal variation more directly, it is also valuable to look at the average wind speeds and wind gust speeds in different months during one year. Table 2.1 presents the Bordeaux average wind speeds and wind gust speeds from January to December in 2008. The RWIS data was downloaded from the WYDOT computer. The values in the table indicate that the average wind speeds and wind gust speeds are much higher in winter months than in spring or summer ones.

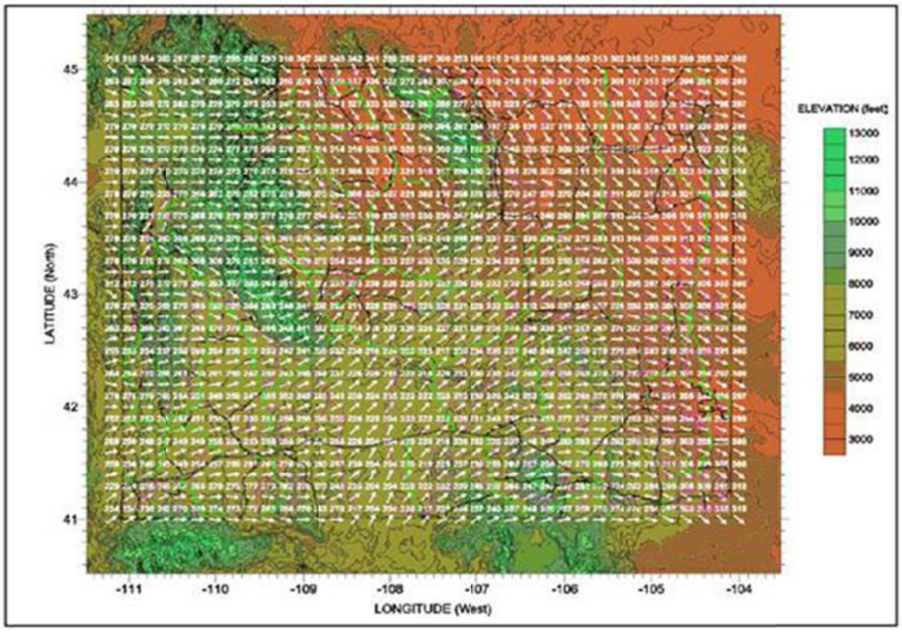
Table 2.1 : Bordeaux Average Wind Speed and Wind Gust Speed (mph)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Wind Speed	25.0	20.3	19.9	21.9	14.1	12.5	10.1	10.6	10.2	12.5	17.7	18.6
Wind Gust	36.5	28.9	31.4	32.0	20.9	20.3	15.6	16.0	15.3	18.3	25.7	27.1

Not only does the wind speed have seasonal variations, but it also has daily variations as well. Figure 2.2 reveals that the weakest winds occur in the mornings and the strongest winds usually occur in midday. The reason why daytime would have higher wind speed than night time is because the atmosphere pressure difference in daytime is usually higher than at night due to solar radiation or temperature differences (Curtis & Grimes, 2004).

2.1.2 Predominant Wind Direction

Concerning the fact that most of the severe winds happened in the winter months in Wyoming, it is valuable to look at the predominant wind directions during those months. Figure 2.3 shows the prevailing snow transport in Wyoming. Most of the directions are west related (Curtis & Grimes, 2004). Prevailing wind direction varies from west-southwest to west to northwest and is affected by local terrain. Focusing on the Southeastern part of the graph, the predominant wind directions in winter are west and northwest.



Source: Control Measures (Tabler, 1997)

Figure 2.3: Prevailing Snow Transport in Wyoming Based on Modeled Data

Predominant wind direction is a crucial factor in evaluating the road hazards. It is intuitive that the wind effect would be greatest if the wind direction is perpendicular to the road direction. The direction of I-25 is north-south and the predominant wind direction is from the west. So a hazardous high winds from the west direction would be of particular concern on I-25.

2.2 Previous University of Wyoming Research

Wyoming is known for its severe weather conditions, particularly in winter. The severe weather conditions are problematic in many ways, most of which increases the safety threat for the drivers on the road. The high vehicle crash rate in Wyoming during winter drew the attention of both the Wyoming transportation authorities and the public. In 2004, a research project sponsored by the Mountain Plains Consortium, the Wyoming Department of Transportation (WYDOT) and the University of Wyoming was carried out to investigate Wyoming truck crashes, which was one of the first studies focused on truck safety in Wyoming (Liesman, 2005). The objectives of that research includes two parts: first, develop a methodology that WYDOT could use to determine which segments of road within the state experienced the highest truck crash rate; second, examine if there is a relation between the measured wind speeds at the nearest Road Weather Information System (RWIS) tower and the likelihood of the crash occurred was an overturned truck crash.

To determine which segments of the road within the state experienced the highest truck crash rate, the researchers in University of Wyoming used a GIS based methodology to record all the historical truck crash locations on a digital Wyoming map. Three models were analyzed in GIS (Grid Model, Sliding Scale Model and Advanced Grid Model) because of their inherent pros and cons. After in-depth analysis and comparison of these three different models, the report concluded that the advanced grid analysis is a suitable model for crash analysis in Wyoming. Compared to the other two models, the advanced grid analysis can be done using standard GIS tools and produces visual results of crash rates. By using the advanced grid analysis, the report identified the following four most hazardous locations in the state with high frequencies of overturning truck crashes (Liesman, 2005):

- On I-80 approximately 35 miles west of Laramie near Arlington
- On I-25 north of Cheyenne about 10 miles south of Wheatland (Bordeaux)
- On I-80 west of Evanston

- At the I-80 and I-25 interchange in Cheyenne

It was determined that the I-80 Evanston and I-80 and I-25 interchange locations were mainly due to geometric factors and not wind factors. From the two remaining sites, Bordeaux was selected as the focus of this research project. The first objective of this current research project is to confirm the previous study concerning the most hazardous location having high frequencies of overturning truck crashes and to use this analysis to set the limits of the proposed high wind warning system. This analysis is presented in Chapter 3.

Another main objective of the previous research was to examine if there is a relationship between the measured wind speeds at the nearest RWIS weather station tower and the likelihood that the crash was an overturned truck crash.

Three logistic models (Arlington model, Wheatland model and statewide model) were estimated based on the SAS statistical software program (Young & Liesman, 2007). For the Arlington model, 1,255 historical crash records for a 10-year period were included of which 273 (22%) were overturning truck crashes. The Wheatland crash dataset contained 348 truck crashes and 119 (34%) of these overturned. The statewide model used the full 9,281 crashes that had wind data available. The three models were run separately with different initial variables, but only the estimates with P-values less than 0.05 would remain.

The result of the model run of the Wheatland model indicated that there are four parameters significant in the model: Slick, Wind_Speed, WindGust_WindSp and Straight. Slick and Straight are binary predictor variables that indicate the road surface condition and road geometric condition. The Slick variable equals to 0 if the road surface is dry and equals to 1 otherwise. The Straight variable equals to 0 if road geometric alignment is straight and equals to 1 otherwise. The Wind_Speed variable stands for wind speed measured by the nearest RWIS tower when the crash occurred and the WindGust_WindSp stands for the difference between measured wind gust speed and wind speed.

The previous research effort provided a foundation for the wind related truck crashes studies in Wyoming, so re-confirming the previous conclusions and refining the truck overturning model are major objectives of this research.

2.3 High Wind Roadway Research

Other areas have also suffered from similar high winds and have implemented programs to study the wind effects on vehicles. This section first looks at previous research on the wind effects on vehicles and then reviews previously implemented high wind warning systems.

2.3.1 Wind Effects on Vehicles

The significance of high winds can be seen if one considers the following equation (Curtis & Grimes, 2004):

$\mathbf{P = 0.00256 \times V^2 \times Cd}$ where,

0.00256 is the mass density of air at normal air pressure.

P is the wind pressure in pounds per square foot (lbs ft^{-2}).

V is the wind speed in miles per hour (mph).

Cd is the shape coefficient number. Most standing structures including cars have a Cd of approximately 2.0.

Since the wind speed (V) on the right of the equation is squared, the wind pressure (P) would increase dramatically if the wind speed increases. Even at Wyoming's higher elevations, where atmosphere is not as dense as that at sea level, pressure on a structure increases remarkably with increasing wind speed. Therefore, high speed winds can be particularly hazardous for high profile vehicles such as trucks and truck trailers.

Research in the United Kingdom investigated the wind-induced road vehicle accidents and classified the wind-induced vehicle accidents into three categories: overturning accidents, side-slip accidents and rotation accidents (Baker, 1985). The study investigated the force and moment system of a vehicle in the high wind condition and used a bus as the testing model. The report concluded that the most likely type of wind-induced accident for the test bus is an overturning crash and the developed methodology can predict accident wind speeds for different accident types, provided that vehicle aerodynamic coefficients are known in detail (Baker, 1985). Since the model and methodology presented in the report only applied to the test bus, the method has not been checked against reality in models of other large vehicles.

To investigate how wind speeds correlated with truck safety, the University of New Brunswick carried out a study called “Impact of Wind Forces on Heavy Truck Stability” in 2005 (Balsom, Wilson, & Hildebrand, 2006). This study used a test truck equipped with equipment that measured vehicle speeds, lateral acceleration and roll angle of the vehicle running on the intersection ramps to test the threshold of the truck rollover. The equipment used in this research includes a Data Acquisition System (DAS) and a weather station near the test ramp. By using a set of sensors and a central processing unit, the DAS collected data on the lateral accelerations experienced by the vehicle, vehicle speed and roll angle of the vehicle. The wind speed and direction were recorded by the vane-and-cup anemometer on the weather station at one-second intervals.

A total of 54 tests runs were conducted during the study period in different wind speed conditions ranging from lowest below 5.5 mph to highest above 12 mph. It was found that there was a significant difference in lateral accelerations between different wind speeds, even when the wind speed is not extreme. The maximum wind speed observed during the testing was approximately 18 mph, which was not perceptible by the driver. In strong winds, when a driver can feel the wind blowing against the truck, the lateral acceleration would be expected to be much higher.

The research did not provide the exact value for lateral acceleration in the winds; maybe because the maximum wind speeds studied was 18 mph. Comparing with the wind speed (maximum of 18 mph) tested in this research, the average wind speeds and wind gust speeds in Wyoming are much higher. Therefore, the lateral accelerations experienced by trucks in the hazardous areas of Wyoming would be much higher than those experienced in the research study in Canada.

Nevada DOT investigated two crash modes: overturning mode and sliding mode in 1995 (Saiid & Maragalas, 1995). The two models were used to determine the cutoff wind speed values for overturning and sliding.

$$v = \left\{ W * \frac{b}{\left[0.00666 * l * \left(h - \frac{h_2}{2}\right) * \left(\frac{h}{2} + \frac{h_2}{4}\right)\right]} \right\}^{0.5}$$

Equation 2.1: Nevada Critical Wind Speed Overturning Model

$$v = \left\{ \frac{W}{\left[0.0333 * l * \left(h - \frac{h_2}{2}\right)\right]} \right\}^{0.5}$$

Equation 2.2: Nevada Critical Wind Speed Sliding Model

The parameters used in the two models are displayed in Table 2.2.

Table 2.2: Parameters Used in the Overturning and Sliding Equations

Variable	Meaning
b	Width (in feet) of the vehicle's base
W	Weight (in pounds) of the vehicle
l	Length (in feet) of the vehicle
h	Height (in feet) of the vehicle
h2	Diameter (in feet) of the vehicle's wheels

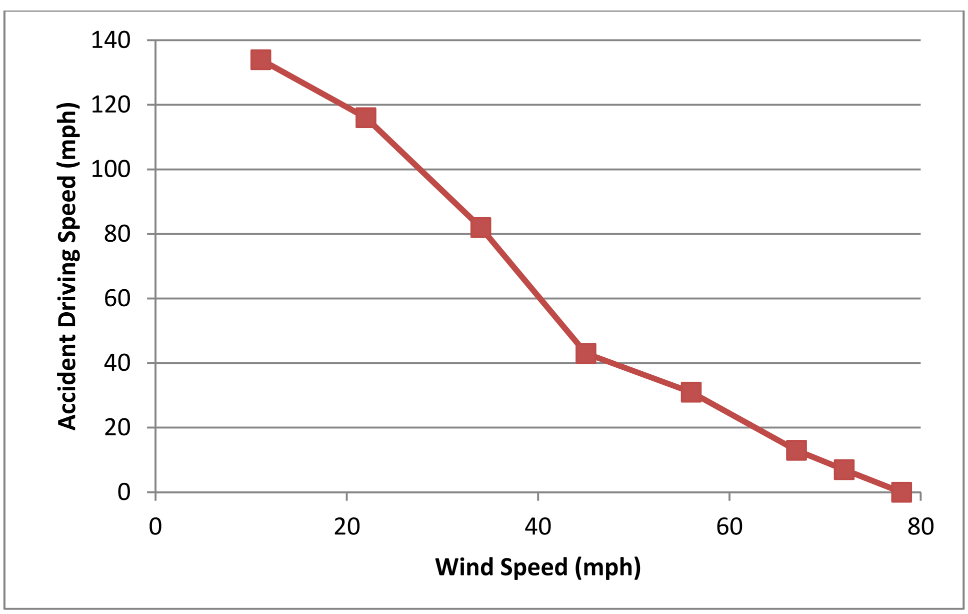
The parameters of vehicle weight, width and length used in the two models indicate that the profile and weight of the vehicle will have direct relation with the Overturning and Sliding of the trucks. Although it is not possible to exactly test the two models in this research study because the parameters of truck width, length and height are not available in the WYDOT crash reports, estimates for these parameters will be obtained and analyzed in the models.

In research conducted by Chen and Cai (2004), a general accident assessment model on roads under windy conditions was introduced that consisted of two parts: the first is the vehicle-wind-roadway global dynamic interaction model and the second is the local analysis of accidents for an individual vehicle model that takes into consideration the dynamic interactions. According to Chen and Cai (2004), this model can be extended to include the road and driver operational situations such as wind, grade, camber, acceleration and deceleration as well as driver behavior. Studies by Baker (1999); Chen and Cai (2004), showed that the driver behavior is important for an accurate simulation of the accident risks. The 2-axle, four wheel vehicle was modeled as a combination of the rigid body connected by several axle mass blocks, springs and damping devices. The dynamic interaction analysis is conducted on the vehicle-bridge system to predict the global dynamic responses of the vehicle and bridge or roadway without considering accident occurrences. The result from the dynamic response model is then used in the accident analysis of the local vehicle vibrations (Chen and Cai, 2004).

Three types of typical accidents; overturning (rollover), rotational (yawing) and side slipping accidents, usually occurs involving high profile vehicles (Baker 1991; Chen and Cai 2004). The global dynamic response of the vehicle-roadway analysis in the vertical, rolling and pitching directions is used as the basis for the local accident analysis. The relative lateral and yaw responses of vehicles are assessed separately with the local accident model, which shows the detailed study of the accident risks of vehicles. In assessing the accident risks of the vehicle, the writers modeled the adverse weather conditions such as rain and snow since these affect the friction force of the road surface and the driver operational conditions such as steering and accelerations/decelerations. The effect of the friction coefficient was considered, since there was no suitable data to simulate the impact on the steering. Because of lack of detailed statistical information for the lateral friction coefficients for wet and icy roads, some friction values were assumed for the model. They continued with the model of the pavement roughness, grade and camber of the road. In addition, a preliminary driver behavior model was developed considering the steering maneuver of drivers during windy conditions when the vehicle is being blown laterally and rotationally across the road. They assumed that the steering angle should be adjusted to correct any lateral displacement of the front wheels (Chen, Cai and Wolshon, 2009).

To avoid the risk of accidents during strong winds, the researchers studied under what allowable driving speed limit to set during such conditions. They referred to the critical driving speed as “accident driving speed” (Chen and Cai, 2004). They indicated that the three typical accidents (overturning, rotation and side slipping accidents) could happen concurrently or sequentially. To predict the accident driving speed under different wind speeds, the driving speed was increased in 1.0m/s increments under each wind speed and during each process, the accident-related response and reaction forces were predicted to check if any of the three accident types may occur during the driving process. The driving speed was increased to the next if no accident occurs during that period.

The study concluded that the accident driving speed generally decreases with the increase in wind speed (Chen and Cai, 2004). Figure 2.4 is based on the results from Chen and Cai study for a 4500 kg (9,920 lb) vehicle that was 13.4 m (45 ft) in length. The figure shows the relationship between accident driving speed (i.e. safe driving speeds) and wind speeds for vehicles on roadways. The study also found out that overturning accidents are most likely to happen when the wind speed is over 20m/s (45mph), while side slipping accidents most likely when wind speed is lower than 20m/s (45mph). The study suggested a critical wind speed of 32m/s (71mph) for which the road should be permanently closed to traffic; however actual limits should be set considering other site-specific and driver behavior factors. (Chen and Cai, 2004).



Source: Chen and Cai, 2004
Figure 2.4: Relationship between Wind Speed and Accident Driving Speeds on Roadways

A recent study conducted in Iceland investigated the parameters that influenced the wind-related accidents of road vehicles. The probabilistic model was used and applied for the assessment of road vehicle stability in windy conditions based on the reliability approach. (Snaebjörnsson, Baker & Sigbjörnsson, 2007). The model was defined on a finite set of basic variables such as wind velocity and direction, frictional coefficient, vehicle speed and roadway camber with the given probabilistic characteristics. According to the report, the model investigated the interrelation between the basic variables and its effect on the probability of accident given in terms of the accident index.

A minivan test vehicle fitted with a sonic anemometer attached to its roof with a GPS was used. The anemometer recorded the effective airflow above the roof of the car, whereas the GPS recorded the vehicle speed, driving direction and the momentary geographical location of the car. Also a fixed nearby weather station recorded the wind speed and wind direction (Snaebjörnsson, Baker & Sigbjörnsson, 2007). The modeling of the road vehicle in a windy environment was done taking into consideration the basic mechanical forces such as gravity forces, elastic and damping forces, inertia forces, frictional forces and the aerodynamic actions due to the relative motion of the vehicle and the wind. The aerodynamic forces were defined using the wind speed and direction as well as the vehicle speed and direction in addition to the shape of the vehicle and the surrounding topography of the road.

The study investigated the aerodynamic forces and moments of the vehicle which used the centre of gravity of the vehicle as the point of action. Due to the inadequate information on the multi-dimensional aerodynamic action process, the study adopted the simplified model where the force and moment coefficients were represented as deterministic functions depending only on the mean wind direction and the stochastic process of the aerodynamic action accounted for by treating the wind speed as a locally stationary Gaussian process (Snaebjörnsson, Baker & Sigbjörnsson, 2007).

According to the study, the potential point of rollover is reached if the friction is high enough to prevent slip. This causes the moment created by the wind-induced forces to exceed the resisting moment due to gravity (Snaebjörnsson, Baker & Sigbjörnsson, 2007). The two models used are:

$$V_{rollover} = \sqrt{\frac{2\mathrm{amg}}{\rho \mathrm{A}(\mathrm{hC}_{\mathrm{M_x}} + \mathrm{hC}_{\mathrm{F_z}} + \mathrm{aC}_{\mathrm{F_y}})}}$$

Equation 2.3: The Relative Wind Speed Model

where

$$\mathrm{C}_{\mathrm{M_x}} = 2.2\sin(\vartheta)$$

$$\mathrm{C}_{\mathrm{F_y}} = 0.75(1.5 - 0.9\cos(4\vartheta) - 0.6\cos(2\vartheta))$$

$$\mathrm{C}_{\mathrm{F_z}} = 5.5\sin(\vartheta)$$

$$U_{rollover} = -R\cos(\vartheta) \pm \sqrt{V^2{}_{rollover} - R^2\sin^2(\vartheta)}$$

Equation 2.4: The Critical Wind Speed Model

The parameters used in the model are displayed below:

Table 2.3: Parameters Used in the Relative and Critical Wind Speed Equations

Variable	Description
m	Mass of the vehicle
g	Acceleration due to gravity
a	Half of the lateral distance between the centers of the wheels
ρ	Density of air
A	Frontal area of the vehicle
h	Height of the centre of gravity
C_{Mx}	Moment coefficient in the x- direction
C_{Fy}	Force coefficient in the y-direction
C_{Fz}	Force coefficient in the z-direction
ϑ	Wind direction relative to the driving direction
R	Driving speed

Overturning of trucks occur when the aerodynamic forces give a rollover moment greater than the restoring moment as provided by the gravity forces. The report concluded that the critical rollover wind speed is reduced by increased vehicle speed for wind directions below 90°. It however stated that for wind directions above 90°, the critical rollover wind speed increases with increased vehicle driving speed. Thus, overturning can only be expected for wind directions between 30° and 120°. It also concluded that the accident index, ß are influenced by the driving speed and it is usually at the minimum for wind direction below 90°. The probability of accident is reduced with a decreased driving speed when the wind is blowing towards the front of the vehicle. Also the safety is increased when the wind is blowing at the back of the vehicle with increasing vehicle speed (Snaebjörnsson, Baker & Sigbjörnsson, 2007). Since the model and methodology presented was applied to a minivan, the method has not been checked against larger vehicles such as trucks and large trailers.

2.3.2 High Wind ITS Warning Systems

The Nevada DOT implemented a high wind warning system on a seven-mile section of US Route 395 because this highway segment suffered from high speed crosswinds. The high speed crosswinds, which are up to 70 mph, were extremely hazardous for high-profile vehicles. The system components of this high wind warning system included two parts: an Environmental Sensor Station (ESS) and two Dynamic Message Signs (DMS) located at each end of the corridor (Goodwin, 2003). The ESS collected weather data such as wind speeds, wind gust speeds, wind direction, precipitation type, air temperature and humidity. The wind speeds and wind gust speeds were the decisive factors to control when to display "NOT ADVISED" or when to display "PROHIBITED" on the DMS. Table 2.3 presents the cutoff values used by Nevada DOT to determine what message was displayed on the DMS.

Table 2.4 : Nevada DOT High Wind Warning System Messages

Average Wind Speed	Maximum Wind Gust Speed	Messages Displayed
15 mph to 30 mph	20 mph to 40 mph	High-Profile Vehicles "NOT ADVISED"
Greater than 30 mph	Greater than 40 mph	High-Profile Vehicles "PROHIBITED"

The Montana DOT High Wind Warning System monitored a 27-mile section on Interstate 90 near Bozeman/Livingston area for high winds (Goodwin, 2003). The high wind warning study used ESS to monitor wind speeds and wind direction and used four DMSs to display advisory messages to motorists. Four DMS were used in this study because of the 27-mile length of the segment. Two DMSs were installed on each end of the road segment to warn motorists traveling in each direction, whereas the other two were located in the middle of the 27-mile segment in each direction. Whenever there were high wind conditions perceived by the ESS, traffic and maintenance managers were alerted and displaying messages were changed based on the wind speeds. When wind speeds along the corridor exceed 20 mph, traffic managers were informed by the ESS warning alert. When wind speeds were between 20 and 39 mph, a warning message of "CAUTION: WATCH FOR SEVERE CROSSWINDS" was displayed on DMS. When severe crosswinds (wind speeds above 39 mph) were detected, DMS would present a restriction message of "SEVERE CROSSWINDS: HIGH PROFILE UNITS EXIT" to direct specified high profile vehicles to exit the freeway and take an alternate route near Livingston. The thresholds used for this warning system were set by the traffic managers' judgment.

Another motorist warning system was implemented by Idaho DOT on a 100-mile section of Interstate 84 in southeast Idaho and northwest Utah (Kyte, Shannon, & Kitchener, 2000). The research project used RWIS to collect weather data such as wind speeds, wind direction, precipitation, air temperature and relative humidity. Forward-scatter detection sensors were used to measure visibility distance, and inductive loop detectors were installed to record vehicle length (for identifying passenger cars or trucks), vehicle speed and travel lane. If there were severe weather conditions spotted by the weather sensors on RWIS, the road, weather and traffic condition data were transmitted to a central computer and warning messages were displayed on four roadside DMS. The effectiveness of the road condition DMS warning messages on drivers' behavior was studied from 1993 to 2000. The study evaluated the difference in traffic speeds when no message was displayed and when a warning message was shown. When DMS displayed high wind warning signs (above 20 mph) in severe weather conditions, average vehicle speeds decreased by 23 percent from 54.8 mph to 42.3 mph. A 35 percent decline in average vehicle speed was perceived when the pavement condition was snow-covered and warning signs were displayed. The project finally made a conclusion that driver behavior was influenced by the advisory DMS information presented by the traffic managers and road safety was improved due to the message displaying.

The Montana and Idaho studies have a similar feature in decision methodology that both of these studies used wind speeds as the decision cutoffs, but did not take into consideration the wind gust speeds, which is also a crucial factor in truck turnover in Wyoming. Nevada model did involve both wind speed and wind gust speed as the decision factor, and the cutoff value of wind gust speeds to prohibit high profile vehicles on the road was 40 mph. Comparing to the wind speed and wind gust speed cutoff in Nevada, high wind hazardous highway segments in Wyoming usually suffer from a much higher wind speeds (above 30 mph) and wind gust speeds (above 50 mph). Another crucial and common feature of these three studies is that all of them did not consider vehicle weight in their studies because of limitation in collecting vehicle weight data.

To address localized high cross wind, the Oregon and California Departments of Transportation used Dynamic Message Signs to alert motorists on high wind conditions starting in 2003. Three high wind sections were selected to install the high wind warning system. The main objective of the projects is to improve the safety and security of the regions' rural transportation system. In 2005, the Western Transportation Institute (WTI) conducted a study to investigate the effectiveness of the three wind warning systems (Manjunathan, 2005). Since the project started immediately after the three systems were installed, the crash data are available for one high wind season and the crash data does not show a statistically significant change in crash rates. However, the estimated benefit-cost ratios calculated in the report indicated that the three high wind warning system will result in direct returns equal to their installation, maintenance and operations costs. The project also evaluated the reaction of the traveler to the systems through surveys. Approximately 80 percent of the respondents "strongly agree" or "agree" that the systems will provide them accurate information on high wind conditions.

A previous research study for WYDOT outlined four-levels of operational strategies in the high wind warning system (Young & Liesman, 2007). The four level of operation are summarized as follows:

- Level 1. Wind and surface variable thresholds for advisory messages for DMSs.
- Level 2. Wind and surface variable thresholds to determine road closure for all vehicles.
- Level 3. Wind, surface, and vehicle profile variable thresholds to determine road closure for all high-profile vehicles.

- Level 4. Wind, surface, vehicle profile, and vehicle weight variable thresholds to determine road closure for all high-profile, light-weight vehicles.

The primary objective of this research is to find a system to improve truck safety during high wind conditions and a similar operational system for the hazardous corridor would be suggested for WYDOT to use in a later chapter.

2.4 Summary

This literature review gives an overview of the previous research studies done both by University of Wyoming and other agencies. One of the common features of the previous high wind warning system is that the decision methodology is based largely on the judgment of the traffic manager, not on the objective weather condition cutoff. The main objective of this research is to develop a scientific based methodology based on observed weather conditions to help traffic managers operate the roadway segment more safely and efficiently.

CHAPTER 3:

PROJECT LOCATION

The section of I-25 south of Wheatland was identified as a high wind hazardous location by a previous study (Liesman, 2005). The first task for this research project was to confirm this area as hazardous and to set the project area limits. The following chapter documents this process and then describes the project area in detail.

3.1 Crash Analysis

In order to identify the most hazardous location along Interstate 25 and re-confirm the previous study concerning the hazardous location, the historical crash data provided by WYDOT between MP 00.00 and MP 120.00 along I-25 from January 1994 to June 2007 was analyzed. Since the historical crash data include all vehicle types, the first step was to separate the truck crashes from the original crash data, forming a truck-only crash dataset. After this step, the truck crash data between MP 00.00 and MP 120.00 includes 577 crashes. The 577 truck crashes were sorted and graphed by 5 miles intervals to find the most hazardous section. Table 3.1 and Figure 3.1 present the results of this analysis, which indicates that the most hazardous location along I-25 is between MP 65.00 and MP 80.00, with the highest number of crashes between MP 70.00 and MP 75.00.

Table 3.1 : Truck Crashes on I-25 at 5 Miles Intervals (Jan. 1994 to Jun. 2007)

Milepost by 5 Miles Intervals	Crash Frequency
5.00-10.00	2
10.00-15.00	0
15.00-20.00	23
20.00-25.00	14
25.00-30.00	25
30.00-35.00	12
35.00-40.00	19
40.00-45.00	14
45.00-50.00	29
50.00-55.00	40
55.00-60.00	20
60.00-65.00	11
65.00-70.00	39
70.00-75.00	112
75.00-80.00	16
80.00-85.00	14
85.00-90.00	43
90.00-95.00	34
95.00-100.00	30
100.00-105.00	23
105.00-110.00	28
110.00-115.00	11
115.00-120.00	18

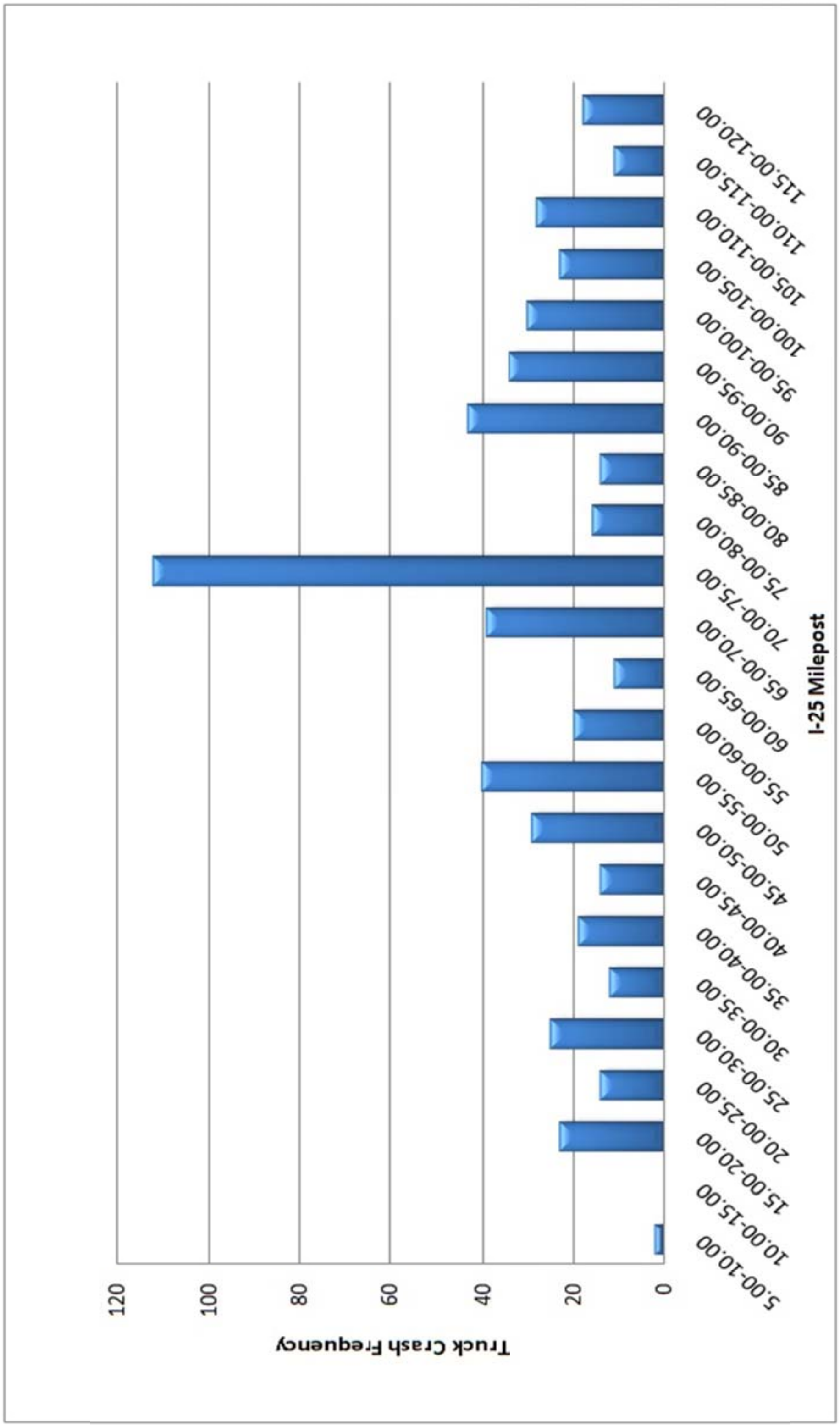


Figure 3.1: Truck Crashes on I-25 with 5 Miles Intervals (Jan. 1994 to Jun. 2007)

The next step was to sort the truck crashes in smaller intervals (0.5 miles) to examine the hazardous segment in detail. Analysis results are shown in Table 3.2 and Figure 3.2.

Table 3.2 : Truck Crashes on Interstate 25 from MP 65.00 to MP 80.00

Milepost by 0.5 Miles Intervals	Crash Frequency	Wind or Blizzard	Overturn
65.00-65.49	6	5	5
65.50-65.99	7	5	5
66.00-66.49	2	2	2
66.50-66.99	1	1	0
67.00-67.49	1	0	1
67.50-67.99	1	1	1
68.00-68.49	0	0	0
68.50-68.99	1	0	0
69.00-69.49	5	5	5
69.50-69.99	5	5	4
70.00-70.49	26	24	22
70.50-70.99	50	46	45
71.00-71.49	3	3	3
71.50-71.99	7	5	4
72.00-72.49	4	2	2
72.50-72.99	2	1	1
73.00-73.49	3	2	3
73.50-73.99	2	2	2
74.00-74.49	1	0	0
74.50-74.99	1	1	1
75.00-75.49	0	0	0
75.50-75.99	0	0	0
76.00-76.49	1	0	0
76.50-76.99	0	0	0
77.00-77.49	1	0	0
77.50-77.99	0	0	0
78.00-78.49	2	1	1
78.50-78.99	3	0	0
79.00-79.49	3	1	0
79.50-80.00	1	1	1
Total	139	113	108

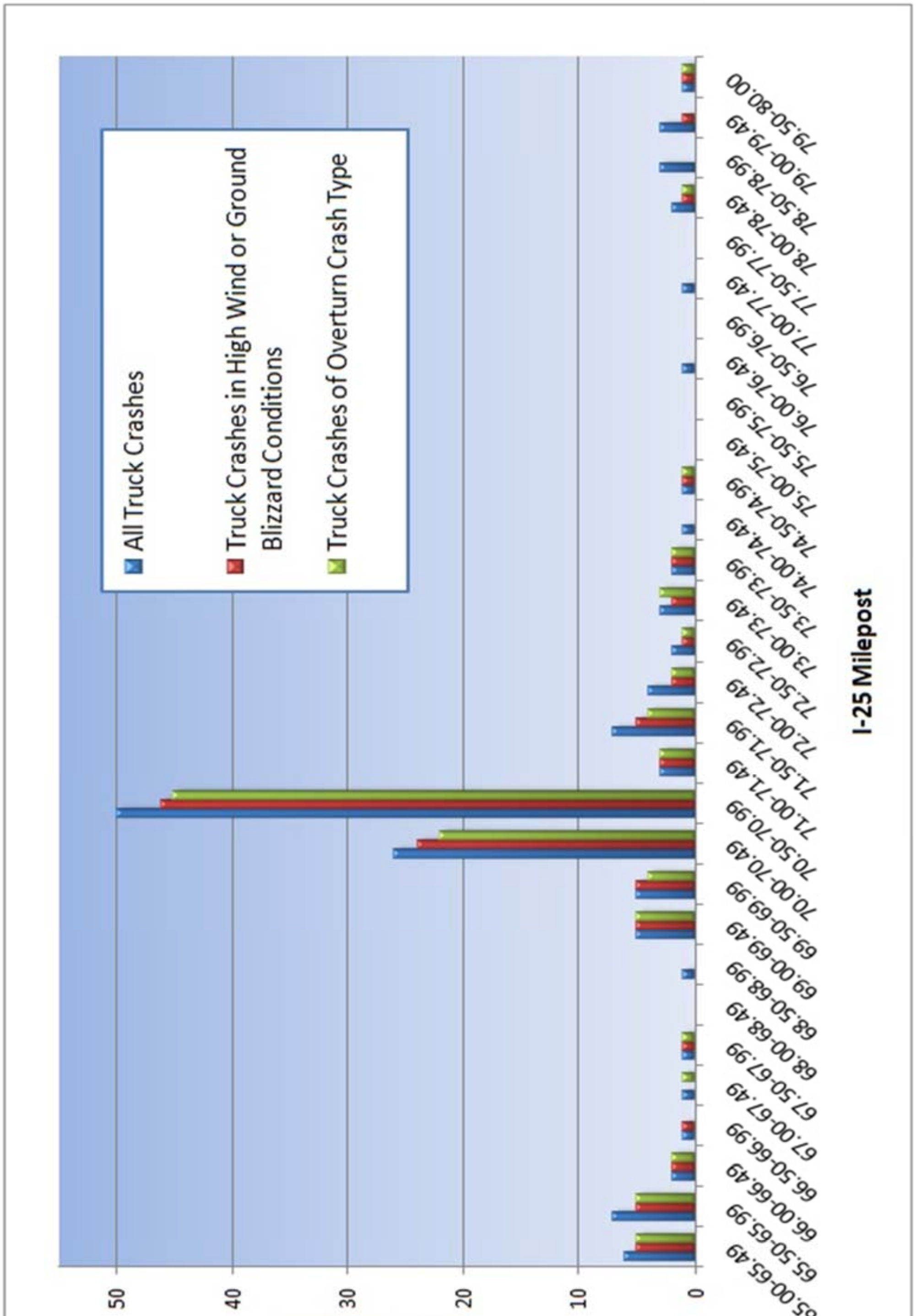


Figure 3.2: Truck Crashes on Interstate 25 from MP 65.00 to MP 80.00

In Table 3.2, three separate crash totals were calculated. The first was a total truck crashes frequency that includes 139 truck crashes that occurred from Milepost 65.00 to Milepost 80.00 between Jan. 1994 and Jun. 2007. The second parameter was truck crashes that occurred during strong wind or ground blizzard conditions. The reason this parameter was taken into consideration is because 81 percent (113 out of 139 cases) of the crashes occurred in high wind or ground blizzard condition. Another critical feature of these crashes is that 77 percent (109 out of 139 cases) of the total truck crashes were overturning crashes. The results of this analysis indicated that the most hazardous section between Milepost 65.00 and Milepost 80.00 is between Milepost 70.00 and Milepost 71.00. Therefore, this section of the roadway was determined to be the main focus for the proposed high wind hazardous system and new equipment was installed along this segment to monitor the roadway. The equipment installed will be described in a later section. The result of this analysis re-confirmed the previous study concerning high wind hazardous locations along I-25 and set the exact boundaries for the study segment.

To be conservative, the Milepost range from 69.50 to 71.50 was selected to be the high wind warning system research boundary. The crash frequency of this 2 mile hazardous section from January 1994 to February 2010 is as shown in Figure 3.3, which includes 157 crashes. From the year 1994 to 2005, the average number of crashes per year within this boundary is 7. This value dramatically increased to approximately 18 between 2006 and 2009. The data for 2010 is incomplete at the time of this report.

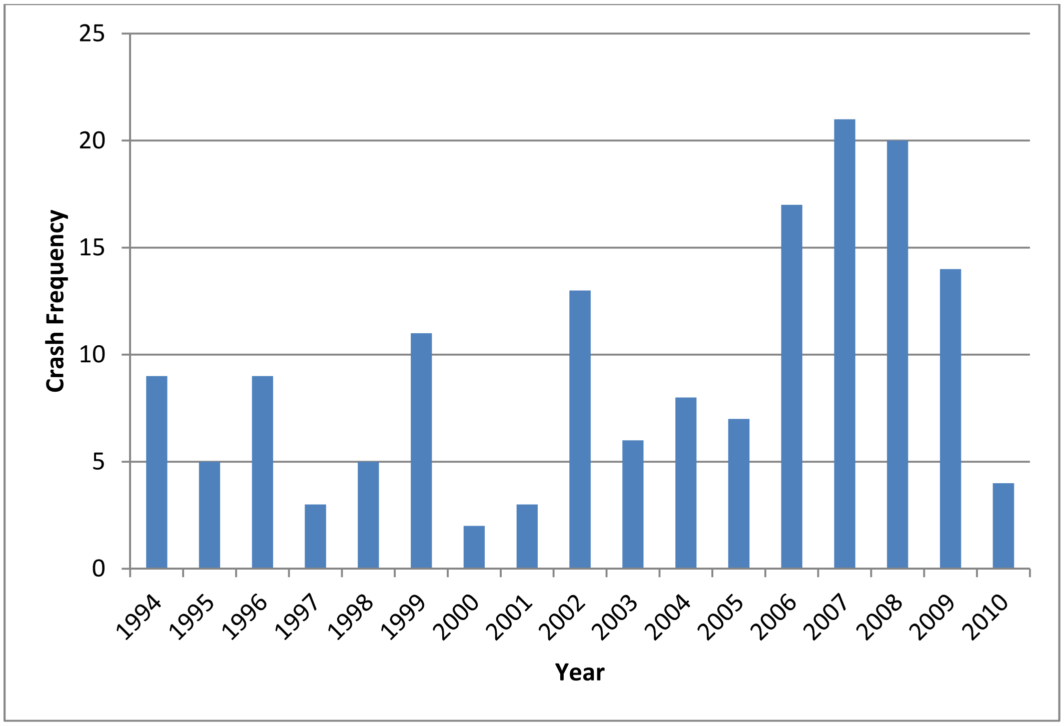


Figure 3.3: Crash Frequency between MP 69.50 to 71.50 from January, 1994 to February, 2010

3.2 Project Location

At Milepost 70.62, Interstate 25 intersects with Bordeaux Road at the Bordeaux Interchange. Figure 3.4 shows the approximate milepost of the Bordeaux Interchange structure (MP 70.62) as well as the mileposts of the two adjacent interchange structures (MP 68.45 and MP 73.03), which are provided to give scale by the aerial photo.

Figure 3.4: Project Location on Interstate 25

Figure 3.5 provides a view of the Bordeaux project location. The roadside terrain is rugged, covered with bushes; and there are no buildings near the interchange. On the northwest of the interchange, there is a small hill where the Road Weather Information System (RWIS) tower is located. According to the crash history data, approximately 70 percent of the overturned truck crashes occurred in the northbound direction of the corridor. From a topographic perspective, the 500-feet-long northbound corridor is located in the middle of two small hills that act like a wind tunnel. Vehicles traveling on the northbound direction would experience a dramatic increase of wind speeds right after the curve (Shown on the right of Figure 3.5).

Figure 3.5: Photo of Bordeaux Project Location

3.3 Data Collection Equipment

The monitoring equipment installed in the project area includes:

- Road Weather Information System (RWIS) Tower
- 2 Pan-Tilt-Zoom (PTZ) Cameras attached to a 2 channel Pelco 4000 Digital Video Recorder
- 2 Wavetronix Speed Sensors

The RWIS equipment was installed previously while the remaining equipment was installed for this project.

3.3.1 Road Weather Information System (RWIS) Tower

A Road Weather Information System (RWIS) Tower is a fixed roadside tower with Environmental Sensor Station (ESS) sensors measuring atmospheric, surface and hydrologic conditions. The RWIS tower enables transportation managers to monitor roadside conditions and to disseminate road weather information to motorists in order to influence their travel decisions. There are typically three types of sensors installed on a RWIS tower: Atmospheric Sensors, Surface Sensors and Hydrologic Sensors (FHWA, 2005). Atmospheric Sensors measure various weather conditions including air temperature, barometric pressure, relative humidity, wind speeds and direction, precipitation, visibility distance, and cloud cover. Surface Sensors measure pavement conditions and subsurface or soil conditions. Hydrologic Sensors use acoustics or sound waves to measure the distance from a transducer to the water surface.

The existing RWIS tower, which is located northwest of the interchange on an adjacent hill, provides the basic weather data at 10 minutes intervals. The key parameters it collects include wind speeds, wind gust speeds, wind direction, surface temperature and subsurface temperature. Figure 3.6 shows the RWIS tower installed at the project location. From the top to the bottom, there are propeller anemometers, PTZ Camera 2, PTZ Camera 1, Hygrometers, RWIS cabinet and DVR cabinet.

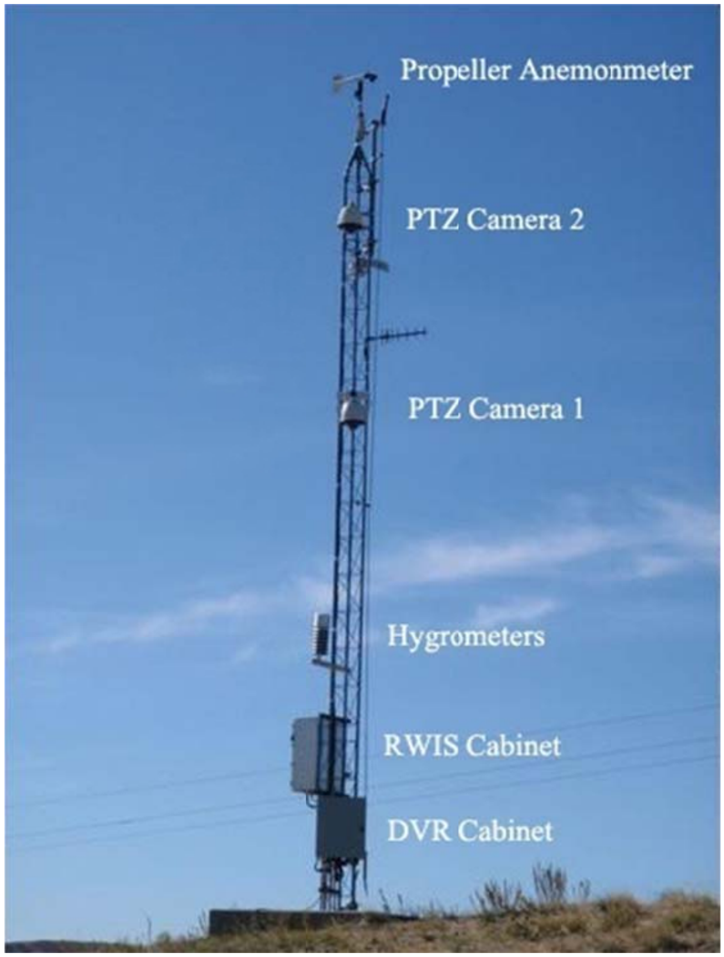


Figure 3.6: RWIS Tower and PTZ Cameras

3.3.2 PTZ Cameras and Pelco DVR4000

As Figure 3.6 shows, two PTZ cameras are installed on the RWIS tower and connected to two separate channels to the Pelco 4000 Digital Video Recorder to collect the video data. Since there are no lights installed at the interchange, the recorded time period on the DVR was set from dawn (6:00 AM) to twilight (7:00PM) in the winter season and from dawn (5:00 AM) to twilight (9:00PM) in the summer season. The storage capacity of Pelco 4000 DVR is 160 Gigabytes, which allows approximately one month of monitoring video for the two cameras before the storage space is full. Once full the DVR begins overwriting the oldest video.

The reason monitoring cameras and the DVR are used in this project is that crash video provides additional information beyond that found in the crash report. Crash video can also provide additional real-time crash information which is not offered in the crash report, such as the real time traffic conditions, road conditions, driver's maneuvers, etc.

In order to monitor the entire hazardous section between MP 69.50 to MP 71.50, the two cameras were pointed to the locations shown in the Figure 3.7. It was thought that the two cameras would cover the entire hazardous corridor. However, the changing position of camera 2, which was required by WYDOT for their traveler information website, missed almost all of the crashes that occurred from November 2008 to January 2009.

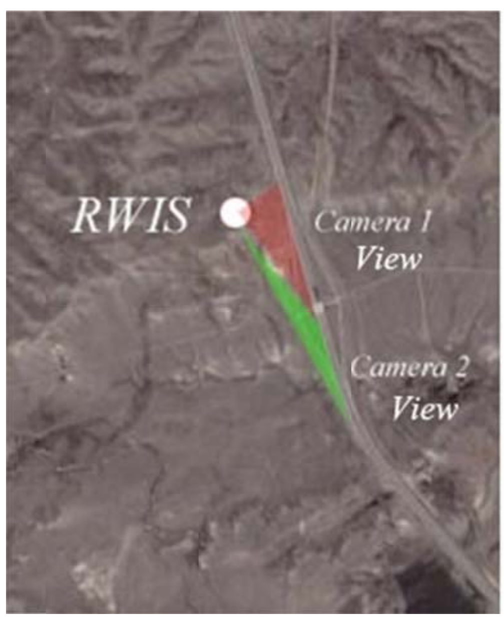


Figure 3.7: First Camera Coverage Plan

In order to catch the crashes in real time, WYDOT re-focused the camera 1 to the most hazardous area from MP 69.50 to MP 70.60 on February 4th, 2009. The re-focusing was proved to be effective because camera 1 recorded a crash occurred shortly after the changing position. Figure 3.8 is a screen shot of the February 6th, 2009 crash video.

Figure 3.8: Screen Shot of February 6th, 2009 Crash in Real Time

3.3.3 Wavetronix Speed Sensors

There are two Wavetronix Smart HD Sensors, shown in Figure 3.9, located in the study area. One is located north of the RWIS tower (N41˚56.516′/ W104˚56.828′) and the other is located south of the RWIS tower (N41˚55.048′/ W104˚55.858′).

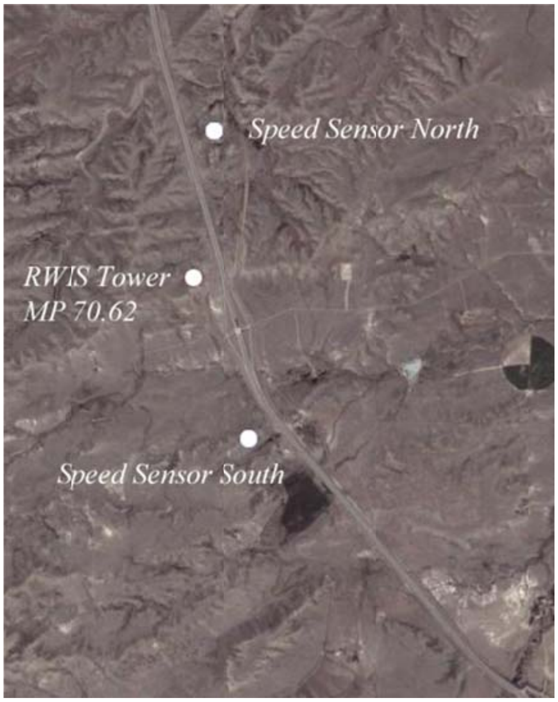


Figure 3.9: RWIS Tower and Speed Sensor Locations

Wavetronix Smart Sensors HD utilizes a 24.125 GHz radio frequency and is capable of measuring traffic volume, classification, average speed, individual vehicle speed, lane occupancy, and presence for as many as ten lanes of traffic. Figure 3.10 shows the inner view of the speed sensor cabinet.

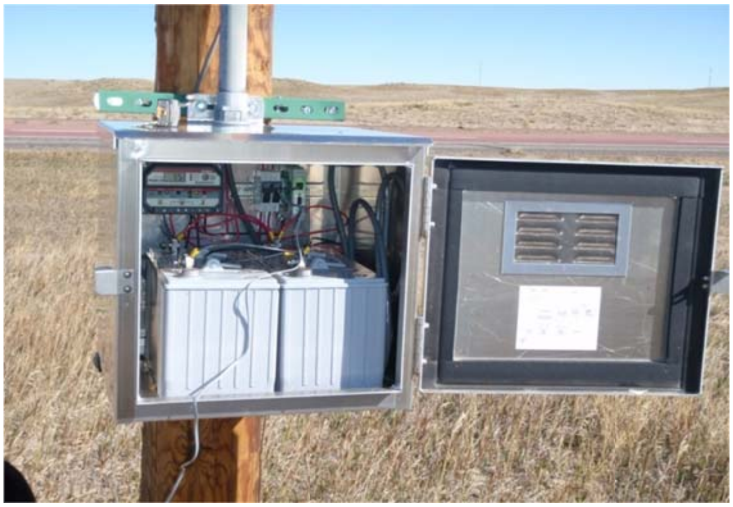


Figure 3.10: North Speed Sensor Cabinet

3.3.4 HOBO Weather Station Equipment

The HOBO U30 weather station is a portable data logging system that uses a network of smart sensors to record weather data. The Hobo weather station was used to provide supplemental roadside wind measurements that were compared to the RWIS wind measurements. The monitoring equipment installed in the project area included the following:

- HOBO U30 NRC Data Logger
- Solar Panel
- 2-Meters Tripod Kit
- Grounding Kit
- Wind Speed/Direction Smart Sensor
- Crossarm for Wind Speed/Direction sensor
- Guy Wire Kit

The HOBO Weather Station Equipment was installed about 40 feet from the edge of the roadway south side of the bridge in the southbound direction near Milepost 70. Figure 3.11 shows the installed HOBO Weather Station Equipment. The wind speed sensor was installed about 7 feet from the ground surface. The HOBO weather station collects the wind speed, gust wind speed, and wind direction at five minute intervals.

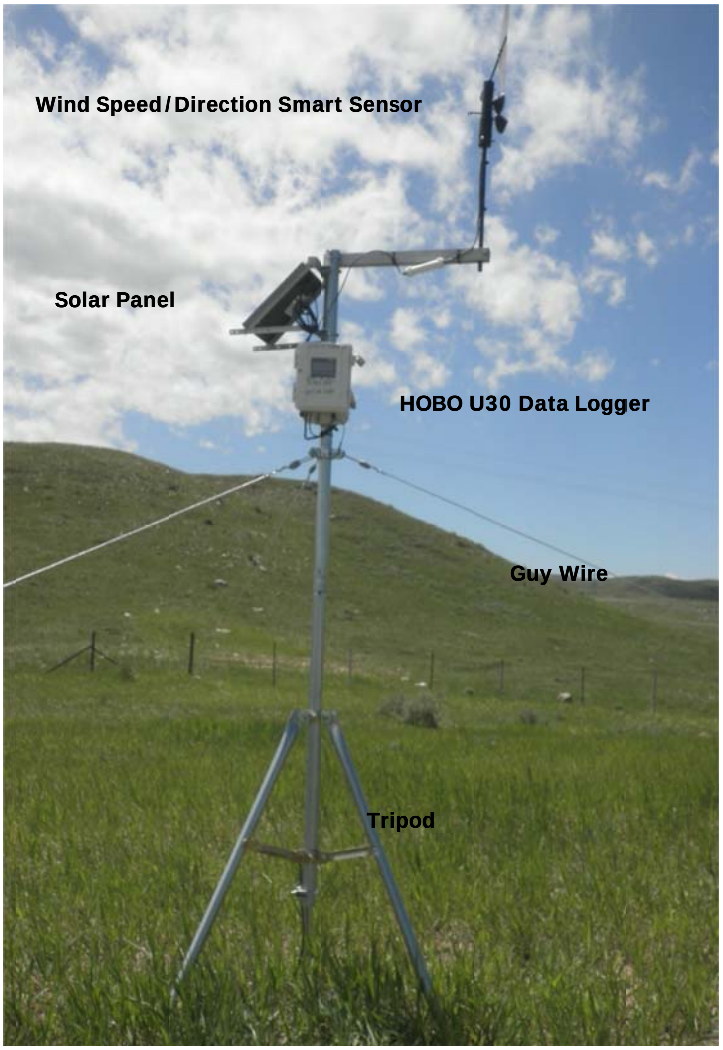


Figure 3.11: The HOBO U30 Weather Station

CHAPTER 4:

DATA SOURCES

This chapter discusses the data collected in this research and describes how the data are processed.

4.1 Wind Warning System Datasets

There are four major data sources in this research: RWIS data, Speed Sensor data, DVR data, and WYDOT Crash Reports.

4.1.1 RWIS Data

The dataset compiled from the existing RWIS includes the weather variables listed in Table 4.1. The parameters of Date and Time mark the weather data in ten-minute intervals. The Surface Status variable is an important parameter because of the bad weather conditions in Wyoming during winter. The different values of surface status include Dry, Frost, Ice Warning, Ice Watch and Chemically Wet. When there are problems with the sensor the value could also be "Error", which occurs infrequently. Another data collection problem was from the Surface Temperature. The Surface Temperature data stopped collecting at 8:45 AM, Oct. 4, 2007 and never resumed. Other parameters such as Subsurface Temperature and Air Temperature were reliable during the study period.

There is a period from Aug.11, 2006 to Feb.15, 2007 when the Wind Direction value was always "North". The reason for the propeller anemometer malfunction is unknown and special care is taken for analyzing that period of weather parameter. Except for the errors listed above, other important parameters for this research -Average Wind Speed, Wind Gust Speed and Wind Direction were intact and accurate.

Table 4.1: RWIS Data Descriptions

Variables	**Description**	**Parameters**
Date	Date of Data Recorded	MM/DD/YYYY
Time	Time of Data Recorded	24 hours unit
SfStatus	Surface Status	"Error" "Dry" "Ice Warning" "Wet"
SfTemp	Surface Temperature	Fahrenheit
SubTemp	Subsurface Temperature	Fahrenheit
AirTemp	Air Temperature	Fahrenheit
WindSpeed	Average Wind Speed	Miles per hour
Gust Speed	Wind Gust Speed	Miles per hour
Wind Direction	Wind Directions	"N" "S" "E" "W" "SW" "NW", etc

The RWIS data was compiled starting from Sep. 28, 2007 to cover the entire research period. The RWIS data were downloaded from a WYDOT computer and stored in two separate text files: air wind data and temperature data. Both text files were then imported to Excel to form a complete weather dataset, which was later combined with speed sensors data. Sometimes the RWIS tower stopped working for several hours due to unknown equipment reasons, but the chance of missing RWIS data is small. Overall, the number of RWIS data records collected is approximately 99 percent of the number of expected data records.

4.1.2 Speed Sensor Data

One of the objectives of this research is to find the relation between high wind conditions and the speeds of large profile vehicles. After the two speed sensors were installed, they suffered many data collection difficulties, such as wrong firmware software, poor sensor alignment and improper bin settings. Useable data did not become available until November 26, 2008 when both the lane alignment and sensor bin settings were set correctly. Since data downloading is time consuming (one hour per one month of data), site visits are conducted frequently to collect the speed sensors data. During each site visit, the sensor clock and sensor alignment are checked first. The sensor clocks make sure the sensors are collecting data that can be coordinated with each other and with the RWIS data. The sensor alignments make sure the two sensors are collecting vehicle speeds accurately.

Figure 4.1 is a sample view of Speed Sensor output, including 7 variables:

- *Name:* the name of each lane or approach
- *Volume*: the number of vehicles detected during the interval (In this study, the interval is set to be 5 minutes)
- *Speed*: the average lane speed during the 5 minutes interval
- *85%:* Shows the 85th percentile speed
- *Headway*: the average time separation between vehicles detected during the interval
- *Gap*: the average time separation between vehicles detected in the interval
- *C1 to C8*: Vehicle classification based on vehicle length

```
#############################################################################################
############################################################################################
#
#              DATE       : November 25, 2008
#              SERIAL NUMBER: SS125 U100000609
#              DESCRIPTION  : SS125 ITS Radar
#              LOCATION     : Unknown
#              ORIENTATION  : SS
#____________________________________________________________________________________________
___________________________________________________________________________________________#
#      |    |Occu-|     | 85% |        Class Count          |     |    |           |              Speed Bins
#      |    |pancy|Speed|Speed|_____________________________________|     |    |  SENSOR TIME
|____________________________________________________________________________________________
# NAME    |VOLUME| (%)  |(MPH)|(MPH)|C1|C2|C3|C4|C5|C6|C7|C8|HEADWAY| GAP |YYYY-MM-DD HH:MM
SP12|SP13|SP14|SP15|Correct|Wrong#
#      |    |    |    |    |10|25|50|60|85|110|255|   |    |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
#############################################################################################
############################################################################################
 LANE_01   6  0.4  77.7  79.0  0  3  0  0  2  1  0  -  150.0  149.5  2008-11-13 00:15:00  -  -  -  -  -  -  -
 LANE_02   1  0.1  67.8  68.0  0  0  0  0  1  0  0  -  900.1  899.2  2008-11-13 00:15:00  -  -  -  -  -  -  -
 LANE_03   0  0.0  65.6  66.0  0  0  0  0  0  0  0  -    0.0    0.0  2008-11-13 00:15:00  -  -  -  -  -  -  -  -
 LANE_04   4  0.4  54.4  57.5  0  1  0  0  2  1  0  -  225.0  224.1  2008-11-13 00:15:00  -  -  -  -  -  -  -
```

Figure 4.1 : Speed Sensors Data Sample

Eight categories of vehicles were classified based on vehicle length. The categories of C1 and C2 stand for small vehicles, whereas categories C3 and above stand for trucks.

- C1 = Very Small (0 – 8’)
- C2 = Small (8 – 20’)
- C3 = Medium Small (20 – 28’)
- C4 = Medium (28 – 40’)
- C5 = Medium Large (40 – 48’)
- C6 = Large (48 – 60’)
- C7 = Larger (60 – 70’)
- C8 = Largest (70’+)

The Wavetronix Speed Sensor collects vehicle speeds for different directions and lanes. Interstate 25 in the project location has two lanes in each direction, so four lanes of vehicle speeds are collected separately at each sensor. For both sensors, the lane_01 was set to be the lane which is near to the sensor, whereas the lane_04 was set to be the lane which is far from the sensor. Take the north sensor for example. Since the north sensor was installed on the east side of the road, the lane_01 was set to be the lane on the right side lane of the northbound direction and the lane_04 was set to be the lane on the right side lane of the southbound direction. To allow comparison between sensors, the lane designations were changed to directional descriptions.

4.1.3 DVR Data

As mentioned before, the Pelco 4000 DVR records everyday from 6:00 AM to 7:00 PM in the winter season since there is no lighting in the project corridor. The Disk Write Mode was set as "First-in, First-out" Mode, which means that after the storage on the DVR is full, the oldest data is overwritten first. Once a wind related accident occurred on the road, the Wyoming Highway Patrol Dispatch Center would send an E-mail to the University of Wyoming research team. The E-mail includes the basic information about the crashes including: the time when the crash occurred, milepost of the crash, northbound or southbound and the type of the accident vehicle. If the wind-related crash occurs during daylight hours and within the monitoring boundary of two cameras, a site visit would be conducted to retrieve the DVR crash video for future analysis. Figure 4.2 and Figure 4.3 are sample screen shots of the view of the two cameras after installation. Only video from crash events are saved from the DVR.

Figure 4.2 : DVR Video of Camera 1

Figure 4.3 : DVR Video of Camera 2

4.1.4 WYDOT Crash Report

WYDOT Crash Reports are another important source of research data. These reports are the official accident reports filed by the Wyoming Highway Patrol for crashes occurring on I-25 and contain details of the crash. Crash reports were compiled for all reported crashes from January 2005 to June 2007. Three factors were investigated from the crash reports and are listed in Table 4.2. Crash reports are also compiled monthly for all reported crashes during the 2008 to 2010 winter seasons.

Table 4.2 : Key Parameters from WYDOT Crash Report

Factors	Parameters
Vehicle Type	Car, Truck, Both, Unknown
Trailer	None, Empty, Lightly Loaded, Loaded, Unknown
Wind	Wind related, Non-Wind related, Unknown

4.2 Data Processing

4.2.1 Combine Historical Crash Data with RWIS Data

In order to evaluate the relationship between crashes and the measured weather conditions when the crashes occurred, historical crash data and RWIS weather data are combined for statistical analysis. Table 4.3 displays the number of crashes used in the SAS analysis.

Table 4.3: Truck Crashes Frequency between MP 69.50 to MP 71.50

Year	Number of Crashes	Crashes Analyzed in SAS
1994	9	8
1995	5	2
1996	9	8
1997	3	3
1998	5	5
1999	11	11
2000	2	2
2001	3	2
2002	13	12
2003	6	6
2004	8	8
2005	7	4
2006	17	12
2007	21	19
2008	20	20
2009	14	14
2010	4	4
Total	157	140

From January 1994 to March 2010, 157 crashes occurred within the Milepost 69.50 to Milepost 71.50. One hundred and forty of them were imported for SAS analysis because the rest of them are either passenger vehicle crashes or weather data is not available.

4.2.2 Combine Vehicle Speed data with RWIS Data

Besides the relation between crashes and RWIS data, it is also valuable to look at the relation between truck speed and weather conditions such as wind speed, lighting condition and road condition. The weather -speed-dataset includes three parts: RWIS weather data, Speed Sensors data and Weather Forecast data. The dataset combination process first imports the speed sensors data to Excel, and then using VLOOKUP function to match the speed sensor time with the nearest RWIS data. Finally, the Weather Forecast data was added to complete the weather-speed dataset. The completed weather-speed dataset was started on from November 26, 2008 when the speed sensor alignment and bin were set correctly and runs through April, 2009.

4.3 High Wind Crashes during 2008 and 2009 Winter Season

During the 2008 to 2009 winter seasons, 17 crashes occurred within this two mile corridor. Table 4.4 is the list of these crashes. Discussed in Chapter 3, the average number of crashes per winter season is 7 from year of 1994 to 2005. This value dramatically increased to approximately 18 between 2006 and 2009.

Of the 17 crashes, 15 of them are overturn crashes. The two exceptions are case 11 and case 17. The first harmful event of the case 11 crash is road approach; and the first harmful event of the case 17 crash is delineator post. 15 out of 17 crashes occurred in high wind conditions with wind speed above 40 mph and wind gust speed above 55 mph. The two exceptions are case 3 and case 17. Case 3 crash occurred with a wind speed of 35 mph and wind gust speed of 47 mph. Case 17 crash occurred on a clear weather day without harmful wind, and no overturning was involved in the crash.

Table 4.4: Excerpt of Crashes that Occurred during the 2008 to 2009 Winter Season

Index	Crash Key	Milepost	Date	Wind Speed	Wind Gust Speed	Wind Direction
1	200820435	70.50	12/5/2008	53	73	W
2	200820436	70.25	12/5/2008	49	70	SW
3	200820441	70.00	12/17/2008	35	47	W
4	200820901	70.00	12/27/2008	50	66	SW
5	200820908	70.75	12/31/2008	40	62	SW
6	200820909	70.50	12/31/2008	45	67	SW
7	200822845	70.00	12/31/2008	47	71	SW
8	200900353	70.62	1/5/2009	58	76	W
9	200900354	70.60	1/5/2009	53	74	W
10	200901773	70.00	1/21/2009	40	57	SW
11	200902570	70.62	2/6/2009	45	62	SW
12	200902571	70.00	2/6/2009	55	68	SW
13	200902572	70.63	2/6/2009	47	72	SW
14	200903550	69.98	3/8/2009	48	68	W
15	200903552	70.50	3/8/2009	45	73	W
16	200904562	69.88	3/8/2009	51	71	W
17	200903566	71.50	3/9/2009	9	11	NE

Another feature of the crash list is that for 76 percent (13 out of 17) of the crashes, two or more crashes occurred in a single day. Multiple crashes occurring in a single day may indicate that the weather was very unfavorable for heavy vehicle driving. The average wind speed and wind gust speed when these 13 crashes occurred are 48.92 and 69.77, respectively. Both the wind speeds and wind gust speeds are approximately 10 mph higher than one crash per day counterparts.

4.4 High Wind Crashes during 2009 and 2010 Winter Season

For the 2009 to 2010 winter seasons, 8 crashes occurred within this two mile corridor, which is considerably less than the previous winter. Table 4.5 shows the list of these crashes. The average number of crashes per winter season was 6 per year from 1994 to 2005. This value dramatically increased to approximately 16 per year between 2006 and 2010.

Of the 8 crashes, 5 of them were overturn crashes. The three exceptions were cases 2, 7 and 8. The first harmful event of the case 2 crash is work zone maintenance equipment; and the first harmful event of the other two cases is a fence. Four out of 8 crashes occurred in high wind conditions with wind speeds above 30 mph and wind gust speed above 50 mph. It is worth noting that two of the crashes occurred during snowy weather conditions with wind speed above 5mph and wind gust speeds above 10mph. There were two crashes recorded that represent both ends of the weather spectrum. Case 4 and case 7. Case 4 crashes occurred with a wind speed of 51 mph and wind gust speed of 70 mph. Case 7 crash occurred on a clear weather dry day without harmful wind, and no overturning was involved in the crash.

Table 4.5: Excerpt of Crashes that Occurred during the 2009 to 2010 Winter Season

Index	Crash Key	Milepost	Date	Wind Speed	Wind Gust Speed	Wind Direction
1	200915686	70.62	10/31/2009	50	63	SW
2	200918191	65.00	12/07/2010	6	11	E
3	200918731	70.25	12/10/2009	35	55	SW
4	200918197	70.50	12/12/2009	51	70	W
5	201000873	70.60	01/12/2010	40	51	SW
6	201000879	70.50	01/18/2010	29	38	SW
7	201002729	69.10	02/03/2010	20	30	SW
8	201002283	66.00	02/18/2010	16	20	N

No multiple crashes occurred in a single day during this winter season. The average wind speed and wind gust speed when these 8 crashes occurred are 30.88 and 42.25, respectively.

Besides the RWIS and speed sensors data collected, the crash videos were also retrieved if available. The video data offers additional information of the truck crash such as traffic condition and the drivers' maneuvering prior to a crash, which are helpful in evaluating the cause of the truck crash. Figure 4.4 is a series of snapshots from the February 6th, 2009 truck crash, which shows a complete process of truck overturning.

Figure 4.4: Snapshots of the Crash Video

4.5 General Statistics

4.5.1 Maximum, Minimum and Average Wind Speed

Although the major wind parameters considered are the wind speed and wind gust speed, the summary of Maximum, Minimum and Average Wind Speed during each day was calculated from September 28, 2007 to October 7, 2007. Table 4.6 is an excerpt from the complete dataset.

Table 4.6 : Excerpt of Maximum, Minimum and Average Wind Speed Table

	Wind Speed			Gust Speed		
	Max	**Min**	**Average**	**Max**	**Min**	**Average**
09/28/07	30	0	13	48	2	20
09/29/07	34	6	17	47	9	25
09/30/07	31	3	17	45	7	25
10/01/07	47	0	19	66	4	29
10/02/07	52	1	25	68	6	38
10/03/07	34	1	14	48	2	21
10/04/07	29	0	12	38	1	17
10/05/07	38	26	32	25	0	9
10/06/07	35	13	21	26	0	15
10/07/07	35	13	21	26	0	15

4.5.2 Predominant Wind Direction Analysis

From the data summary of Predominant Wind Analysis (Table 4.7), it is clear that the predominant wind directions were west and southwest for the project area and the relation between wind speed and wind direction is really profound when wind speed reached 40mph. Once the speed of the wind reaches to 40 mph, all the wind directions are recorded as west or southwest.

Table 4.7 : Predominant Wind Direction When Speeds Are above 30mph and 40mph

Directions	E	W	N	S	NE	NW	SE	SW	Total
Wind Speed Above 40 mph	0	256	0	0	0	0	0	366	622
Wind Speed Above 30 mph	0	1029	10	8	0	7	0	1344	2398

4.6 Summary

This chapter provides an overview of the data collected in this research and how combined datasets were developed. The remaining chapters focus on the data analysis.

CHAPTER 5:

TRUCK CRASHES CAUSATION STUDY

After the most hazardous section along the Interstate 25 (between MP 70.00 and 71.00) was confirmed and the high wind warning system boundary was determined (between MP 69.50 and 71.50), the next step is to analyze the historical crash data to investigate the causes of the truck crashes.

In 2003, the Federal Motor Carrier Safety Administration (FMCSA) and National Highway Traffic Safety Administration (NHTSA) conducted a research effort called the Large Truck Crash Causation Study (LTCCS) to determine the reasons for large trucks crashes (FMCSA, 2007). The LTCCS data included 120,000 large truck crashes that occurred between April 2001 and December 2003. Several variables were included in the truck crashes dataset and one of the most crucial variables is critical reason. The report classified the critical reasons of the truck crashes into three main categories: driver, vehicle and environmental condition (roadway or weather). Table 5.1 is the estimated number of truck crashes classified by critical reasons in the report.

Table 5.1: Estimated Number of Trucks Crashes by Critical Reasons

Source: Large Truck Crash Causation Study (FMCSA, 2007)

Critical Reasons	Number of Trucks	Percent of Total
Driver	68,000	87%
• Non-Performance	9,000	12%
• Recognition	22,000	28%
• Decision	30,000	38%
• Performance	7,000	9%
Vehicle	8,000	10%
Environment	2,000	3%
Total	78,000	100%

The nationwide study indicated that driver factors are the most critical reasons in truck crashes, whereas vehicle and environment factors account for only 10% and 3% of the total truck crashes, respectively. However, of the 140 truck crashes between MP 69.50 to 71.50 on Interstate 25 from January, 1994 to April, 2010, about 90% of the truck crashes occurred in high wind conditions (crashes occurred with an average wind speed above 45 mph and average wind gust above 55 mph). This indicates that environmental factors play an important role in truck crashes on this road segment. Another crucial feature of the crashes that occurred between MP 69.50 to 71.50 is that approximately 82% of the crashes are truck crashes with overturning as the first harmful factor. This feature suggests that vehicle factors, such as vehicle type, are also an important reason for these crashes.

Since driver factors, such as recognition and decision errors, are hard to predict, regulate and avoid, this chapter only focuses on the environment and vehicle factors that cause truck crashes. The first part of this chapter will analyze the relation between truck crashes and environmental parameters, build the statistical model for the environmental relation analysis, and determine threshold values for the proposed high wind warning system. The second part will present the relation between truck crashes and vehicle factors such as vehicle weight and vehicle speed.

5.1 Truck Crash and Environment Factors Relationship Study

5.1.1 Methodology

As explained in Chapter 3, the high wind and historical crash data were merged for the statistical analysis. The statistical software used for this analysis is Version 9.2 of the SAS statistical software program.

The first step is to select a suitable model for the data analysis and then to determine which response parameter should be used in the model. One of the most crucial features of truck crashes within this hazardous segment is overturning. It was found that there were 140 truck crashes occurred in the hazardous location between 1994 and 2010, and 115 (82%) of the total crashes are overturning crashes. In addition, overturning is a common feature of the high wind crashes. Therefore, a binary response variable is selected in the model with the value of 1 for an overturning crash and 0 for a non-overturning crash. The logistic regression model is selected to be the analysis model because the response variable of logistic nonlinear regression has only two possible outcomes, which can be represented by a binary indicator variable taking on values of 0 or 1.

Since the analysis model needs to have a binary response variable and many predictor variables, the multiple logistic regression is selected for the relation analysis. Equation 5.1 shows the multiple logistic regression model used in this analysis. The multiple logistic regression model, which has more than one predictor, is an extension of the simple logistic regression model.

$$E\{Y_i\} = \frac{exp^{(\beta_0+\beta_1 x_1+\cdots+\beta_k x_k)}}{1 + exp^{(\beta_0+\beta_1 x_1+\cdots+\beta_k x_k)}}$$

Equation 5.1: Multiple Logistic Regression Model

The model selected is based on the same equation used in the previous research (Young & Liesman, 2007). The difference is that the previous model used a larger crash dataset which included 258 crashes. Since not all the crashes occurred near the Bordeaux RWIS tower, the distance from the crash location to the RWIS tower was considered as a predictor variable. However, the dataset used in this research is a smaller dataset that only covers the crashes that occurred between MP 69.50 to MP 71.50.So the distance to the tower was not considered. It is expected that crashes close to the RWIS tower would be better correlated to the weather data than the earlier dataset. From January, 1994 to April, 2010, there were 157 crashes documented within this 2-mile-section, 140 of them were used in the logistic regression model analysis. The remaining 17 crashes were not used either because they involved only passenger vehicles or occurred at a time when no RWIS data was available.

The next step is to choose predictor variables (β_1 to β_k) to be included in the model. In order to reveal the relation between high wind weather conditions and truck overturning, the predictor variables need to contain all possible weather condition parameters. During the process of model analysis, insignificant predictor variables are deleted from the model and only significant predictor variables that correlate to truck overturning crashes remain. Using a 95% confidence interval, all the parameters with P-value larger than 0.05 will be removed from the model one at a time starting with the largest values until all remaining parameters have P-values smaller than 0.05. In addition, the Hosmer and Lemeshow goodness-of-fit test is used to test whether the overall model fits the data well. A small chi-squared value and a large P-value in the Hosmer and Lemeshow goodness-of-fit test indicate the model does not have a significant lack of fit, or vice visa.

5.1.2 Multiple Logistic Regression Model

According to the methodology described in the previous section, all possible weather condition data are imported into SAS to include in the initial model. The predictor variables used in the first model and the model run result are listed in Table 5.2.

Table 5.2 : Predictor Variable Estimate of the First Model

Predictor Variable	Estimate	P-value
Intercept(β_0)	-1.7483	0.0782
Lighting Condition (β_1)	0.1952	0.8049
Road Condition (β_2)	-2.6857	0.0061
Wind Speed(β_3)	0.1252	0.0801
Wind Gust(β_4)	-0.0350	0.5257
Wind Direction Binary(β_5)	0.3387	0.7799

Since the P-value of lighting condition is 0.8049, which is much larger than the cutoff value of 0.05 and larger than any other P-values, the output of the first model indicates that lighting condition is not significant for the model and is therefore removed from the model. This filtering process is repeated until all the estimates of the model have P-value less than 0.05. The final model result is displayed in Table 5.3.

Table 5.3: Variable Estimate of the Final Model

Predictor Variable	Estimate	P-value
Intercept(β_0)	-1.7522	0.0426
Road Condition(β_1)	-2.5628	0.0048
Wind Speed(β_2)	0.0893	<0.0001

For the final model, all the predictor variables β_0, β_1 and β_2 have P-values less than 0.05. The Hosmer and Lemeshow goodness-of-fit test gives a result of Chi-square value of 11.0985 and P-value of 0.1962. The chi-square value is less than the target X^2 (0.95, 8) value of 15.51 and the P-value is larger than the cutoff of 0.05. The result of Hosmer and Lemeshow goodness-of-fit indicates that the model does not have a significant lack of fit and the model fit the data well.

$$E\{Y_i\} = \frac{exp^{(-1.7522-2.5628x_1+0.0893x_2)}}{1+exp^{(-1.7522-2.5628x_1+0.0893x_2)}}$$

Equation 5.2: Multiple Logistic Regression Model Result

This equation indicates the relation between road condition, wind speed and the chances of crash is an overturning crash. The estimate of road condition (β_1 = -2.5628) is a negative value, which means that the chance of having an overturning crash is increased when the road condition is "dry" (value of 0), whereas the chances of having an overturning crash is decreased when the road conditions are "Wet" or "Ice warning" (value of 1). While this result may seem to be counter intuitive, the previous study of this research has a similar conclusion (Young & Liesman, 2007). It was believed that the severe road condition is a visible hazard, whereas the hazardous wind condition is not as easy to perceive as a snowy weather or slick road. The lower chances of having overturn crashes when road condition is bad indicate that drivers are alert when they perceive the potential hazard on the road and drive with special care, which may include driving maneuvers such as slower speed and keeping alert. Another interpretation is that high wind events are often associated with clear skies.

The estimate of wind speed ($\beta_2 = 0.0893$) is a positive value, which means that the chance of having overturn crash is increasing as the wind speed increases. In order to reveal how the increasing of wind speeds and different road condition would relate to the overturning of the trucks, the fitted values of the equation are displayed in Figure 5.1 and Table 5.4.

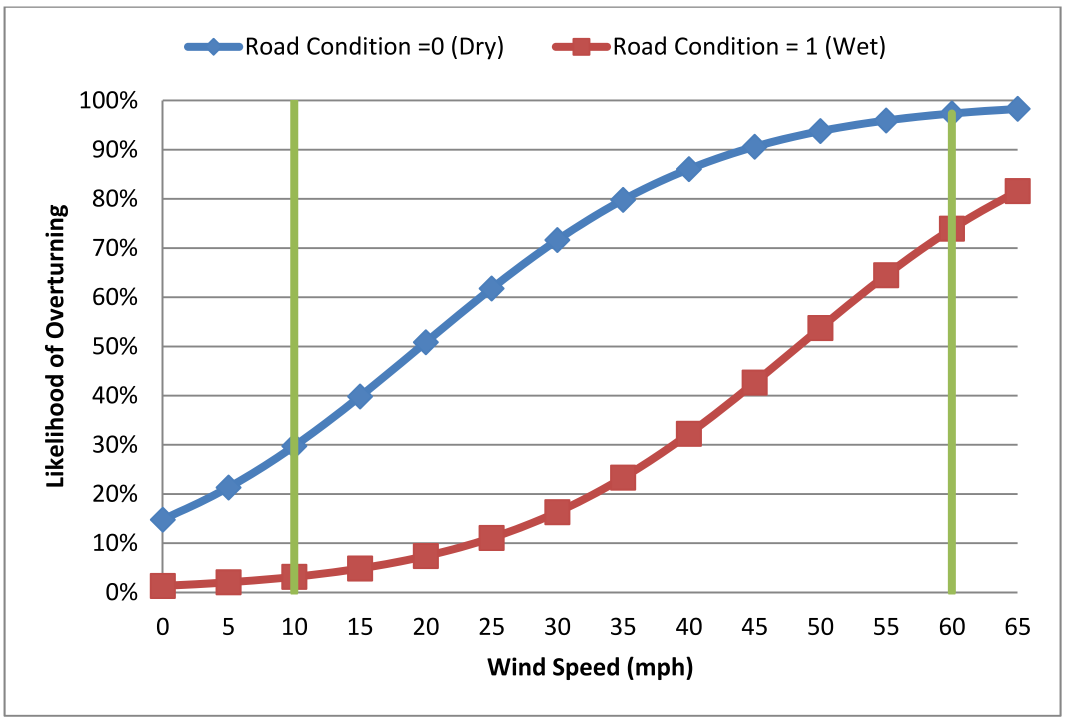


Figure 5.1: Relationship between Wind Gust Speeds and Truck Overturning

Table 5.4: Relationship between Road Condition, Wind Speeds and Truck Overturning

Wind Speed (X_2)	Fitted Value when X_1=0 (Dry Road)	Fitted Value when X_1=1 (Wet Road)
0	14.78%	1.32%
5	21.32%	2.05%
10	29.75%	3.16%
15	39.83%	4.85%
20	50.84%	7.39%
25	61.78%	11.08%
30	71.64%	16.30%
35	79.79%	23.33%
40	86.05%	32.23%
45	90.60%	42.64%
50	93.78%	53.74%
55	95.93%	64.49%
60	97.36%	73.94%
65	98.29%	81.60%

Both Figure 5.1 and Table 5.4 indicate that the fitted value of the equation when X_1=0 (road condition is dry) is much larger than the value when X_1=1 (road condition is wet or ice warning). Figure 5.1 estimates the likelihood of truck overturning at different wind levels (from 0 mph to 65 mph), but only the wind speed boundary of 10 mph to 60 mph is considered in the High Wind Warning System. Since that is the data range the model was determined from. Data points outside this range should be considered unreliable.

It was mentioned in Chapter 2 that the model from the previous research includes four parameters in the final run: Road Condition, Wind Speed, Wind Gust Wind Speed Difference and Roadway Geometry (Young & Liesman, 2007). All the four parameters in the previous research were tested in the new model, but only the Road Condition and Wind Speed remain in this model. Roadway

Geometry is eliminated because the earlier model included a larger segment of the Interstate 25 corridor. Crashes occurred on both straight and curved road segments, whereas the crashes in this study mainly occurred on a straight roadway. The difference between the wind gust and average wind speed variable was eliminated because of interaction problems between the wind speeds and wind gust speeds. This difference may have been triggered by the fewer number of crashes available within the two mile hazardous area compared to the larger analysis. The previous study model used 258 of crashes but this study has 140 crashes. The use of a smaller dataset could lead to the interaction problem between the wind speeds and wind gust speeds.

5.1.3 Second Order Model Test

Although the model in the previous section is seen to be an acceptable model for the dataset, it is still valuable to check the interaction between the predictor variables, because the three parameters in the model: wind speeds, wind gust speeds and wind directions are highly correlated. Wind speeds and wind gust speeds are correlated because wind gust speeds is defined as variation of 9 knots between wind speeds and wind gust speeds (NWS, 2009). Wind speed and wind directions are correlated because once the speed of the wind reaches to 40 mph, all the wind directions are recorded as west or southwest during the 2008-2009 winter season.

The initial model was re-run with three additional interaction variables: wind speed squared, wind gust speed squared, and the product of wind speed and wind gust speed. Table 5.5 shows all the predictor variables in the first run of this model. The methodology of eliminating parameters is same as the previous model: all the parameters with P-values larger than 0.05 will be removed from the model one at a time until all remaining parameters have P-values smaller than 0.05.

Table 5.5 : Predictor Variable Estimate of the Second Order First Model

Predictor Variable	Estimate	P-value
Intercept (β_0)	-5.6342	0.0111
Lighting Condition (β_1)	0.1424	0.8763
Road Condition (β_2)	-3.8405	0.0024
Wind Speed (β_3)	0.3935	0.2806
Wind Gust (β_4)	0.0318	0.9164
Wind Direction Bi (β_5)	-1.6598	0.2825
Wind Speed* Wind Gust (β_6)	0.0147	0.4235
Wind Speed* Wind Speed (β_7)	-0.0125	0.2607
Wind Gust* Wind Gust (β_8)	0.00653	0.4123

The final model running of the second order model is displayed in Table 5.6.

Table 5.6: Variable Estimate of the Second Order Final Model

Predictor Variable	Estimate	P-value
Intercept(β_0)	-4.7962	0.0138
Road Condition(β_1)	-3.0451	0.0015
Wind Speed(β_2)	0.2972	0.0029
Wind Speed* Wind Speed (β_3)	-0.00287	0.0179

The final second order model, shown in Equation 5.3, includes three parameters: road condition, wind speed and wind speed squared. All the estimates have P-values less than 0.05.

$$E\{Y_i\} = \frac{exp^{(-4.7962-3.0451x_1+0.2972x_2-0.00287x_3)}}{1+exp^{(-4.7962-3.0451x_1+0.2972x_2-0.00287x_3)}}$$

Equation 5.3: Multiple Logistic Regression Second Order Model

The Hosmer and Lemeshow goodness-of-fit test was conducted to test the model fit. The Hosmer and Lemeshow goodness-of-fit has a Chi-square value of 5.5714 and P-value of 0.6951. The chi-square value is less than the target X^2 (0.95, 8) value of 15.51 and the P-value is larger than the cutoff of 0.05, so the result of Hosmer and Lemeshow goodness-of-fit indicates that the data fit the model well. The fitted values of the equation are displayed in Table 5.7 and Figure 5.2.

Table 5.7: Relationship between Road Condition, Wind Speeds and Truck Overturning

Wind Speed (X_2)	**Fitted Value when X_1=0 (Dry Road)**	**Fitted Value when X_1=1 (Wet Road)**
0	0.82%	0.04%
5	3.29%	0.16%
10	10.80%	0.57%
15	27.21%	1.75%
20	50.00%	4.54%
25	69.85%	9.93%
30	82.30%	18.12%
35	88.99%	27.79%
40	92.41%	36.70%
45	94.08%	43.07%
50	94.73%	46.10%
55	94.62%	45.59%
60	93.73%	41.55%
65	91.65%	34.32%

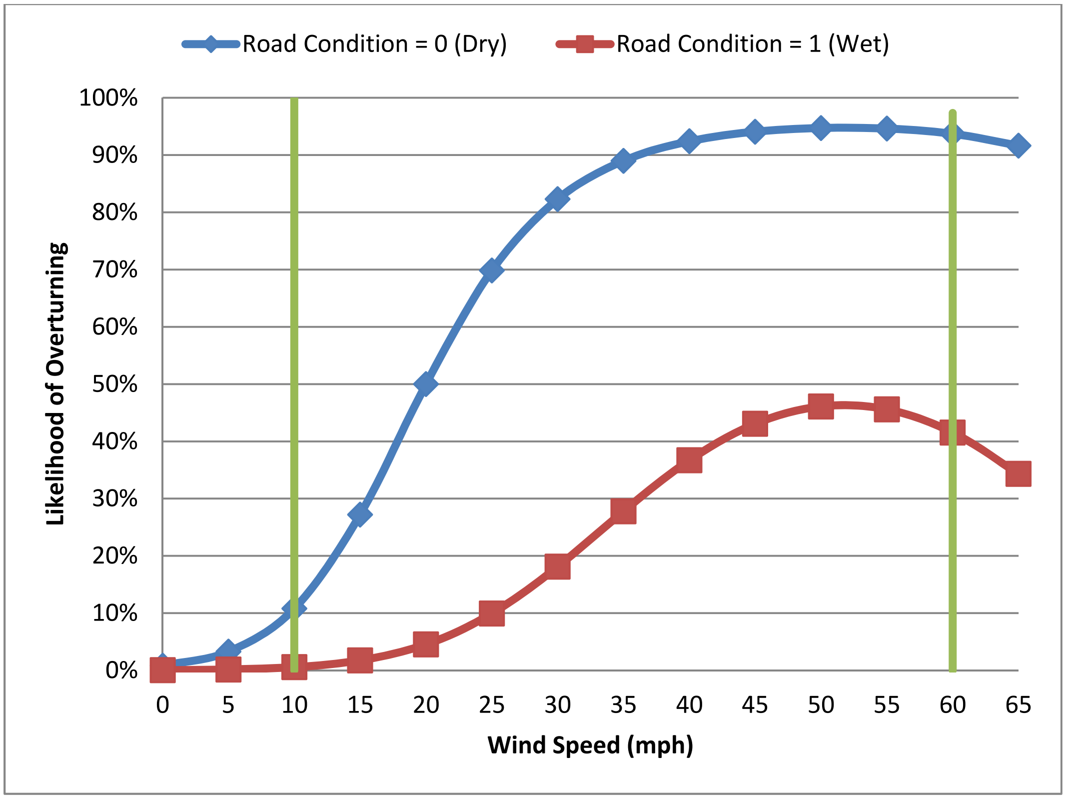


Figure 5.2: Relationship between Wind Gust Speeds and Truck Overturning

As the Figure 5.2 illustrates, the second order model indicate a similar trend as the previous model. Same as the previous model estimates, though the likelihood of overturning of all wind levels are graphed, the main focus is the High Wind Warning System boundary, which lies between wind speeds 10 mph to 60 mph.

There are three differences between the two models. First, the second order model curve indicates a non-linear curve which is steeper than the first order model, whereas the first order model gives out a linear trend line. Second, the second order model indicates that the chances of having overturned crash would lower if the wind speeds pass 50 mph, but the previous model suggests that the chances of overturned crash is higher as the wind speed increases. This feature is likely because when the wind speed is extremely high, the driver may be more cautions and drive defensively. Although the wind speeds beyond 60 mph are not considered in the High Wind Warning System, it is still valuable to investigate the model and likelihood of overturning as more crash data become available. Another difference is that the description of the Intercept (β_0). The previous model indicated that 14.78% of chances of overturned crash when wind speed is zero and road condition is dry. The second order interaction model illustrates the intercept (β_0) better because the chances of having overturned crashes are 0.82% when wind speed is zero and road condition is dry. The difference in the interpretation of intercept has minimal impact on the model because the High Wind Warning System boundary starts at wind speed of 10 mph. Therefore, considering the High Wind Warning System boundary (10 mph to 60 mph) of the two logistic models, the difference is minimal except on the magnitude of likelihood of overturning. The difference in the likelihood of overturning for High Wind Warning System boundary wind speed levels is approximately 10 mph. The second order model is used for the analysis in the High Wind Warning System threshold, since the Hosmer and Lemeshow goodness-of-fit test indicated a better fit than the first order model.

5.2 Wind Speed and Vehicle Speed Relationship Study

The analysis of SAS model in the previous section indicated that the chances of having overturning crashes are significantly lower if the road condition is bad (wet, icy or slick). This seemingly counter intuitive result occurred possibly because the hazardous road conditions are obvious and easy to perceive. The drivers may be more alert and drive slower when they perceive the potential hazards. This section focuses on how observed vehicle speeds changed in high wind conditions compared to normal good weather.

Two Wavetronix Smart Sensors were used in this study to collect traffic volume, vehicle classification and average vehicle speed data. The speed sensor data were combined with the RWIS dataset and the vehicle speeds were classified based on two different wind conditions. One category is the vehicle speeds when wind speeds are above 30 mph and wind gust speeds are above 50 mph; another category is the vehicle speeds when wind speeds are below 10 mph. Ideally, this analysis would only focus on truck speeds rather than on all types of vehicle including passenger cars. However, the data output of the Wavetronix Smart Sensors averaged the vehicle speeds in five minutes intervals. The truck speeds cannot be separated from the averaged vehicle speeds. Table 5.8 presents the vehicle speeds in different wind conditions.

Table 5.8: Vehicle Speed in Different Wind Conditions

Sensor	Category	Average Vehicle Speed(mph)
South Sensor	Wind Speed > 30 Wind Gust >50	69.13
	Wind Speed < 10	73.96
North Sensor	Wind Speed > 30 Wind Gust >50	68.45
	Wind Speed < 10	73.44

The result of this analysis indicated that there were only minimal differences in the two wind condition categories. This result may be caused by the truck not being able to be separated from the dataset because of the five minute bins. Passenger cars are less likely to reduce their speed in high wind conditions.

To continue to research this issue, the bin size on the speed sensors were reduced from five minute intervals to 10 second intervals during the 2009-2010 winter season in an attempt to separate car and truck observations. At this smaller bin size the majority of records would only have one vehicle observation and using the vehicle classification information the observation could be flagged as a truck or car observation. To find the relationship between high wind conditions and the observed individual speeds of the cars and trucks traversing the corridor, data from both the Speed Sensors and RWIS were downloaded. At the ten second bin size, the speed sensors' memory was able to store up to a week of data before the oldest data is overwritten with new data ("first-in" "first-out"). Because of the change to 10 seconds bins it was not able to download a full month of data as previously done. Due to the time consuming nature of downloading data (about 1 hour for a day's data), it was proposed to download two "Good" and three "Bad" days of data within the week of a reported accident. The days were selected by checking the Bordeaux RWIS data to get the representative days. The "Good" day indicates that the average wind speed and gust wind speed are less than 10 mph and 15 mph respectively with no precipitation and dry road conditions for 24 hour period. For the "Bad" days, the average wind speed and gust wind speed are greater than 30 mph and 40 mph respectively with dry road conditions and no precipitation for a period of 4 hours or more.

During each site visit, the sensor clock and alignment were first checked to ensure that data collected from the sensors can be coordinated with each other and with the RWIS data. Two days of data were downloaded from the speed sensors during a site visit on December 22, 2009 as a result of a reported accident which occurred on December 10 and December 12, 2009. The two days were December 16 and 17 representing one "bad" and "good" day respectively. The reason why only two days were able to be downloaded was that, in the course of downloading the data from the speed sensor, the older data (from December 15 to December 22) were overwritten.

To find the speeds of cars and trucks with respect to the wind speed event, data from both the speed sensor and RWIS for the two days were merged. The time periods, wind speed and road condition were characterized as; from 6am – 6pm was termed as daytime and a value of 1 was assigned, and from 6pm – 6am a value of 0 was assigned and termed as nighttime. Dry road condition was assigned a value of 1 whereas wet, icy or slick a value of 0. Wind speed of 10mph or less was given a value of 0, and wind speed of 30mph or greater a value of 1. The eight categories of vehicles from the speed sensor were used to differentiate between the trucks and cars. The categories of C1 and C2 (vehicles 20 feet or less) represented cars (small vehicles) whereas categories C3 and above were classified as trucks (vehicles greater than 20 feet in length).

Table 5.9 below presents the combined average vehicle speed and standard deviation for cars and trucks under different wind conditions.

Table 5.9: Vehicle Speed in Different Wind Conditions

Vehicle Type	Category	Average Vehicle Speed (mph)	Standard Deviation
Cars	Wind Speed <=10mph	76.65	4.86
	Wind Speed >=30mph	77.09	7.03
Trucks	Wind Speed <= 10mph	69.75	8.42
	Wind Speed >=30mph	67.72	8.63

The results of this analysis indicated minimal differences in the two wind condition categories for each vehicle type. As can be seen from the table, passenger cars have higher average speed even during high wind conditions whereas trucks reduce their speeds slightly during high wind condition.

5.2.1 Statistical Modeling Results

The combined dataset from the 10 second speed sensor and RWIS data were used for the statistical analysis. The statistical software used for this analysis is the version 9.2 of SAS. The first step was to change all the variables into a binary response variable. For instance, a value of 0 for wind speeds of 10mph or less (low wind speed) and a value of 1 for wind speeds greater than 30mph (high wind speed). The modeling only considered dry road conditions to remove the speed effects due to wet or icy road conditions from the model. A 95% confidence interval used in the analysis, and all the parameters with P-value larger than 0.05 were not considered significant. The null hypothesis for this statistical modeling was to test whether the car or truck speeds have the same speeds during both low and high wind events. The interactions between low and high wind events for car and truck speeds were also included for the hypothesis testing.

Results from the car model indicated a P-value of 0.1750 and 0.4371 for low and high wind conditions respectively. This shows that passenger cars drive at the same speeds during low and high wind events. For the interaction between low and high winds, it shows a P-value of 0.5783 greater than 0.05, which means that car speeds are the same during both low and high wind conditions. This model confirms the results obtained in Table 5.9. For the truck model, a P-value of 0.0784 and 0.1018 was obtained for the low and high wind conditions respectively. This indicates that truck speeds are the same during low and high wind conditions. Although the P-value is greater than 0.05 for the individual wind conditions, the interaction between low and high wind conditions shows a P-value of 0.0359 which is less than the 0.05 was obtained. This indicates that the trucks speeds are not the same during both low and high wind conditions. The complete results from the analysis are found in Appendix D.

5.3 Truck Crash and Vehicle Weight Relationship Study

The Large Truck Crash Causation Study suggested that vehicle factors are another critical reason for large truck crashes. This conclusion is confirmed for this study by the fact that 90% of the vehicle crashes between MP 69.50 and 71.50 are truck crashes. The typical feature that trucks are more likely to have crashes than small cars in the Bordeaux area indicates that vehicle factors play a role in the trucks overturning in the hazardous location.

In a previous study of Wyoming truck crashes, the research found that the large trucks are more vulnerable than small vehicles in high wind conditions because large trucks have higher profile-weight ratio than small vehicles

(Liesman, 2005). In addition, it is common sense that high profile trucks are unstable since their center of gravity points are higher. Therefore, the truck dimensions and weight are vehicle factors that are analyzed in this research.

5.3.1 Methodology

The methodology used in the weight analysis is similar to the previous wind relationship study except that the weight of truck is taken as a separate parameter. In the previous model, the analysis dataset includes all truck crashes regardless of the weight of the truck. To examine how weight of the truck can affect with the logistic regression model, the truck crashes dataset was split into three parts:

- Truck weight identified as empty or lightly loaded when the crash occurred.
- Truck weight identified as weighted when the crash occurred.
- Truck weight identified as unknown when crash occurred.

Since not all the crash reports documented the weight of the trucks, the third category of unknown weight is included. The second order interaction model was re-run with a new binary parameter of weight (weight equals to 0 for empty or lightly loaded truck and equals to 1 for loaded truck). Since not all the overturned crashes have weight data, a subset of the previous data was formed for weight analysis. Table 5.10 shows the number of overturned crashes in different categories.

Table 5.10: Weight Classification of the Overturned Crashes

Weight Classification	Number of Crashes
Empty	12
Lightly Loaded	17
Loaded	16
Total	45

The result of the model did not perform well because the binary weight parameter was not signification in the model. This is largely triggered by the small number of crashes in each category. The alternative method is to split the dataset into different weight categories and re-run the model. By comparing the fitted value of same predictor variable of wind speed, the role of weight in the high wind warning system can be revealed.

5.3.2 Model Results

Ideally, the result of the weight analysis would compare the two weight categories of "Empty or Lightly Loaded" and "Loaded". However, since there are only 16 loaded crashes, the wind speed was not significant in the small dataset model. So the two categories were selected as "Empty or Lightly Loaded" and "Composite", which contain all the crashes data regardless of weight parameter.

After splitting the dataset, logistic regression models are built separately based on two different weight categories. The selection and decision methodology of model fit is similar to the first multiple logistic regression model. All the estimates in the final model need to have a P-value less than 0.1 and the Hosmer and Lemeshow goodness-of-fit test need to be conducted to test the fitness of the model. This analysis used a P-value of 0.1 indicating a lower confidence threshold because of the relatively less number of crashes in the dataset.

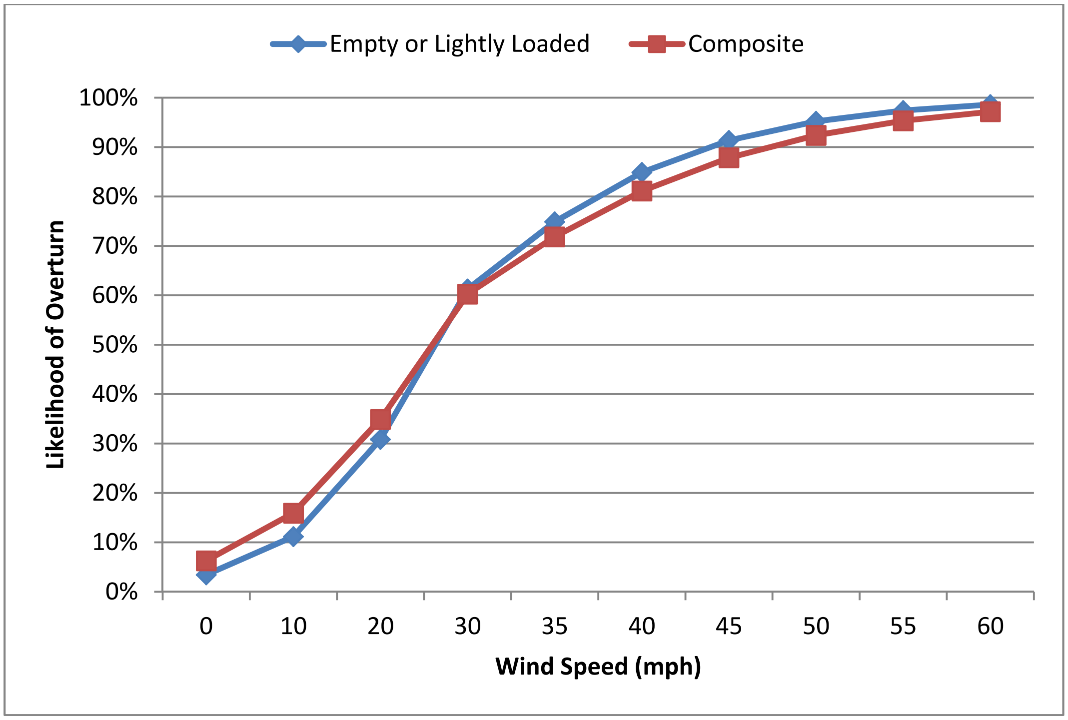


Figure 5.3: Weight Analysis Result

The result of the weight analysis indicates that weight did play a role in the overturn model. The chances of empty or lightly loaded category overturn within the wind speed boundary of 35 mph to 60 mph, is about 5% higher than the composite counterpart. At the 30mph wind speed limit, both the composite and the empty or lightly loaded category have equal chance of overturn. If the data can be split with a category of loaded truck, the difference is expected to be more dramatic.

5.4 Nevada Wind Speed Model Estimation

In Chapter 2, the Nevada Wind Speed Overturning Model and the Wind Speed Sliding Model was introduced. These two models use the vehicle weight and vehicle dimension parameters to estimate the overturning and sliding risks relative to wind speeds. Table 5.11 shows the FHWA vehicle weight and vehicle classification on I-25 in a single day using data from a permanent weigh-in motion-station located north of Cheyenne (VTRIS, 2009). Of the 579 trucks recorded, class 9 single trailer 5-axles makes about 70 percent of the truck volume.

Table 5.11: FHWA Weigh-in-Motion Data on I-25

FHWA Vehicle Classifications	Class	Average Number	Average Gross Weight (lbs)	Empty/ Lightly Loaded (lbs)	Empty / Lightly Loaded (%)
Single Unit 2-axle	5	47	18917	9900	8.51
Single Unit 3-axle	6	13	28149	16500	15.38
Single Unit 4-axle	7	1	53011	19800	0.00
Single Trailer 4-axles or less	8	15	34335	27500	33.33
Single Trailer 5-axles	9	406	55455	30800	7.88
Single Trailer 6-axles or less	10	37	63815	34100	10.81
Multi- Trailer 5-axles or less	11	5	52789	37400	20.00
Multi- Trailer 6-axles or less	12	8	56823	41800	12.50
Multi- Trailer 7-axles or less	13	47	71940	46200	23.40
Total	-	579	-	-	-

Of the 140 crashes in this study, the two major types of vehicle, which makes up approximately 95% of the dataset, are high profile truck and pick-up with single trailer. In order to fit the Nevada Model, the Single Trailer 5-axles truck and motor home pick-up trailer are selected and all the weight and dimension parameters are imported to the model (AASHTO, 2004). Table 5.12 is the weight and dimension parameters of the two vehicle types.

Table 5.12: Weight and Dimension Parameters of Single Trailer 5-axles Truck and Motor Home Pick-up Trailer

Dimension	Single Trailer 5-axles	Pick-up Motor Home Trailer
Width of vehicle's base	6 ft	6 ft
Weight of the vehicle	55,000 lbs	19,000 lbs
Length of the vehicle	73.5 ft	30 ft
Height of the vehicle	14 ft	10 ft
Diameter of the wheel	4 ft	1.5 ft

The next step is to fit the Nevada Wind Speed Overturning Model and the Wind Speed Sliding Model using the estimated parameters. Table 5.13 displays the two models estimation. Partial loaded and empty Single Trailer 5-axles are using truck weight of 42,000 lbs and 30,000 lbs, respectively. The partial loaded and empty values were from the Cheyenne weigh-in-motion station summary.

Table 5.13: Nevada Model Estimation

Wind Speed Cutoff (mph)	Single Trailer 5-axles			Pick-up Trailer Loaded
	Average Loaded	Partial Loaded	Empty	
Sliding Model	43	38	32	24
Overturning Model	84	73	62	49
Historical Overturned Crashes Average	51	47	38	54

The result of the Nevada Model estimation suggests that the Nevada Overturning Model for the Single Trailer 5-axles is not conservative enough, because the average wind speeds of historical overturned crashes are 10 mph higher than the values in the Sliding Model and much less than the values in the Overturning Model. This difference is possible because there might be wind speed differences between the location where crash occurred and the location where RWIS is located. The cutoff selection in the later chapter would use the findings in the Nevada Model as the secondary factors to propose optimal thresholds for the High Wind Warning System.

5.5 HOBO Wind Speed Estimation

The next step was to determine whether the wind speeds experienced by the trucks at the roadway level is significantly different than the measured wind speeds at the RWIS tower, which is installed near the top of an adjacent hillside. To find the correlation of wind speed and wind gust speed between the HOBO Weather Equipment, which was installed adjacent to the roadway, and the RWIS, average wind and wind gust speed data were downloaded from both the portable HOBO Data logger and the RWIS during the winter period from March 12 to May 25, 2010. The HOBO weather station was situated about 40 feet from the roadway edge of the south side of the interchange bridge in the southbound direction and the RWIS Station situated on a hill further away from the roadway. The two stations are located about 200 yards apart.

The data from both the portable HOBO Weather station was compared to the Permanent RWIS station; the differences between them were computed to see whether there was any correlation. A positive difference indicates that data from the permanent RWIS station is greater than that of the portable HOBO station and vice versa. It was observed from the downloaded data that, there were some zero readings from the portable HOBO station whereas the permanent RWIS Station have some readings(less than 10 mph) during very low wind speed events and vice versa. The reason could be the different location of the respective weather stations. It was observed from the HOBO data that on May 18, a wind speed of 105 mph was recorded, whereas a wind speed of 19 mph was recorded from the permanent RWIS on that same day. Results showed that the permanent RWIS recorded higher wind speeds for most of the days as compared to the HOBO stations.

Figure 5.4 shows the wind speed difference between the permanent RWIS and the HOBO stations against the RWIS wind speed. This showed a correlation of data between the two weather stations. Using a statistical model fitting the coefficient of determination, R^2-value of 0.2062 was obtained. This indicates that about 21% of the total variation in the wind speed difference between the permanent and the HOBO station accounts for a linear relationship of the RWIS wind speed. The figure indicates that there is a relationship between the two wind speeds and that the RWIS speeds are typically higher than the roadway wind speeds and that this difference increases as the wind speeds increase.

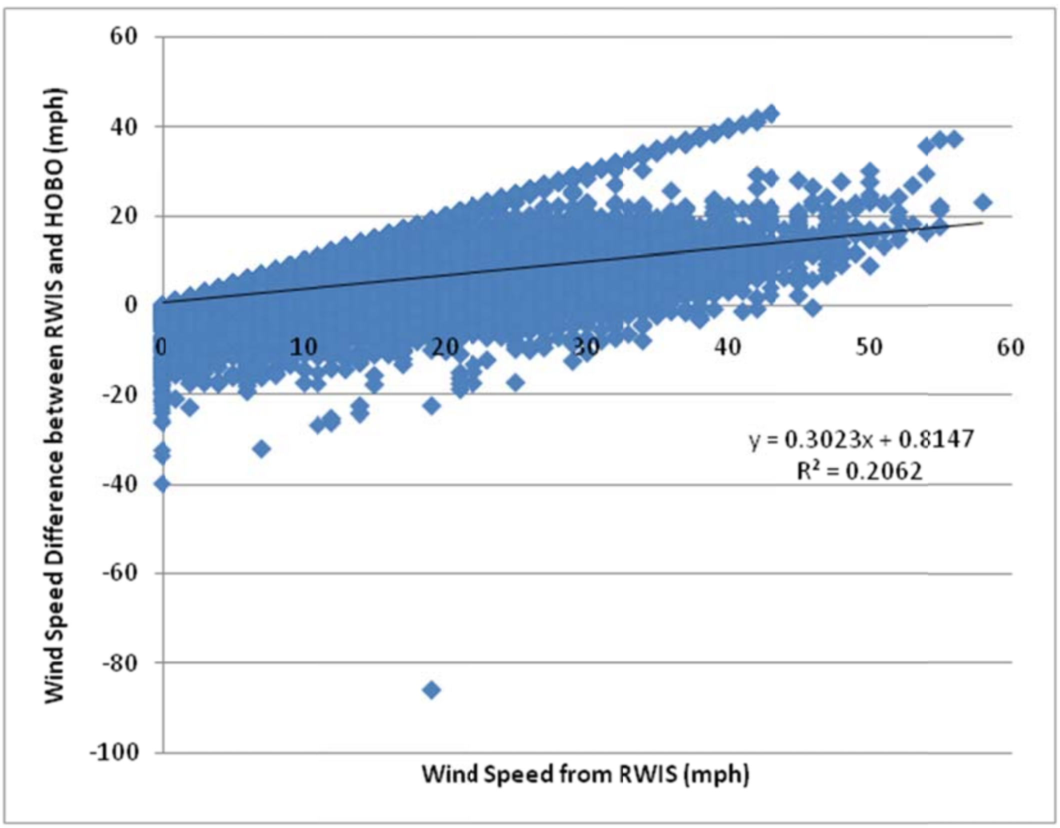


Figure 5.4: Relationship between Wind Speed difference between RWIS and HOBO against RWIS Wind Speeds

The conclusion that the measured wind speeds are higher at the RWIS station than at the road surface means that the differences between the Nevada model and the crash experience at Bordeaux cannot be accounted for as originally theorized (see previous section).

CHAPTER 6:

HIGH WIND WARNING SYSTEM AT BORDEAUX

In Chapter 2, high wind warning systems implemented by other states such as Nevada, Montana and Idaho were introduced. Some of the common features of these high wind warning systems were RWIS and DMS. The RWIS is used in collecting the real-time weather data, whereas the DMS is used in distributing the different warning messages to the drivers. However, these systems did not use an analytic based decision methodology to correlate the hazardous high wind conditions with the warning messages on the DMS. This chapter discusses the proposed high wind warning system at Bordeaux and offers suggestions to WYDOT for operating the system based on the data analysis from the previous chapter.

6.1 Technology Available for the High Wind Warning System

Besides RWIS and DMS, Highway Advisor Radio (HAR), Weigh-in-Motion (WIM) and CB wizards can also be used in the high wind warning system. The static warning sign of "High Wind Area" and wind socks are currently used at Bordeaux area to remind travelers of the potential hazardous wind. However, unlike a snow storm or an icy road, potential high wind speeds and wind gusts are not usually perceived as a threat by drivers (Young & Liesman, 2007). Therefore, the High Wind Warning System needs to utilize technology to adequately warn drivers of the potential hazards.

6.1.1 Dynamic Message Sign

Dynamic Message Sign (DMS), which displays words, numbers or symbols on LCD panels along the roadway that can be changed by command remotely, is an effective way to distribute real-time warning messages to drivers. Almost all the previously implemented High Wind Warning Systems discussed earlier used DMS to display the warning messages. A sample of roadside DMS is shown in Figure 6.1.

Figure 6.1: Roadside DMS

There are four existing DMSs along I-25:

- North Bound, Milepost 1.25 near the state line
- North Bound, Milepost 15.4 near Cheyenne
- South Bound, Milepost 77.8 near Wheatland
- South Bound, Milepost 184.15 near Casper

At the Bordeaux Area, it is suggested that WYDOT use at least two roadside DMSs, one in each direction, to inform the driver potential high wind conditions of the hazardous segment. The suggested DMS signs can be placed near Chugwater to the south and near Wheatland to the north (using the existing sign at Wheatland). The advantage of this placement is that once the driver is informed of hazardous conditions on the DMS, they can make a decision to exit the roadway at these towns to wait for the weather conditions to improve. Two new DMS adjacent to the Bordeaux interchange are planned for installation. These DMS will be used to direct heavy vehicles to the exit ramps to avoid the interchange bridge, where the wind effects can be greater. While these signs will help trucks avoid the bridge section many of the crashes occur before and after the interchange ramps. It is possible that there could be a safety advantage for drivers to utilize the Bordeaux interchange off-ramps to avoid the I-25 Bridge over the surface road, where the wind strength at the road surface is at its highest. Crash history indicated that most of the crashes were occurring before trucks have an opportunity to exit.

The DMS's near Cheyenne and Casper should also be used to distribute high wind warning messages since these locations provide drivers with more choices for alternative routes that avoid the Bordeaux area.

6.1.2 Highway Advisory Radio

Highway Advisory Radio (HAR) is another effective way to disseminate potential warnings to the driver. HAR can cover a much broader area than DMS does. It is suggested that WYDOT use HAR to cover the section between Chugwater to the south and Wheatland to the north to provide the drivers with the option of staying in those towns to wait over the hazardous weather conditions.

The three existing HAR on I-25 covers areas of Cheyenne, Wheatland and Casper, and can be used for distributing warning messages to the drivers. However, it is also important to point out that AM Radio is losing popularity and some new car models are not equipped with AM radio. HAR has the disadvantage in that it requires action from the drivers in order to receive the information.

6.1.3 CB Wizard Alert System

The CB Wizard Alert System was designed and patented by Highway Technologies Inc., which provides truck drivers with warning of upcoming delays or incidents on the road to enable them to stop safely. The CB Wizard unit transmits one of three pre-recorded alert messages over the CB channel (usually channel 19) to the drivers every 30, 60 or 90 seconds. A study conducted by the Iowa State University indicated that sixty-three percent of the truck drivers have positive opinion on the CB Wizard (Tom, 2000). Figure 6.2 is an example of on board CB Wizard Alert System.

Figure 6.2: CB Wizard Alert System on Board

The placement strategy of CB Wizard system is similar to the HAR radio, which can be placed either near the hazardous location to get the most accurate broadcast or covering a broader segment from Chugwater to Wheatland. One issue with the CB wizard system is that the off the shelf technology does not allow for the system to be controlled remotely. Given the remote location of the project site this would be necessary in advance to the system to be useful. Currently WYDOT is working to modify a CB wizard to see if remote functionally is possible.

6.1.4 WYDOT Travel Information Service

To facilitate drivers in getting the most accurate road weather information, WYDOT provides the Travel Information Service to the public. This service can be accessed by checking the WYDOT website (www.wyoroad.info) or by a phone using either the 1-888-WYO-ROAD (1-888-996-7623) or 511 numbers. Getting the real time road weather information would help truck driver make decisions both prior to their trip and on the road. Any warnings and closures that become part of the High Wind Warning System would be made available on the existing traveler information system.

6.1.5 Weigh in Motion System

Weigh-in-motion (WIM) devices are designed to record truck axle weights and gross weights as they pass by a sensor. Unlike the static weigh stations, the WIM system does not require the truck to stop, which makes the system much more efficient to use. As discussed in the previous chapter, the empty weight or lightly loaded trucks are more vulnerable to the high wind than the fully loaded counterparts. So the WIM can be introduced to the high wind warning system to identify the high risk vehicles.

Use of WIM technology could be developed at the project site to identify and possibly prohibit travel of high risk vehicles. It is suggested that WYDOT use WIM system accompanied with small, roadside DMSs. Once the WIM detect the risk vehicle under certain weather circumstance, the DMS signs could distribute vehicle specific warning messages to the driver.

6.1.6 Over Height Vehicle Detection System

The high profile vehicle, especially those empty one, has higher center of gravity therefore are more likely to overturn. The Over Height Vehicle Detection System can detect the high profile vehicle and distribute warning message to the driver. The Over Height Vehicle Detection System is widely used near bridges and tunnels. The standard component of the system includes detectors, warning signs, alarms and mounting poles. This technology could be used along with WIM technology to determine height to weight factors and small roadside DMSs to provide vehicle specific warning messages to the driver.

6.2 Operational Levels and Equipment Involved

The main objective of this research is to develop a high wind warning system that can be used by WYDOT to improve the truck safety in high wind conditions near Bordeaux area. A previous research effort in the University of Wyoming suggested that WYDOT consider four operational levels based on their increasing use of technology to operate the system (Young & Liesman, 2007). This paper will use three operational levels to manage the high wind warning system based on the level of restrictions.

- Level 1: Wind speeds and road surface variable thresholds for advisory warning messages of DMSs.
- Level 2: Wind speed, road surface variable, vehicle type and vehicle weight thresholds to determine road closure for all high-profile, light-weight vehicles.
- Level 3: Wind speed, road surface variable and vehicle type variable thresholds to determine road closure for all high-profile vehicles.

Level 1 uses the basic technology of RWIS, DMS, CB Wizard, Traveler Information System and HAR. RWIS is used to collect and record the weather data such as wind speed, wind gust speed, wind directions and road surface conditions; the remaining technology is used to broadcast the warning messages to travelers.

The determination of threshold conditions to trigger warning messages needs to consider many factors. On one hand, the wind speeds cutoff cannot be too high otherwise the warning may not adequately warn and protect travelers from potential hazards. On the other hand, the wind speed cutoff cannot be too conservative or the warning messages will be triggered too frequently. This may lead to the message being disregarded. The average wind speeds when the 140 crashes occurred is 46 mph. If 46 mph is chosen as the advisory warning cutoff, less than half of the crashes (i.e. 56 out of 140 crashes) would have occurred when the warning messages were not triggered. Therefore, to be conservative, a lower 30 mph is recommended as the trigger of the advisory warning message. 30 mph is the 12.14% crash likelihood occurrence during that wind speed event, which means that 87.86% of the historical crashes would not have occurred when the hazard system was active. Figure 6.3 below shows the cumulative crash frequency of wind speed when crash occurred. Table 6.1 shows the data in tabular format.

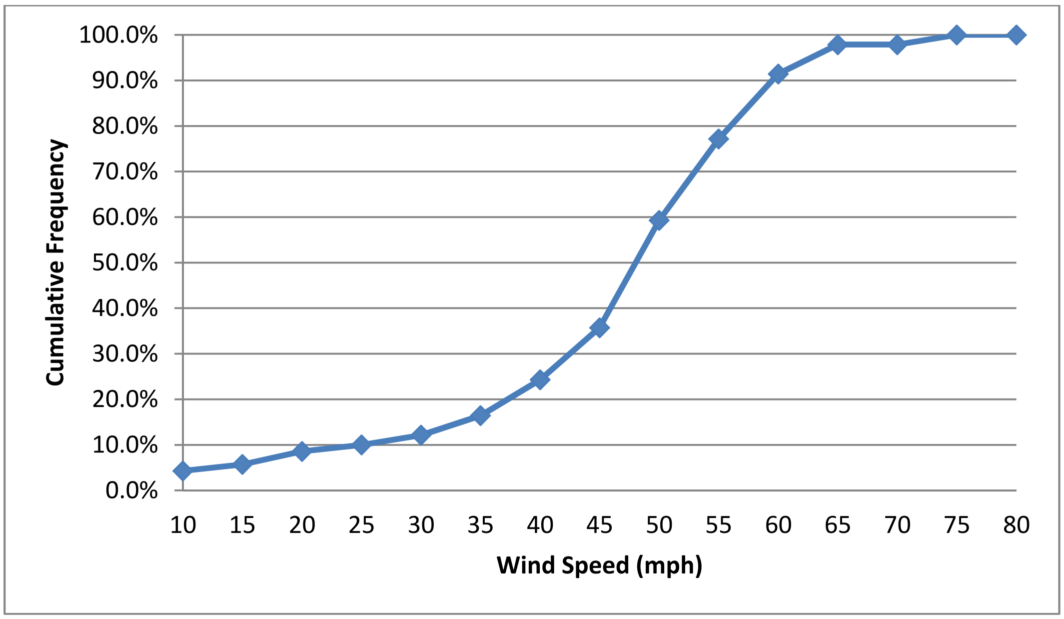


Figure 6.3: Cumulative Crash Frequency of Wind Speed When Crash Occurred

Table 6.1: The Cumulative Frequency of Wind Speeds During Crash Period from 1994 – 2010.

Wind Speed (mph)	Wind Speed Frequency	Percent	Cumulative Frequency
<=10	6	4.29%	4.29%
> 10 and <=15	2	1.43%	5.71%
> 15 and <=20	4	2.86%	8.57%
> 20 and <=25	2	1.43%	10.00%
> 25 and <=30	3	2.14%	12.14%
> 30 and <=35	6	4.29%	16.43%
> 35 and <=40	11	7.86%	24.29%

> 40 and <=45	16	11.43%	35.71%
> 45 and <=50	33	23.57%	59.29%
> 50 and <=55	25	17.86%	77.14%
> 55 and <=60	20	14.29%	91.43%
> 60 and <=65	9	6.43%	97.86%
> 65 and <=70	0	0.00%	97.86%
> 70 and <=75	3	2.14%	100.00%
> 75 and <=80	0	0.00%	100.00%
Total	140	100.00%	

The models discussed in Chapter 5 indicated that wind speeds were better than wind gust speeds at predicting wind hazards in the Bordeaux area. Previous work in other corridors around Wyoming indicated the opposite suggesting that the appropriate wind variable for monitoring is likely specific to the site (Young and Liesman, 2007). Since there may be an interest to view the Bordeaux crashes from the wind gust speed context the same crashes shown in Figure 6.3 are shown again in Figure 6.4 using wind gust speed as the x-axis.

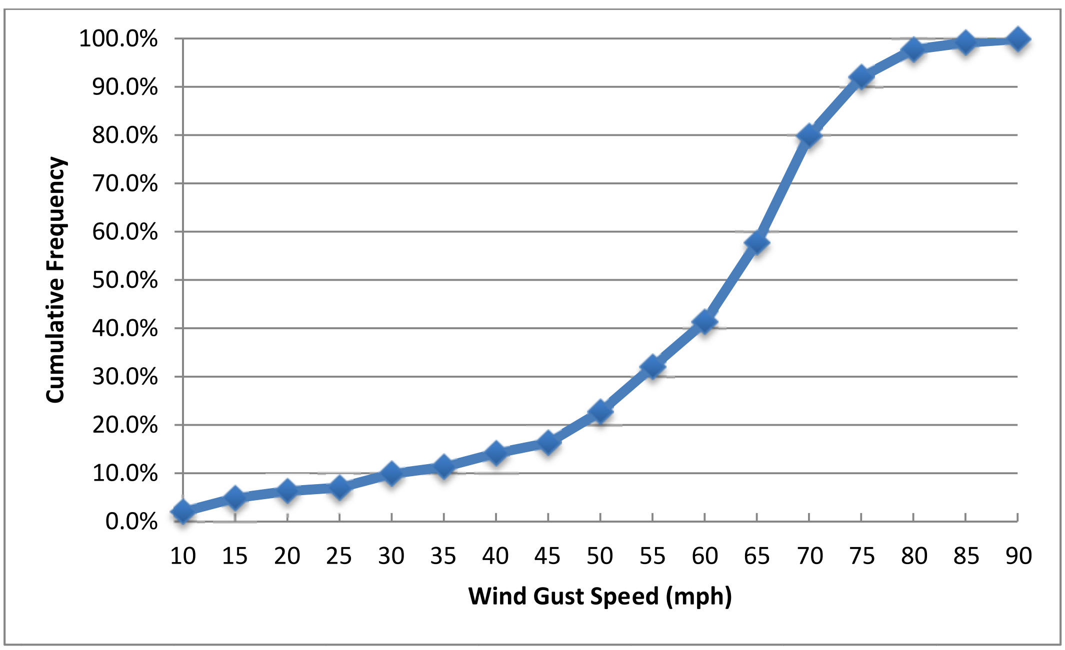


Figure 6.4: Cumulative Crash Frequency of Wind Gust Speed When Crash Occurred

In the second order model, the 30 mph threshold relates to a likelihood of 82.30% overturning in dry road condition. To be conservative, all the suggested thresholds of wind speed are based on the dry road condition, because the model and historical crash data suggests that larger profile vehicles are less likely to have overturned crashes in wet road condition. 30 mph approximately equals to the cutoff value for the Nevada Sliding Model for the empty truck, which is 32 mph.

To verify the frequency of advisory wind warning triggered, the wind speeds frequency during the 2009 to 2010 winter season (November 1^{st}, 2009 to April 30^{th}, 2010) is displayed in Table 6.2. The RWIS tower collects weather information at 5-minutes interval, and there were 51,651 data records collected for the 6-month winter season when high winds are more frequent. If the advisory wind warning cutoff was set at 30 mph, 91.09% of the time would be below this cutoff and 8.91% of the time the warning signs would be activated. This equates to approximately 384 hours of warning message operation. The low value of 8.91% ensures that the warning message does not activate too frequently.

Table 6.2: Wind Speeds Frequency during 2009 to 2010 Winter Season

Wind Speeds (mph)	Wind Speed Frequency	Percent	Cumulative
<= 10	16240	31.4418%	31.44% (<=10)
>= 10 and <= 20	18059	34.9635%	66.41% (<=20)
>= 20 and <= 30	12749	24.6830%	91.09% (<=30)
>= 30 and <= 35	2999	5.8063%	96.89% (<=35)
>= 35 and <= 40	1137	2.2013%	99.10% (<=40)
>= 40 and <= 45	372	0.7202%	99.82% (<=45)
>= 45 and <= 50	79	0.1529%	99.97% (<=50)
>= 50 and <= 55	11	0.0213%	99.99% (<=55)
>= 55 and <= 60	5	0.0097%	100% (<=60)

>= 60 and <= 65	0	0.0000%	100% (<=65)
Total	51,651	100%	-

Level 2 uses the same equipment as Level 1 except adds height detection devices and weigh-in-motion technology. As discussed earlier, low weight or empty vehicles are more vulnerable to the high wind conditions than fully loaded vehicles. Height detection devices would recognize high profile vehicle and weigh-in-motion system is used to estimate lower weight vehicles on the road and transmit warning messages, or even stop them from entering the hazardous location.

The average wind speed of the historical overturned crashes for the empty trucks is 38 mph. It is suggested that WYDOT use a wind speed cutoff of 40 mph as the threshold for the warning messages or road closure for the high profile, light weight trucks. In Table 6.2, the operational time for Level 2 is about 0.90%, which equates to 39 hours of operation. As an interim measure before WIM and height detection is installed the Level 2 threshold can be defined as the point where the “No Light Trailers” advisory is posted.

Level 3 uses the same technology of Level 1 with the possible addition of height detection and weigh-in-motion in available. Of the 140 crashes, 71 (51%) of them occurred on the same day as another crash. The repeat truck crashes on the same day indicate that the weather is not suitable for large truck driving on these days. The average wind speed when these 71 crashes happened is 51 mph, which is higher than the average value of 140 crashes of 46 mph. Using the same methodology in the Level 1, 15th percentile of wind speed for the 71 crashes is 42 mph. It is suggested that WYDOT use wind speed cutoff 45 mph as the threshold to close corridor to all vehicles classified as large trucks. According to Table 6.2, the frequency of wind speeds above 45 mph is 0.18%. This equates to approximately 8 hours of road closure for all high profile vehicles. This recommendation for road closure to trucks is more restrictive than the current policy of posting “No Light Trailers” where the definition of a “Light Trailer” is subjective. Identifying a heavy vehicle is more enforceable than identifying a light trailer, which typically can only be done after the fact.

In Chapter 2, a relationship between accident driving speed and wind speed was introduced by studies conducted by Chen and Cai. They concluded that accident driving speed (i.e. safe driving speed) decreases with the increase in wind speeds. This relationship can be seen in Figure 2.4. From the graph, it can be deduced the 75mph accident driving speed corresponds to approximately a 36 mph wind speed. With respect to the wind speed thresholds recommended in the previous sections, a reduction in the accident driving speed below 75mph is not needed for wind speeds below 36 mph. Thus the 36 mph wind speed from this model falls within the wind speed threshold of 30 mph and 45 mph recommended to trigger the advisory warning message and for the road closure to all high profile vehicles respectively.

The threshold selected in this phase of study considers the second order model, the historical truck overturning data, the wind frequency in winter and the Nevada model. WYDOT could refine the threshold values of different levels during the system operation.

6.3 Improve Truck Stability in High Wind Conditions

There are research studies available in recent years dealing with improving truck rollover stability. The approaches for the improving of rollover stability include: Driver Training, Electronic Stability Aids, Improve Cargo Tank Design and Improve Highway Design (Pape, Mcmilan, & Greenberg, 2008).

Driver Training is believed to be one of the most effective way to improve truck rollover safety, because driver error account for about 75 percent of all rollovers. In the case at Bordeaux, it is crucial to communicate the potential high wind hazards to the driver inside the vehicle and let the driver be fully aware the severity of hazardous wind. High wind warning signs, DMS, CB Wizard and HAR are effective way to disseminate warning messages.

Electronic Stability Aids are popular among truck users because of its effectiveness and low cost. The Electronic Stability Aids slow the vehicle when it is in danger of rollover as a result of high speed. This technology may not be effective at Bordeaux because the first harmful reason of rollover is high wind but not high speed of the vehicle.

Improving cargo tank design is another effective way to improve truck stability, since the likelihood of vehicle rollover depends on the height of its center of gravity, track width and the lateral force on the tractor (Pape, Mcmilan, & Greenberg, 2008). The rollover threshold equals approximately to the ratio of half track width to the height of the center of gravity. So it is always better to have the tank loaded than empty or lightly loaded. To summarize, the following suggestions can help the truck drivers to improving safety in high wind conditions:

- Plan the trip ahead, try to avoid severe weather condition if possible (high wind, icy road, fog and night).
- Be alert if a reported wind speed is above 40 mph or a wind gust speed is above 50 mph.
- Slow down during wind events over 35mph.
- Avoid driving empty or light weighted truck in high wind conditions.
- Use the off-ramp and on-ramp to avoid the hazardous interchange bridges.

6.4 Survey of Trucking Companies

Further to this research effort to develop a high wind warning system at Bordeaux (~ Milepost 70.0) to address the safety concerns of overturning truck crashes due to the high wind, the research team undertook a trucker survey for trucking companies and drivers who frequent the corridor. The purpose of the survey was to collect information from the trucking companies and drivers about what type of information they would like to see displaced on High Wind Warnings and how they would like to receive that information.

6.4.1 Survey Description

The survey looked for feedback at two main areas of information: High Wind Warning Systems and High Wind Hazards. For the High Wind Warning Systems, the research team was looking for feedback on the type of information preferable to receive by the trucking companies and drivers; when and where that information is most useful. Some of the questions found in the High Wind Warning System Survey include:

- What type of information do you wish to receive from a high wind warning system?
- How is the best way to receive high wind information?
- At what point in the trip is it most useful to receive high wind information?

The High Wind Hazards Survey looked at the dynamics of truck crashes that occur due to high winds. The intended outcome from this survey is to develop a risk model that will help further define the relationship between wind speeds, truck configurations and truck weight. Some of the questions found in the High Wind Hazard Survey include:

- At what wind threshold do you currently view high winds as being a hazardous situation?
- Have you previously been involved in a high wind crash at Bordeaux or elsewhere? If so:
    - At what wind speed would you estimate the conditions?
    - At what speed would you estimate you were traveling at?
    - At what weight would you estimate your truck to be at?
    - What truck configuration did you have?

- Have you ever used defensive methods to attempt to reduce high wind hazards? If so, what methods have you used?

The complete surveys can be found in the Appendix E.

6.4.2 Survey Outreach Efforts

The research team contacted the Wyoming Trucking Association through an email message sent on February 5, 2010 in an effort to get information/feedback from truckers who frequent the project area on their preference for when, where and what type of information they would like to receive from the high wind warning systems. A news item was prepared about the survey effort and sent to Wyoming Trucking Association members in the February 2010 General Bulletin. A presentation about the effort was also made at the Wyoming Trucking Association's Council of Safety Supervisors Meeting on February 19, 2010.

On March 28, 2010 the research team undertook a field survey along the I-25 corridor to distribute 70 flyers and questionnaires and also conducted interviews with truck drivers. The flyers and questionnaires were sent to the truck rest stops along I-25 starting from the Cheyenne truck stop where some of the flyers and questionnaires were given to the drivers whilst some were interviewed. From the Cheyenne truck rest stop, the research team traveled to Chugwater rest stop to distribute flyers and questionnaires. From there, the team traveled to Douglas where truck drivers were interviewed and some of the flyers and questionnaires were distributed. The final stop was at Casper Flying J Travel Plaza which serves as truck rest stop, shop and a gas station. At this rest stop, some of the flyers and questionnaires were left behind and interviews were conducted with truck drivers.

Apart from the field survey, letters were sent to some trucking companies known to frequent the corridor and some of these trucking companies have previously been involved in high wind accidents in the project area. On May 10 2010, 37 letters were sent to these trucking companies asking them to complete an survey online.

6.4.3 Survey Results

Even given the extensive outreach effort described in the previous section, only four responses were received from the trucking companies. Two were received online and two from the distributed questionnaires.

6.4.4 Survey Conclusions

From the four responses, all the drivers indicated they had traveled the Bordeaux project area one way or the other with frequency ranging from daily to less than once per month. Three of the four (75%) drivers who traveled the Bordeaux area have experienced the high wind conditions before. Most of these drivers usually undertake long haul trips. With respect to the medium through which drivers wish information sent, 100% of the drivers favored the use of the Roadside Dynamic Message Signs above all the media. Twenty-five percent prefer the use of the Highway Advisory Radio, Radio Broadcast and the 511 or 1-888-WYOROAD (1-888-996-7623) Phone Service numbers. The drivers interviewed see as important the inclusion of additional information sources such as the CB Alert System and

Additional Dynamic Message Signs. The CB Alert System (also known as CB Wizards) broadcast warning messages over CB Channel 19 at 30, 60 or 90-second intervals. When activated the CB system select one of three prerecorded warning messages based on three alert levels for high wind conditions. The device monitors CB transmissions and only broadcasts during lulls between transmissions.

With respect to the locations at which to place the warning systems, 75% of the drivers preferred the High Wind Warning System to be positioned at the closest towns to the project area (i.e. Wheatland to the north and Chugwater to the south). Fifty percent of the drivers preferred the signs to be located about half a mile prior to the hazard area on both sides. Others (about 50%) preferred the system to be positioned in the major cities prior to the hazard area (i.e. Casper in the north and Cheyenne in the south). The type of actions that most drivers interviewed would like to take when the high wind hazard warning information is triggered, is to reduce their speed and/or stop and wait for the high wind hazard to subside. Fifty percent of the drivers said they would prefer to choose a different route to avoid the hazard. Due to this, 25% of the respondents prefer the hazard signs to be placed at the two interchange bridges prior to the hazard area so that they could turn back anytime there is a high wind condition.

The specific type of high wind warning information that 100% of respondents' preferred to be displayed regarding high wind conditions are: Average Wind Speeds, Wind Gust Speeds, Wind Direction, Wind Forecasts and Road Surface Conditions. Out of these, about 25% of drivers think that wind speed, wind gust speed and wind forecasts are the most important information they would wish to be displayed on the DMS during high wind hazard condition. .Regarding defensive driving techniques during high wind conditions, all the respondents suggested that drivers hold on strong to the steering wheels during high wind event to keep the truck straight on the road, avoid over-taking and reduce their speed.

CHAPTER 7:

CONCLUSIONS AND RECOMMENDATIONS

This chapter will summarize the results from the wind speeds relationship analysis and the decision methodology for a high wind warning system. Suggestions for the future studies of this research area will be presented.

7.1 Conclusions

7.1.1 Hazardous High Wind Corridor Location

By sorting the historical crashes for a fifteen years period along I-25 by milepost, the most hazardous section between was found to be Milepost 70.00 and Milepost 71.00. Therefore, this section of the roadway was determined to be the main focus for the proposed high wind hazardous system and new equipment was installed along this segment to monitor the roadway. The result of this analysis re-confirmed the previous study concerning high wind hazardous locations along I-25. To be conservative, the Milepost range from 69.50 to 71.50 was selected to be the high wind warning system research project boundary.

7.1.2 Relationship between Overturning Crash and Weather Conditions

Two multiple logistical regression models were estimated and analyzed in this study. The second order model was selected as the final model for evaluation and threshold selection. The three predictor variables remained in the final second order model: Wind Speed, Wind Speed squared and Road Surface Condition. The estimate of the wind speed is a positive value of 0.297, which indicates that the chance of an overturning crash is increasing as the wind speeds increase. The estimate of road condition involving in the model has a negative value of 2.563, which means that the chance of having overturning crash is increased when the road condition is “dry”. This seemingly counter intuitive result is confirmed by the previous study and is likely due to the fact that drivers are more likely to make extra safety precautions to the easily perceivable hazard such as snowy weather or an icy road. The estimate of the wind speed squared is a negative value of 0.0029, which triggers the likelihood of overturning curve to drop after the wind speed reach 50 mph. This is likely a limitation of the data range used to estimate the model. From a practical point of view the high wind warning system will take a conservative approach and assume a dry road condition and will assume the risk is maximized at the 50 mph threshold.

7.1.3 Relationship between Wind Speed and Vehicle Speeds

The results of the relationship study of overturning crash and truck speeds indicates that there are some speed differences in different wind conditions, even though the differences in speed are not dramatic. The speeds of the truck were not differentiated from that of the passenger cars using the five minutes bins of the Wavetronix Speed Sensor. The truck and passenger car speeds were evaluated separately after the speed sensor was changed to 10 seconds bins. Passenger cars have higher average speed during high wind conditions whereas the trucks reduce their speeds slightly during high wind conditions. Previous research (see Chapter 2) indicated that speed reductions below the 75 mph posted speed improved safety only when wind speeds where above around 37 mph.

7.1.4 Relationship between Overturning Crash and Truck Weight

The Nevada Overturning and Sliding Models and the previous study concluded that the truck weight would play a role in the truck safety study. The historical crash data also indicated the similar trend in that fully loaded vehicles are less likely to overturn than the empty ones. The average wind speed of the loaded truck overturned is 51 mph, whereas the average wind speed of the empty truck overturned is 38 mph. The findings of how truck weight relates to overturning crashes could lead to different strategies for the High Wind Warning System.

7.1.5 High Wind Warning Systems

The main objective of this research is to develop a High Wind Warning System that can be used by WYDOT to improve the truck safety in high wind conditions near the Bordeaux area. Three operation levels were presented in this research:

- Level 1: Wind speeds and road surface variable thresholds for advisory warning messages of DMSs.
- Level 2: Wind speed, road surface variable, vehicle type and vehicle weight thresholds to determine road closure for all high-profile, light-weight vehicles.
- Level 3: Wind speed, road surface variable and vehicle type variable thresholds to determine road closure for all high-profile vehicles.

Level 1 uses the basic technology of RWIS, DMS, CB Wizard, Traveler Information System and HAR. RWIS is used to collect and record the weather data such as wind speed, wind gust speed, wind directions and road surface conditions; the remaining technology is used to broadcast the warning messages to travelers. To be conservative, wind speed of 30 mph is recommended as the trigger of the advisory warning message. 30 mph is the 12.14% wind speed during the crash occurrence, which means that 87.86% of the historical crashes would not have occurred when the hazard system was active. Based on the SAS analysis in Chapter 5, trucks are more likely to have overturning crashes in dry road condition than in wet road condition. So all the wind speeds thresholds were selected according to the dry road condition curve. If the advisory wind warning cutoff was set as 30 mph, 91.09% of the time would be below this cutoff and 8.91% of the time the warning signs would be activated. This equates to approximately 384 hours of warning message operation.

Level 2 uses the same equipment as Level 1 except adds height detection devices and weigh-in-motion technology. Height detection devices would recognize high profile vehicle and weigh-in-motion system is used to estimate lower weight vehicles on the road and transmit warning messages, or even stop them entering the hazardous location. The average wind speed of the historical overturned crashes for the empty trucks is 38mph. It is suggested that WYDOT use a cutoff of 40 mph as the threshold for the warning messages or road closure for the high profile, light weight trucks. The operational time for Level 2 is about 0.9%, which equates to 39 hours of operation in a winter season of 6 month.

Level 3 uses all the technology of Level 1 plus the addition of height detection devices. Of the 140 crashes, 71 (51%) of them occurred on the same day as another crash. The repeat truck crashes on the same day indicate that the weather is not suitable for large truck driving on these days. The average wind speed when these 71 crashes happened is 51 mph, which is higher than the average value of 140 crashes of 46 mph. Using the same methodology in the Level 1, 15th percentile of wind speed for the 71 crashes is 42 mph. It is suggested that WYDOT use wind speed cutoff 45 mph as the threshold to close corridor to all vehicles classified as large trucks. The frequency of wind speeds above 45 mph is 0.18%. This equates to approximately 8 hours of road closure for all high profile vehicles.

Comparing to the previous High Wind Warning System implemented by other agencies, the High Wind Warning System developed in this study used a systematic methodology for selecting thresholds and operational levels. The threshold selected in this phase of study considers the second order model, the historical truck overturning data, the wind frequency in winter and the Nevada model. WYDOT could refine the threshold values of different levels during the system operation. The next stage of this research would also evaluate the thresholds selection and finalize the High Wind Warning System. Two new Dynamic Message Signs (DMS) adjacent to the Bordeaux interchange were recently installed. These DMS will help to direct trucks to exit ramps to avoid the interchange bridge. In addition, travelers surveyed would like to receive high wind hazard warning through the Highway Advisory Radio, Radio Broadcast, 511(1-888-WYOROAD) Phone Service and CB Alert System as well. The methodology developed in this study could be used for other high wind locations except specific crash and weather data need to be collected accordingly.

The research effort presented in this report addresses the research objectives proposed in Chapter 1, including re-confirming the most hazardous location, relation analysis between the high wind conditions and likelihood of overturning crashes, relation study between high overturning crashes with the truck speeds and truck weight, and finalizing the High Wind Warning System.

7.2 Recommendations and Future Work

The low number of crashes in the dataset also interfered with the relation study between overturning crashes and truck weight. Ideally, the truck weight could be classified into two categories of "Empty and Lightly Loaded" and "Loaded". However, since there were only 16 crashes documented as "Loaded", the SAS model cannot be built on this small dataset and a "Composite" category was used in the weight analysis. It is suggested that WYDOT collect the truck weight parameter as much as possible in the future, and hopefully the model can be estimated based on the suggested weight categories.

In conversations with trucking stakeholders the need for the relationship between truck weight and configuration and crash risk needs to be more fully defined. This would require having access to better weight information on vehicles in the project corridor.

The recommended threshold values for wind hazard advisories and road closures in this report can be incorporated into the operations of the existing WYDOT Traffic Management Center (TMC) in Cheyenne that is managed by the ITS Program. If additional technology is installed such as weigh-in-motion, vehicle profile detection, and additional traveler information sources as discussed in Chapter 6 are installed the operation protocol at the TMC can be updated as recommended in the report.

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Appendix A: Bordeaux Site Visit Reports

- Nov. 25, 2008 Site Visit
- Dec.12, 2008 Site Visit
- Jan.08, 2009 Site Visit
- Jan.30, 2009 Site Visit
- Feb.12, 2009 Site Visit
- Mar.12, 2009 Site Visit
- Nov.10, 2009 Site Visit
- Dec.22, 2009 Site Visit
- Jan.2,0 2009 Site Visit

Bordeaux Project Site Visit Report

November 25, 2008

Arrived at the Bordeaux RWIS tower at about noon on November 25th, 2008. The weather was fine, except for strong winds on the hill where the RWIS is located.

DVR4000 Data:

The DVR is recording well. The time period for recording is from 6:00 AM in the morning to 7:00 PM in the evening. The total data usage is 25% for 12 days of recording data, which means that the entire storage would have about 40 days of historical video data before the earliest data is overwritten. I downloaded the 5 minutes video recordings for both cameras.

The only problem was that camera 2 was still changing monitoring positions (Three positions are: one on the south of the intersection, one on the curve, and one on the north of the bridge). Hopefully WYDOT would reset the 2 cameras so that they can have a full coverage of the hazardous section.

Figure 1: Camera 1 on the North of the Overpass

Figure 2: Camera 1 View on the South of the Overpass

Figure 3: Camera 2 - Position 2 View on the South Portion of the Overpass

Figure 4: Camera 2 - Position 3 View on the Roadway Segment

Speed Sensor Data:

Before downing the speed sensors data, the alignment of the sensors were checked. Both sensors were within the green boundary after the WYDOT adjusted the cameras on Nov 14th 2008. Speed sensor data was downloaded from both sensors for the period Nov 13th to Nov 23th. However, since both the sensors were aligned on Nov 14th, the valid data collected should be started from Nov 15th 2008. For this time period the sensor interval was set to 15 minutes. After downloading the sensor intervals were changed to 5 minute bins.

Data Summary:

DVR:

- 5 minutes of recording data for both cameras (Nov 18th 2008 14:34)

The video stored in the "Site Visit\Nov.25 2008 Site Visit\2 DVR Data" folder of the project server. For every minute of video, the size of the video file approximately equal to 100 Megabytes.

Speed Sensors:

- North Sensor: Nov.13th 2008 00:00:00 to Nov.23th 2008 23:59:59
- South Sensor: Nov.13th 2008 00:00:00 to Nov.23th 2008 23:59:59

The video stored in the "Site Visit\Nov.25 2008 Site Visit\1 Speed Sensors Data" folder of the project server. The bins of the data were 15 minutes for both sensors. After the data downloaded, the bins were set as 5 minutes.

Bordeaux Project Site Visit Report

December 12, 2008

Arrived at the Bordeaux RWIS tower at around noon on December 12th, 2008. The weather was cloudy with a breezy wind. Since there was a wind related crash reported by the WHP Dispatch Center, the main objective of this site visit was to retrieve the crash video recorded by the DVR. During the site visit the Speed Sensor Data was also retrieved.

DVR Data

Three DVR videos were retrieved (R:\BordeauxHighWind\Site Visit\Dec.12 2008 Site Visit\DVR).

- Camera 1: Captured a small part of the truck crash but did not capture the entire crash (shown in Picture 1) because the camera was in the wrong position part of the time.

Figure 1: Crash View Captured by Camera 1

- Camera 2: Crash occurred between 08:31: 36 AM and 08:34: 44 AM on Dec. 5th 2008. Camera 2 didn't capture the entire crash because the camera was pointing in other directions when the crash occurred.
- Camera 2: Highway Patrol arrived. DVR captured the scene after HP arrived.

Description of the crash process captured by the two cameras:

- At 08:31:36, a car was spotted pulling over on the northbound of I-25 (MP: 70.50)

- Two minutes later at 08:33:40, a person walked to the crash location. Maybe he perceived the crash at that time.

- Part of the truck accident was captured by camera 2 at 08:34:47.

- At 08:36:03, another truck pulled over behind the accident truck

- HP arrived at 08:52:06

Speed Sensors Data

Before downloading the data, the alignment of the speed sensors was checked. Both of them have a slight misalignment problem because the alignment condition on the management software turned from green to yellow since the last site visit, showing the sensors were slightly misaligned but still acceptable. The sensor alignment will continue to be monitored on future site visits.

Two sets of data were retrieved (R:\BordeauxHighWind\Site Visit\Dec.12 2008 Site Visit\Speed Sensor).

- North Sensor: Nov.24th 2008 00:00:00 to Dec.11th 2008 23:59:59
- South Sensor: Nov.24th 2008 00:00:00 to Dec.11th 2008 23:59:59

Coordinates of the Speed Sensors

North Sensor: N41˚56.516'/ W104˚56.828'

South Sensor: N41˚55.048'/ W104˚55.858'

Summary:

- DVR data – although part of the accident was captured by the two cameras, the entire crash was missed because of the changing monitoring position of camera 2. This was a known issue prior to the crash and it is currently being worked out with the WYDOT ITS Program to resolve this as soon as possible so future crashes can be recorded.
- Speed Sensor Data – up-to-date data from both sensors were retrieved and the coordinates of the two speed sensors were recorded.

Bordeaux Project Site Visit Report

January 08, 2009

Arrived at the Bordeaux RWIS tower at noon on January 8th, 2009, and experienced strong winds at the RWIS tower. From Dec.26th 2008 to Jan. 6th 2009, there were five crashes reported by the Wyoming Highway Patrol and the project site. Two of them happened at night, while the other three occurred in the afternoon around 1:00 PM. The main objective of this site visit was to retrieve the crash video recorded by the DVR. During the site visit, the Speed Sensor Data was also retrieved and a field trip to the crash location was conducted.

DVR Data

Four DVR videos were retrieved (R:\BordeauxHighWind\Site Visit\Jan.08 2009 Site Visit\DVR).

- Dec 31 2008 14:16 PM
- Jan 05 2009 1:00 PM
- Jan 05 2009 1:30 PM
- Night Video

The first three videos captured the three crashes that occurred in during the afternoon hours. The last video documents the performance of the camera at night. During the night time, the project location does not have any lighting except the headlights of the vehicles. Therefore, the DVR is recording only during the day time as before. This video was retrieved to confirm that this was an appropriate practice.

Camera 2 Direction Problem

As discussed in the previous two site visit reports, camera 2 was changing focus direction all the time, which had no benefit of documenting crash video in real time. From Nov 25th 2008 to Jan 8th 2009, there were five crashes recorded by the camera 2, but none of them documented the when crash occurred. The cycle of the camera 2 consists of four positions as follows:

Position 1: camera view is around the curve (south of the overpass)

Position 2: camera view is on the south portion of the overpass

Position 3: camera view is on the roadway segment north of the overpass

Position 4: camera view is on the roadway segment north of the overpass

Cycle of Camera 2:

Total	Around 6 minutes
Position 1	30 seconds
Position 2	3 minutes and 45 seconds
Position 3	30 seconds
Position 4	1 minute and 10 seconds

All the five crashes occurred within the view of position 1, but camera 2 only focuses in that direction for thirty seconds during each cycle. What is worse, the position 2, which has covered by the camera 1 already, takes up more than half of the cycle. So the chance of recording crash in real time is rather small if the camera 2 is kept in the current cycle.

Suggestion of Redirection on Camera 2

The suggestion of redirection of cameras is shown in Figure 1. The focusing position of camera 1 has good coverage of the road north of the overpass. It is suggested that camera 2 could zoom out a little bit and fix on the current position 1. If that is the case, the two cameras could have full coverage of the hazardous area. If WYDOT plans to change the focus position of camera 2, it is also suggested mount the camera to a lower height in the RWIS tower, since the camera 2 suffers from great vibrations during high wind conditions, which affects the video quality.

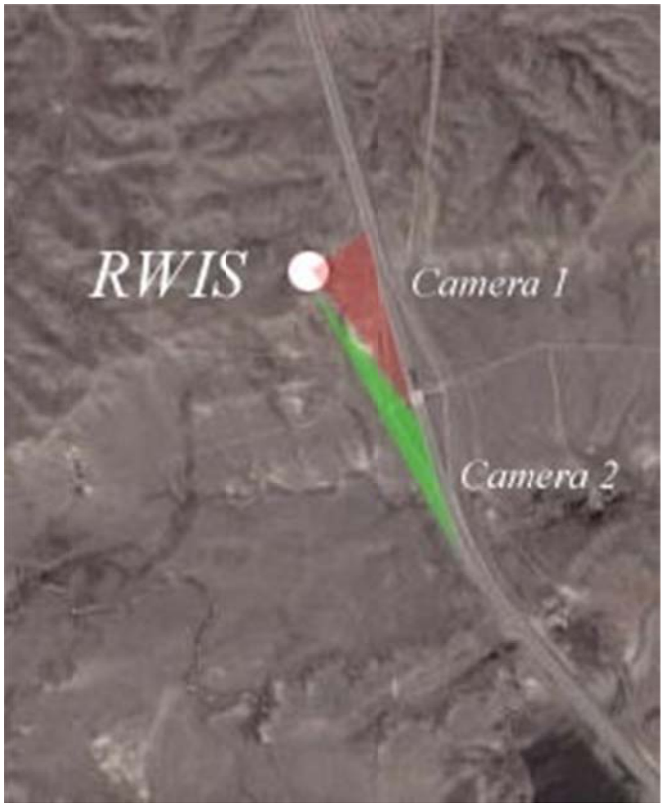


Figure 1: Suggestion of Cameras Redirection

Speed Sensors Data

Before downloading the data, the alignment of the speed sensors was checked. The south sensor was aligned in the green area, whereas the north sensor was still aligned in the yellow area. Two sets of data were retrieved (R:\BordeauxHighWind\Site Visit\Jan.08 2009 Site Visit \Speed Sensor).

- North Sensor: Dec.12th 2008 00:00:00 to Jan. 7th 2009 23:59:59
- South Sensor: Dec.12th 2008 00:00:00 to Jan. 7th 2009 23:59:59

Site Visit in Crash Location

After all the data were collected, a field trip to the crash location, south of the overpass, was conducted. Once on the entrance of the northbound ramp, the wind strength was observed to increase dramatically. The 300-feet-long side shoulder of northbound road was full of vehicle debris and burned grass, which indicates that crashes had occurred there. From a topographic perspective, this 300-feet-long shoulder is located in the middle of two small hills which act like a wind tunnel. Vehicles traveling on the northbound direction would experience a dramatic increase of wind speeds right after the curve. Figure 2 and Figure 3 document the condition of the roadway shoulders at the crash location.

Figure 2: Burning Grass on side of the shoulder

Figure 3: Northbound Crash Location Wind Shock Waving

Summary of Finding

- DVR data – To get a better view of crashes occurred in real time, it is suggested that WYDOT could redirect and fix the focus position of camera 2 on the curve as discussed above. It is also suggested that camera could be mounted in a lower position on the RWIS tower.
- Speed Sensor Data – up-to-date data from both sensors were retrieved.

Bordeaux Project Site Visit Report

January 30, 2009

Arrived at the Bordeaux RWIS tower at noon on January 30th 2009, experienced high winds and strong wind gust at the RWIS tower. From Jan.7th 2009 to Jan. 28th 2009, there were two crashes reported by the Wyoming Highway Patrol. One of them happened on Jan 10th 2009 11:18AM at MP 69.00; another crash occurred on Jan 21st 2009 15:58PM at MP 70.00. The main objective of this site visit was to retrieve the two crash video recorded by the DVR, and retrieved the up-to-date speed sensor data.

DVR Data

Two DVR videos were retrieved (R:\BordeauxHighWind\Site Visit\Jan.30 2009 Site Visit\DVR).

- Jan 10 2009 11:28 AM
- Jan 21 2009 15:48 PM

Figure 1: Jan 10 2009 10:21 AM

The camera didn't catch the crash on Jan 10 2009 11:28 AM, because the crash occurred on MP 69.00, which is beyond the scope of camera 2.

Figure 2: Jan 21 2009 15:46 PM

Since the redirection of camera 1 hasn't conducted by WYDOT, the two cameras didn't document the crash in real time.

Speed Sensors Data

Before downloading the data, the alignment and system time of the speed sensors were checked. Both of the sensors didn't have time drift problem. The south sensor was aligned in the green area, whereas the north sensor was still aligned in the yellow area. Two sets of data were retrieved (R:\BordeauxHighWind\Site Visit\Jan.30 2009 Site Visit \Speed Sensor).

- North Sensor: Jan. 8th 2009 00:00:00 to Jan. 29th 2009 23:59:59

- South Sensor: Jan. 8th 2009 00:00:00 to Jan. 29th 2009 23:59:59

Summary of Finding

- DVR data – Two crashes video occurred between Jan.7th 2008 and Jan. 28th 2009 were retrieved.
- Speed Sensor Data – up-to-date data from both sensors were retrieved.

Bordeaux Project Site Visit Report

February 12, 2009

Arrived at the Bordeaux RWIS tower at noon on February 12th 2009 and experienced breezy wind conditions at the RWIS tower. From Jan.28th 2008 to Feb. 10th 2009, there were two crashes reported by the Wyoming Highway Patrol. One of them occurred on Feb 6th 2009 at 11:20 AM at MP 71.00 and the other crash occurred on Feb 6th 2009 13:43 PM at MP 70.00. The main objective of this site visit was to retrieve the two crash videos recorded by the DVR and to retrieve the up-to-date speed sensor data. In order to catch the crashes in real time, WYDOT re-focused camera 1 (i.e. fixed position camera) to the most hazardous area on the north rim of the overpass (MP 69.50 and to MP 70.60). This site visit also served the purpose of confirming that the re-focused camera properly covered the most hazardous area.

DVR Data

Two DVR videos were retrieved (R:\BordeauxHighWind\Site Visit\ Feb.12 2009 Site Visit\DVR).

- Feb 6th 2009 13:38 PM crash in real time
- Feb 6th 2009 13:43 PM Highway Patrol Arrived

The first crash occurred on Feb 6th 2009 11:20AM at MP 71.00, which was beyond the scope of both cameras, so there was no video available for this crash. The second crash, happened on Feb 6th 2009 13:43PM at MP 70.00, lies within new focus area for camera 1, and the DVR captured the entire crash. A series of four pictures shown below illustrate the crash sequence. It is discernable from the pictures that the truck turnover was elicited by the high speed gust wind.

Speed Sensors Data

Before downloading the data, the alignment and system time of the speed sensors were checked. Both of the sensors were found to be properly aligned. The south sensor was aligned in the green area, whereas the north sensor was still aligned in the yellow area. Two sets of data were retrieved (R:\BordeauxHighWind\Site Visit\ Feb.12 2009 Site Visit\Speed Sensor).

- North Sensor: Jan. 30th 2009 00:00:00 to Feb. 11th 2009 23:59:59
- South Sensor: Jan. 30th 2009 00:00:00 to Feb. 11th 2009 23:59:59

Summary

- DVR data – Two DVR videos of Feb 6th 2009 13:38 PM crash were retrieved.
- Speed Sensor Data – up-to-date data from both sensors were retrieved.

Bordeaux Project Site Visit Report

March 12, 2009

Arrived at the Bordeaux at noon on March 12th 2009 and experienced high wind at the RWIS tower. WHP Dispatch Center reported that there were three wind-related crashes that occurred on March 8, 2009, the main objective of this site visit was to retrieve the three crash videos recorded by the DVR and to retrieve the up-to-date speed sensor data.

DVR Data

Three DVR videos were retrieved (R:\BordeauxHighWind\Site Visit\ Mar.12 2009 Site Visit\DVR).

- Mar 8th 2009 3:49 and 4:44 AM – the 2 crashes occurred before 6:00 AM when DVR set to begin recording each day
- Mar 8th 2009 6:36 AM crash happened in real time
- Mar 10th 2009 12:30 PM - Camera 1 broken

WHP Dispatch Center reported that there were three wind-related crashes occurred at 3:49 AM, 4:44 AM and 6:36 AM on March 8, 2009. Since the DVR was set to record from 6:00 AM to 7:00 PM each day the first two crashes were not captured by the DVR. At 6:00 AM when the video began recording, it is discernable that there were two overturned trailers lying on the northbound shoulder

The second DVR video captured the entire crash that happened on March 8th 2009 at 6:36 AM at MP 70.00. The series of six pictures shown below illustrate the crash sequence.

For an unknown reason, the camera 1 broke down on March 10, 2009 at 12:29:45 PM. The last message displayed on the screen is present below. After that, everything is upside down and only the sky is shown.

Speed Sensors Data

Before downloading the data, the alignment and system time of the speed sensors were checked. Both of the sensors were found to be properly aligned. The south sensor was aligned in the green area, whereas the north sensor was still aligned in the yellow area. Two sets of data were retrieved (R:\BordeauxHighWind\Site Visit\ Feb.12 2009 Site Visit\Speed Sensor).

- North Sensor: Feb. 12th 2009 00:00:00 to Mar. 11th 2009 23:59:59
- South Sensor: Feb. 12th 2009 00:00:00 to Mar. 11th 2009 23:59:59

DVR and Speed Sensor Time Configuring

Both DVR and Speed Sensor time setting were changed (set 1 hour ahead) because of the daylight savings change that occurred on Sunday in March 8th. In addition the recording time settings on the DVR were set to a longer period from 5:00 AM to 9:00 PM every day because of the longer daylight hours.

Summary

- DVR data – Two DVR videos on March 8th 2009 crashes were retrieved
- Camera 1 was found to be broken
- Speed Sensor Data – up-to-date data from both sensors were retrieved

Bordeaux Project Site Visit Report

November 10, 2009

I arrived at the Bordeaux RWIS tower at about 1:30pm on November 10th, 2009. The weather was a little bit cloudy with strong winds on the hill where the RWIS is located.

DVR Data:

The DVR was recording well. The time period for recording is from 5:00 AM in the morning to 9:00 PM in the evening. From the Dispatch report, the crash occurred around 08:33am on October 31st, 2009 northbound at MP70. I downloaded about 10 minutes of video recordings from 08:30 am to 08:40am on the day of the crash from camera 1. The average wind speed and wind gust speed at the time of the crash as observed from the RWIS are 50mph and 63mph respectively.

Camera 1 was monitoring positions on the bridge and to the south before the curve. The problem with camera 1 was that the crash could not be captured since its coverage does not seem to include the crash location, which occurred before MP70 thus beyond the coverage area of camera 1.

Camera 1 was only monitoring on the south of the bridge. No visuals were downloaded from Camera 2. The DVR video could not capture the actual accident but a vehicle which seems to be a police car pulled over just seconds after the accident. This can be seen from the picture below.

Figure 1: Camera 1 view on the south of the bridge

Speed Sensor Data:

Before downloading the speed sensor data, the alignment of the sensors were checked. Both sensors were within the green boundary indicating proper alignment. Speed sensor data was downloaded from both sensors for the period October 1st to October 31st. The sensor interval during this period was set at 5minutes. After downloading, the sensor interval was changed to a 10 second bin on both sensors.

Data Summary:

DVR:

- 10 minutes of recording data for Camera 1 (Nov 10th 2009 15:50)

The video stored in the "BordeauxHighWind\Site Visit\Nov.10 2009 Site Visit\DVR Data" folder of the project server. For the 10 minutes of video downloaded the size of the video file approximately equal to 1.2 Gigabytes. The crash occurred outside of camera range. The truck was not visible before the crash. No video was downloaded from camera 2.

Speed Sensors:

- North Sensor: October 1st 2009 00:00:00 to October 31st 2009 23:55:00
- South Sensor: October 1st 2009 00:00:00 to October 31st 2009 23:55:00

The Speed sensor is stored in the "BordeauxHighWind\Site Visit\Nov.10 2009 Site Visit\Speed Sensor" folder of the project server. The bins of the data were 5 minutes for both sensors.

Bordeaux Project Site Visit Report

December 22, 2009

I arrived at the Bordeaux RWIS tower at 9:45 AM in the morning of December 22, 2009. The weather was clear but there were high winds at the RWIS tower. WHP Dispatch Center reported that there were two wind-related crashes involving commercial vehicles that occurred on December 10 and December 12, 2009. The main objective of this site visit was to retrieve the two crash videos recorded by the DVR and also to download the up-to-date speed sensor data.

DVR Data

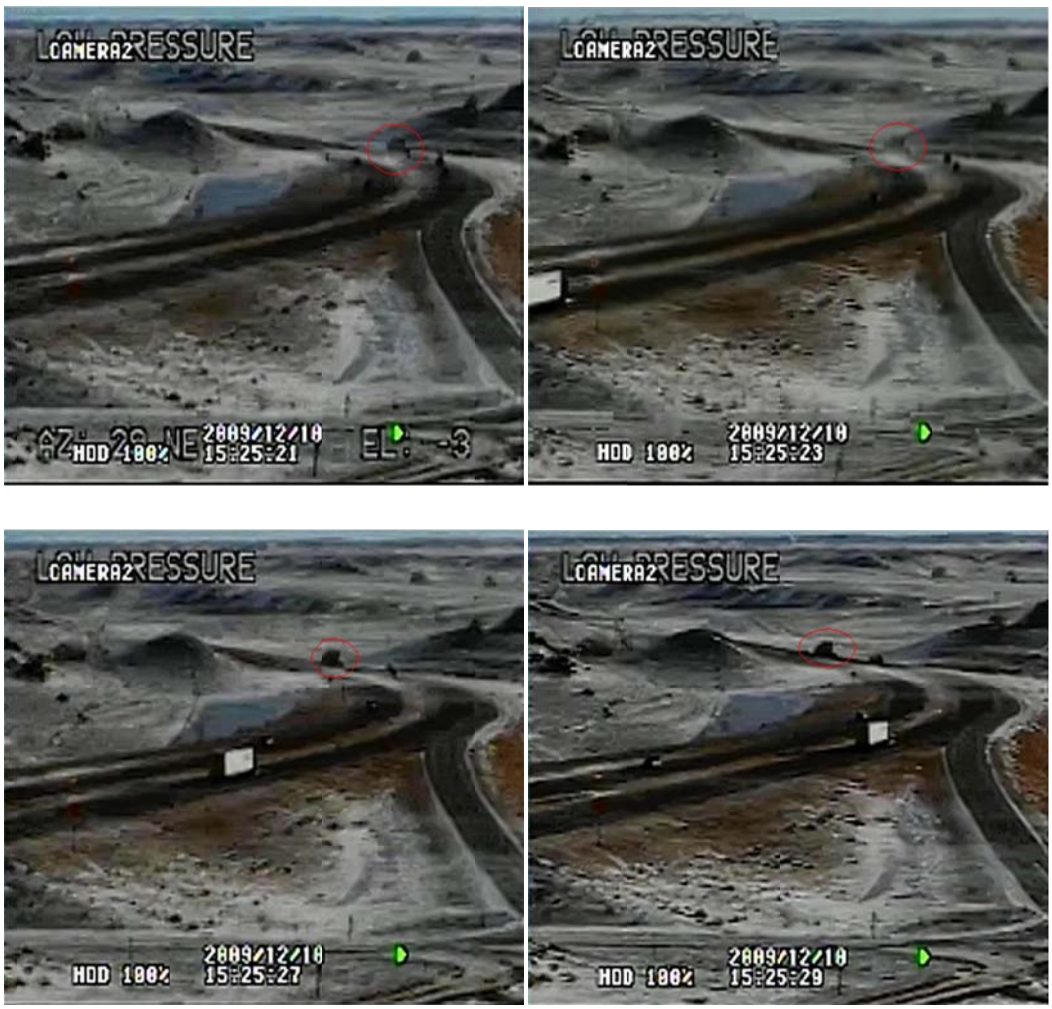
The DVR video was recording well. The time period for recording was from 5:00 AM in the morning to 9:00 PM in the evening.

DVR videos retrieved for the two crashes are stored in "BordeauxHighWind\Site Visit\ Dec. 22 2009 Site Visit\DVR Data".

- The first crash occurred on December 10th 2009 at approximately 3:24 PM involving a Gray 2007 Peterbilt truck at Milepost 70 on the southbound direction. Wind Speed and Wind Gust Speed data obtained from the RWIS were 35mph and 55mph respectively. I downloaded approximately 6minutes and 30minutes of recorded crash video from camera 1 and camera 2 respectively.
- The second crash occurred on December 12th 2009 at approximately 12:41PM involving a Red Volvo at Milepost 70 on the northbound. Wind

Speed and Wind Gust Speed data obtained from the RWIS are 51mph and 70mph respectively. I downloaded approximately 4minutes and 6minutes of recorded crash video from camera 1 and camera 2 respectively.

The DVR video from Camera 2 captures the entire crash sequence for the accident that happened on December 10, 2009 at 3:24PM at MP 70.00. The following pictures show the crash sequence.



Speed Sensor Data

The alignment and system time of the speed sensors were checked before downloading the data. Both sensors were found to be properly aligned in the green boundary. The sensors were reading at an interval of 10 seconds bin. Before downloading, it was realized that the sensor storage timeline was between December 15 and 22. I tried changing this to include the crash days i.e. December 10 and December 12 but to no avail. This was unlikely because the 10 seconds bins used the available sensor memory and older data records were overwritten. However, I managed to download data from both sensors from December 16 to December 17 representing one good day (average wind speed <= 10mph) and one bad day (average wind speed > 30mph). Only two days of speed sensor data was downloaded because during the downloading process, the older data were overwritten. The two days of data downloaded took a tremendous amount of time approximately 3hours.Speed sensor data downloaded were stored in "BordeauxHighWind\Site Visit\ Dec.22 2009 Site Visit\Speed Sensor".

- **North Sensor:** December 16, 2009 from 00:00:00 to 23:59:50 (10 seconds bins)

  December 17, 2009 from 00:00:00 to 23:55:00 (10 seconds bins)

- **South Sensor:** December 16, 2009 from 03:45:40 to 23:59:50 (10 seconds bins)

  December 17, 2009 from 00:00:00 to 23:55:00 (10 seconds bins)

Data Summary:

DVR:

- Four DVR videos were downloaded for the two crashes from each of the cameras. The video stored in “BordeauxHighWind\Site Visit\ Dec.22 2009 Site Visit\DVR Data” folder of the project server.

Speed Sensors:

Two days of data were downloaded from December 16 to December 17. The downloading time took approximately 3 hours. The speed sensor data is stored in “BordeauxHighWind\Site Visit\ Dec.22 2009 Site Visit\Speed Sensor” folder of the project server.

After reviewing the data more closely back at the office it was found that the south speed sensor was not recording data properly since all the ten second intervals observed zero “0” vehicles.

Bordeaux Project Site Visit Report

January 20, 2010

I arrived at the Bordeaux RWIS tower at 4:45 pm of January 20, 2010. There was clear weather at the time of the visit. The WHP Dispatch Center reported that there were two wind-related crashes involving commercial vehicles that occurred on January 12 and January 18, 2010. The main objective of this site visit was to retrieve the two crash videos recorded by the DVR and also to download the up-to-date speed sensor data.

DVR Data

The DVR video was recording well. The time period for recording was from 5:00 AM in the morning to 9:00 PM in the evening. DVR videos retrieved for the two crashes are stored in \BordeauxHighWind\Site Visit\ 20 Jan. 2010 Site Visit\DVR Data".

- The first crash occurred on January 12th, 2010 at approximately 9:26 PM involving an empty 5th wheel gooseneck trailer at Milepost 70 on the northbound direction. Wind Speed and Wind Gust Speed data obtained from the RWIS are 40mph and 51mph respectively. I did not download any crash video for this accident because the DVR records from 5:00 AM to 9:00 PM and the accident occurred after this time period.

- The second crash occurred on January 18th, 2010 at approximately 1:43PM involving a Davidson Industries tractor trailer at Milepost 70 on the northbound. Wind Speed and Wind Gust Speed data obtained from the RWIS are 29mph and 38mph respectively. I downloaded approximately 4 minutes and 6 minutes of recorded crash video from camera 1 and camera 2 respectively.

The DVR video from Camera 1 captures the truck moving on the northbound ramp.

Figure 1: Picture showing the truck moving onto the northbound ramp


LOW PRESSURE
CAMERA1
2018/01/18
13:33:39
HDD 100%


LOW PRESSURE
CAMERA1
2018/01/18
13:33:43
HDD 100%

Speed Sensor Data

The alignment and system time of the speed sensors were checked before downloading the data. Both sensors were found to be properly aligned thus in the green boundary. The sensors were reading at an interval of 10 seconds bin. I downloaded data from both sensors from January 17 to January 18 representing one good day (thus average wind speed <= 10mph) and one bad day (thus average wind speed > 30mph) respectively. The reason why I downloaded two days of speed sensor data was because during the downloading process, the older data were overwritten.

Speed sensor data downloaded was stored in \BordeauxHighWind\Site Visit\ 20 Jan. 2010 Site Visit\Speed Sensor.

- **North Sensor:** January 17, 2010 from 00:00:00 to 03:27:50
- **South Sensor:** January 17, 2010 from 06:33:00 to 23:59:50

January 18, 2010 from 00:00:00 to 23:50:00

Data Summary:

DVR:

- Two DVR videos were downloaded for the crash which occurred on January 18th from each of the cameras. There was no videos for the first accident which occurred on January 12th because the time of the accident occurred outside of the DVR recording period thus from 5:00AM to 9:00PM. The video stored in "R:\BordeauxHighWind\Site Visit\ 20 Jan. 2010 Site Visit\DVR Data" folder of the project server.

Speed Sensors:

Data was downloaded from January 17 to January 18 representing one good day (thus average wind speed <= 10mph) and one bad day (thus average wind speed > 30mph) respectively. The reason why I downloaded two days of speed sensor data was because during the downloading process, the older data were overwritten.

Speed sensor data downloaded was stored in \BordeauxHighWind\Site Visit\ 20 Jan. 2010 Site Visit\Speed Sensor.

- **North Sensor:** January 17, 2010 from 00:00:00 to 03:27:50
- **South Sensor:** January 17, 2010 from 06:33:00 to 23:59:50

  January 18, 2010 from 00:00:00 to 23:50:00

Appendix B: Historical Crash Data (SAS Input)

KEY	MILEPOST	ACC_DATE	TIME	ROAD	Wind_Speed	Wind_Gust	Wind_Dir	A1ST_HARMF
9417364	07050	11/29/1994	1530	DRY	46	51	W	OVERTURN
9417366	07047	11/29/1994	1530	DRY	46	51	W	OVERTURN
9417367	07032	11/29/1994	1530	DRY	46	51	W	OVERTURN
9417481	07030	11/30/1994	0515	DRY	54	62	W	OVERTURN
9417483	07030	11/30/1994	1100	DRY	49	61	W	OVERTURN
9418529	07043	12/16/1994	0845	DRY	42	50	W	OVERTURN
9418530	07032	12/16/1994	0645	DRY	42	50	W	OVERTURN
9418531	07050	12/16/1994	2155	DRY	47	56	W	OVERTURN
9516628	07042	11/9/1995	0710	DRY	57	70	SW	OVERTURN
9517980	07047	11/30/1995	0420	DRY	25	32	W	OVERTURN
9601347	07082	1/23/1996	1155	DRY	42	47	W	OVERTURN
9602444	07075	1/23/1996	1155	DRY	42	47	W	OVERTURN
9602800	07062	2/6/1996	0950	DRY	62	69	W	OVERTURN
9606777	07040	4/24/1996	1540	DRY	64	72	SW	OVERTURN
9606778	07042	4/24/1996	1540	DRY	64	72	SW	OVERTURN
9620131	07052	12/5/1996	0143	DRY	73	79	SW	OTHER NON-COLLISION
9620505	07050	12/14/1996	0115	DRY	57	67	W	OVERTURN
9621001	07059	12/19/1996	2245	DRY	59	67	W	OVERTURN
9702240	07062	1/30/1997	1700	DRY	57	64	W	OVERTURN
9718222	07062	11/12/1997	1300	DRY	31	37	W	OVERTURN
9721474	07060	12/18/1997	0345	DRY	14	16	SW	OTHER SIGN
9818265	07062	11/21/1998	1145	DRY	61	70	W	OVERTURN
9818642	07000	11/25/1998	0350	DRY	39	48	SW	OVERTURN
9819073	07000	11/25/1998	0550	DRY	42	51	W	OVERTURN
9819547	07035	12/8/1998	0110	DRY	50	55	SW	OVERTURN
9820413	06990	12/18/1998	1215	ICY	31	35	NW	MV-MV
9900489	07070	1/11/1999	0005	DRY	50	55	SW	OVERTURN
9900716	7040	1/14/1999	2115	DRY	40	48	SW	OTHER SIGN

KEY	MILEPOST	ACC_DATE	TIME	ROAD	Wind_Speed	Wind_Gust	Wind_Dir	A1ST_HARMF
9900717	07050	1/14/1999	0950	DRY	46	57	SW	OVERTURN
9902193	07062	2/2/1999	0730	DRY	63	70	SW	OVERTURN
9902194	07040	2/2/1999	0930	DRY	59	68	W	OVERTURN
9902669	07062	2/2/1999	0943	DRY	56	65	W	OVERTURN
9903892	07040	3/1/1999	1205	DRY	45	57	W	OVERTURN
9907686	07051	5/12/1999	1145	DRY	20	27	W	OVERTURN
9918671	07062	11/25/1999	0155	DRY	50	60	W	OVERTURN
9918672	07062	11/25/1999	0330	DRY	61	71	W	OVERTURN
9920002	07020	12/16/1999	0230	DRY	51	59	W	OVERTURN
0000115	07030	1/6/2000	1100	DRY	32	36	SW	OVERTURN
0002732	07062	2/14/2000	2335	DRY	47	55	W	GUARDRAIL OTHER
0102312	07150	2/2/2001	1630	DRY	53	63	W	OVERTURN
0119781	07100	12/13/2001	1940	DRY	52	59	W	OVERTURN
0200956	07050	1/19/2002	0425	DRY	52	64	SW	OVERTURN
0201332	07062	1/25/2002	0700	DRY	56	67	W	OVERTURN
0201333	07061	1/25/2002	0835	DRY	49	55	W	OVERTURN
0201334	07054	1/24/2002	2115	DRY	53	64	SW	OVERTURN
0203529	07050	3/3/2002	1500	ICY	38	41	W	OTHER NON-COLLISION
0203680	07035	3/3/2002	1443	ICY	38	41	W	MV-MV
0203839	07050	3/3/2002	1500	ICY	38	41	W	OTHER OBJECT
0205090	07050	3/28/2002	1415	DRY	40	49	W	OVERTURN
0205259	07039	3/27/2002	1235	DRY	49	63	SW	OVERTURN
0208045	07060	5/22/2002	0840	DRY	71	82	SW	OVERTURN
0208131	06990	5/22/2002	1300	DRY	58	69	W	OVERTURN
0208283	07050	5/22/2002	0840	DRY	71	82	SW	OVERTURN
0301208	7053	1/26/2003	1208	DRY	7	9	NW	OTHER NON-COLLISION
0318070	7062	11/11/2003	0845	DRY	55	67	SW	OVERTURN
0318617	7050	11/18/2003	1100	DRY	49	63	SW	OVERTURN

KEY	MILEPOST	ACC_DATE	TIME	ROAD	Wind_Speed	Wind_Gust	Wind_Dir	A1ST_HARMF
0318794	7100	11/29/2003	1220	DRY	60	71	W	OVERTURN
0318891	7042	11/29/2003	0935	DRY	47	58	W	OVERTURN
0318892	7060	11/29/2003	1100	DRY	55	66	W	OVERTURN
0401803	07062	1/28/2004	16:32	DRY	57	68	W	OVERTURN
0401823	07075	01/28/2004	18:30	DRY	53	60	W	OVERTURN
0401824	07050	01/28/2004	20:45	DRY	50	57	W	OVERTURN
0402197	07067	02/05/2004	20:50	ICY	19	22	NW	GUARDRAIL IN MEDIAN
0403512	07035	02/29/2004	21:10	ICY	26	29	NW	OVERTURN
0407601	07050	05/26/2004	11:20	DRY	40	53	W	OVERTURN
0419451	07109	12/11/2004	11:20	DRY	61	72	W	OVERTURN
0421466	07062	12/24/2004	10:59	DRY	54	59	SW	OVERTURN
0501542	07062	01/18/2005	07:50	DRY	59	65	SW	OVERTURN
0501800	06995	01/18/2005	06:10	DRY	60	68	W	OVERTURN
0507441	07000	05/17/2005	12:00	DRY	55	65	SW	OVERTURN
0517371	07050	11/03/2005	09:45	DRY	62	72	SW	OVERTURN
0601079	07061	01/09/2006	10:00	ICY	29	36	SW	GUARDRAIL IN MEDIAN
0601720	07069	01/10/2006	11:35	DRY	58	69	W	OVERTURN
0601723	07061	01/10/2006	11:30	DRY	58	69	W	OVERTURN
0601807	07050	01/10/2006	18:48	DRY	50	59	W	OVERTURN
0602248	07047	02/01/2006	08:45	DRY	52	62	W	OVERTURN
0604126	07053	02/27/2006	11:55	DRY	41	50	SW	OVERTURN
0618804	07062	11/16/2006	13:15	DRY	43	61	W	GUARDRAIL BY STRUCTURE
0620288	07106	11/30/2006	16:10	DRY	50	67	W	OVERTURN
0620289	07050	11/30/2006	18:48	DRY	59	79	W	OVERTURN
0620291	07040	11/30/2006	16:40	DRY	48	63	W	OVERTURN
0620733	07150	11/30/2006	18:50	DRY	59	79	W	OVERTURN
0622657	07043	12/13/2006	11:40	DRY	54	70	W	OVERTURN
0700370	07050	01/03/2007	17:00	DRY	58	79	W	OVERTURN

KEY	MILEPOST	ACC_DATE	TIME	ROAD	Wind_Speed	Wind_Gust	Wind_Dir	A1ST_HARMF
0700371	07042	01/07/2007	14:35	DRY	57	73	W	OVERTURN
0700372	07050	01/03/2007	15:40	DRY	47	67	W	OVERTURN
0700651	07060	01/06/2007	14:45	DRY	54	70	SW	OVERTURN
0700662	07062	01/18/2005	22:40	DRY	57	68	W	OVERTURN
0701529	06995	01/06/2007	10:20	DRY	64	88	W	OVERTURN
0701603	07042	01/07/2007	15:25	DRY	55	80	W	OVERTURN
0701606	06995	01/10/2007	09:20	DRY	39	52	W	OVERTURN
0701614	07062	01/10/2007	11:35	DRY	32	52	S	OVERTURN
0703847	07052	02/16/2007	06:30	DRY	45	71	W	OVERTURN
0703883	07060	02/20/2007	11:57	DRY	48	59	SW	OVERTURN
0704116	07000	02/20/2007	11:05	DRY	42	65	W	OVERTURN
0705462	07050	02/20/2007	07:20	DRY	46	64	W	OVERTURN
0707102	07062	04/19/2007	11:19	DRY	51	65	SW	OVERTURN
0710040	07042	06/06/2007	13:36	DRY	43	61	W	OTHER NON-COLLISION
0711607	07065	06/07/2007	00:45	DRY	50	80	W	OVERTURN
200721687	70.50	12/3/2007 ~	1545	DRY	50	66	W	OVERTURN
200721689	70.50	12/4/2007 ~	1255	DRY	52	75	W	OVERTURN
200724359	70.62	12/16/2007	1355	DRY	42	65	W	OVERTURN
200800269	71.50	1/10/2008 ~	1345	DRY	51	78	SW	DELINEATOR POST
200801402	70.53	1/10/2008 ~	1350	DRY	48	75	W	OVERTURN/ROLLOVER
200801405	70.42	1/10/2008 ~	1628	DRY	46	66	SW	OVERTURN/ROLLOVER
200801512	70.52	1/31/2008 ~	1228	DRY	51	67	W	OVERTURN/ROLLOVER
200802633	70.42	1/29/2008 ~	1625	DRY	55	71	W	OVERTURN/ROLLOVER
200802659	69.90	2/18/2008 ~	930	DRY	22	30	NW	OVERTURN/ROLLOVER
200802716	70.30	1/10/2008 ~	1521	DRY	49	68	SW	JACKNIFE
200803289	70.30	1/10/2008 ~	1521	DRY	50	69	SW	JACKNIFE
200804927	70.65	3/14/2008 ~	2031	Ice	6	7	N	GUARDRAIL FACE
200806248	70.62	3/29/2008 ~	1315	DRY	45	63	SW	OVERTURN/ROLLOVER

KEY	MILEPOST	ACC_DATE	TIME	ROAD	Wind_Speed	Wind_Gust	Wind_Dir	A1ST_HARMF
200811260	70.00	7/6/2008 ~	1230	DRY	4	12	SE	COW
200811270	69.60	8/18/2008 ~	445	DRY	0	4	S	DEER
200812336	71.00	8/11/2008 ~	2005	DRY	11	14	SE	DEER
200820435	70.50	12/5/2008 ~	830	DRY	53	73	W	OVERTURN/ROLLOVER
200820436	70.25	12/5/2008 ~	925	DRY	49	70	SW	OVERTURN/ROLLOVER
200820441	70.00	12/17/2008 ~	2016	DRY	35	47	W	OVERTURN/ROLLOVER
200820901	70.00	12/27/2008 ~	2130	DRY	50	66	SW	OVERTURN/ROLLOVER
200820908	70.75	12/31/2008 ~	1515	DRY	40	62	SW	OVERTURN/ROLLOVER
200820909	70.50	12/31/2008 ~	1545	DRY	45	67	SW	OVERTURN/ROLLOVER
200822845	70.00	12/31/2008 ~	1422	DRY	47	71	SW	OVERTURN/ROLLOVER
200900353	70.62	1/5/2009 ~	1259	DRY	58	76	W	OVERTURN/ROLLOVER
200900354	70.60	1/5/2009 ~	1327	DRY	53	74	W	OVERTURN/ROLLOVER
200901773	70.00	1/21/2009 ~	1555	DRY	40	57	SW	OVERTURN/ROLLOVER
200902570	70.62	2/6/2009 ~	1115	DRY	45	62	SW	ROAD APPROACH
200902571	70.00	2/6/2009 ~	1345	DRY	55	68	SW	OVERTURN/ROLLOVER
200902572	70.63	2/6/2009 ~	1355	DRY	47	72	SW	OVERTURN/ROLLOVER
200903550	69.98	3/8/2009 ~	355	DRY	48	68	W	OVERTURN/ROLLOVER
200903552	70.50	3/8/2009 ~	740	DRY	45	73	W	OVERTURN/ROLLOVER
200903566	71.50	3/9/2009 ~	1420	DRY	9	11	NE	DELINEATOR POST
200904562	69.88	3/8/2009 ~	435	DRY	51	71	W	OVERTURN/ROLLOVER
200915686	70.62	10/31/2009	0834	WET	50	63	SW	OVERTURN/ROLLOVER
200918191	65.00	12/7/2009	0700	SNOW	6	11	E	WORK ZONE/MAINTENANCE EQUIPMENT
200918731	70.25	12/10/2009	1520	DRY	35	55	SW	OVERTURN/ROLLOVER
200918197	70.50	12/12/2009	1230	DRY	51	70	W	OVERTURN/ROLLOVER
201000873	70.60	1/12/2010	2110	DRY	40	51	SW	OVERTURN/ROLLOVER
201000879	70.50	1/18/2010	1330	DRY	29	38	SW	OVERTURN/ROLLOVER
201002729	69.10	2/3/2010	0500	DRY	20	30	SW	FENCE
201002283	66.00	2/18/2010	1115	SNOW	16	20	N	FENCE

Appendix C: SAS Output of the Multiple Logistic Model

- First Multiple Logistic Model
- Final Multiple Logistic Model
- Second Order Interaction First Model
- Second Order Interaction Final Model

First Multiple Logistic Model

The LOGISTIC Procedure

Model Information

Data Set	WORK.BOR	
Response Variable	OVERTURN	OVERTURN
Number of Response Levels	2	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Number of Observations Read	140
Number of Observations Used	133

Response Profile

Ordered Value	OVERTURN	Total Frequency
1	0	24
2	1	109

Probability modeled is OVERTURN=1.

NOTE: 7 observations were deleted due to missing values for the response or explanatory variables.

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	127.572	89.939
SC	130.463	107.281
-2 Log L	125.572	77.939

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	47.6339	5	<.0001
Score	55.2613	5	<.0001
Wald	27.6139	5	<.0001

The LOGISTIC Procedure

NOTE: The following parameters have been set to 0, since the variables are a linear combination of other variables as shown.

Wgust_Wspeed = -Wind_Speed + Wind_Gust

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.7483	0.9928	3.1010	0.0782
Lighting_Condition	1	0.1952	0.7903	0.0610	0.8049
Road_Condition	1	-2.6857	0.9784	7.5344	0.0061
Wind_Speed	1	0.1252	0.0716	3.0628	0.0801
Wind_Gust	1	-0.0350	0.0551	0.4028	0.5257
Wind_Direction_Bi	1	0.3387	1.2119	0.0781	0.7799
Wgust_Wspeed	0	0	.	.	.

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
Lighting_Condition	1.216	0.258	5.721
Road_Condition	0.068	0.010	0.464
Wind_Speed	1.133	0.985	1.304
Wind_Gust	0.966	0.867	1.076
Wind_Direction_Bi	1.403	0.130	15.091

Association of Predicted Probabilities and Observed Responses

Percent Concordant	86.0	Somers' D	0.722
Percent Discordant	13.8	Gamma	0.723
Percent Tied	0.2	Tau-a	0.215
Pairs	2616	c	0.861

The LOGISTIC Procedure

Partition for the Hosmer and Lemeshow Test

		OVERTURN = 1		OVERTURN = 0	
Group	Total	Observed	Expected	Observed	Expected
1	15	1	2.62	14	12.38
2	13	11	8.54	2	4.46
3	13	11	11.12	2	1.88
4	13	12	11.57	1	1.43
5	13	10	11.90	3	1.10
6	13	13	12.10	0	0.90
7	13	12	12.31	1	0.69
8	13	13	12.48	0	0.52
9	13	13	12.60	0	0.40
10	14	13	13.75	1	0.25

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
11.4185	8	0.1791

Final Multiple Logistic Model

The LOGISTIC Procedure

Model Information

Data Set	WORK.BOR	
Response Variable	OVERTURN	OVERTURN
Number of Response Levels	2	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Number of Observations Read	140
Number of Observations Used	140

Response Profile

Ordered Value	OVERTURN	Total Frequency
1	0	24
2	1	116

Probability modeled is OVERTURN=1.

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	130.280	85.322
SC	133.222	94.147
-2 Log L	128.280	79.322

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	48.9580	2	<.0001
Score	57.0076	2	<.0001
Wald	29.2926	2	<.0001

The LOGISTIC Procedure

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.7522	0.8640	4.1130	0.0426
Road_Condition	1	-2.5628	0.9087	7.9542	0.0048
Wind_Speed	1	0.0893	0.0206	18.8445	<.0001

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
Road_Condition	0.077	0.013	0.458
Wind_Speed	1.093	1.050	1.138

Association of Predicted Probabilities and Observed Responses

Percent Concordant	84.4	Somers' D	0.698
Percent Discordant	14.5	Gamma	0.706
Percent Tied	1.1	Tau-a	0.200
Pairs	2784	c	0.849

Partition for the Hosmer and Lemeshow Test

Group	Total	OVERTURN = 1 Observed	OVERTURN = 1 Expected	OVERTURN = 0 Observed	OVERTURN = 0 Expected
1	14	1	2.33	13	11.67
2	15	12	9.65	3	5.35
3	14	14	12.20	0	1.80
4	14	11	12.70	3	1.30
5	14	12	12.96	2	1.04
6	12	11	11.25	1	0.75
7	15	14	14.20	1	0.80
8	12	12	11.50	0	0.50
9	16	16	15.49	0	0.51
10	14	13	13.73	1	0.27

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
11.0985	8	0.1962

Second Order Interaction First Model

The LOGISTIC Procedure

Model Information

Data Set	WORK.BOR
Response Variable	OVERTURN OVERTURN
Number of Response Levels	2
Model	binary logit
Optimization Technique	Fisher's scoring

Number of Observations Read	140
Number of Observations Used	133

Response Profile

Ordered Value	OVERTURN	Total Frequency
1	0	24
2	1	109

Probability modeled is OVERTURN=1.

NOTE: 7 observations were deleted due to missing values for the response or explanatory variables.

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	127.572	86.380
SC	130.463	112.393
-2 Log L	125.572	68.380

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	57.1922	8	<.0001
Score	64.4206	8	<.0001
Wald	27.0255	8	0.0007

The LOGISTIC Procedure

NOTE: The following parameters have been set to 0, since the variables are a linear combination of other variables as shown.

Wgust_Wspeed = -Wind_Speed + Wind_Gust

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-5.6342	2.2186	6.4491	0.0111
Lighting_Condition	1	0.1424	0.9145	0.0242	0.8763
Road_Condition	1	-3.8405	1.2651	9.2149	0.0024
Wind_Speed	1	0.3935	0.3646	1.1643	0.2806
Wind_Gust	1	0.0318	0.3027	0.0110	0.9164
Wind_Direction_Bi	1	-1.6598	1.5445	1.1550	0.2825
Wgust_Wspeed	0	0	.	.	.
Wind_Speed*Wind_Gust	1	0.0147	0.0183	0.6405	0.4235
Wind_Spee*Wind_Speed	1	-0.0125	0.0111	1.2650	0.2607
Wind_Gust*Wind_Gust	1	-0.00653	0.00797	0.6721	0.4123

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
Lighting_Condition	1.153	0.192	6.922
Road_Condition	0.021	0.002	0.256
Wind_Direction_Bi	0.190	0.009	3.924

Association of Predicted Probabilities and Observed Responses

Percent Concordant	88.3	Somers' D	0.772
Percent Discordant	11.1	Gamma	0.776
Percent Tied	0.5	Tau-a	0.230
Pairs	2616	c	0.886

The LOGISTIC Procedure

Partition for the Hosmer and Lemeshow Test

		OVERTURN = 1		OVERTURN = 0	
Group	Total	Observed	Expected	Observed	Expected
1	15	1	1.70	14	13.30
2	14	10	9.19	4	4.81
3	13	13	11.17	0	1.83
4	13	11	12.07	2	0.93
5	13	10	12.25	3	0.75
6	13	13	12.41	0	0.59
7	13	13	12.47	0	0.53
8	13	13	12.53	0	0.47
9	13	13	12.57	0	0.43
10	13	12	12.64	1	0.36

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
14.4264	8	0.0713

Second Order Interaction Final Model

The LOGISTIC Procedure

Model Information

Data Set	WORK.BOR	
Response Variable	OVERTURN	OVERTURN
Number of Response Levels	2	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Number of Observations Read	140
Number of Observations Used	140

Response Profile

Ordered Value	OVERTURN	Total Frequency
1	0	24
2	1	116

Probability modeled is OVERTURN=1.

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	130.280	92.745
SC	133.222	98.628
-2 Log L	128.280	88.745

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	39.5356	1	<.0001
Score	43.9707	1	<.0001
Wald	25.6870	1	<.0001

The LOGISTIC Procedure

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-2.7066	0.8489	10.1666	0.0014
Wind_Speed	1	0.1041	0.0205	25.6870	<.0001

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
Wind_Speed	1.110	1.066	1.155

Association of Predicted Probabilities and Observed Responses

Percent Concordant	83.5	Somers' D	0.681
Percent Discordant	15.4	Gamma	0.689
Percent Tied	1.1	Tau-a	0.195
Pairs	2784	c	0.841

Partition for the Hosmer and Lemeshow Test

Group	Total	OVERTURN = 1 Observed	OVERTURN = 1 Expected	OVERTURN = 0 Observed	OVERTURN = 0 Expected
1	14	3	3.20	11	10.80
2	14	9	9.57	5	4.43
3	14	14	11.58	0	2.42
4	14	11	12.31	3	1.69
5	14	12	12.69	2	1.31
6	13	12	12.00	1	1.00
7	15	14	14.05	1	0.95
8	12	12	11.43	0	0.57
9	16	16	15.44	0	0.56
10	14	13	13.72	1	0.28

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
7.6645	8	0.4669

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Appendix D: SAS Output for the Average Speeds of the Vehicle

- Average Speeds of Cars
- Average Speeds of Trucks

SAS OUTPUT FOR THE AVERAGE SPEED OF CARS

The GLM Procedure

Class Level Information

Class	Levels	Values
HighWindSpeed	17	8 30 31 32 33 34 35 37 38 39 40 41 42 43 44 45 47

Number of Observations Read	216
Number of Observations Used	216

The GLM Procedure

Dependent Variable: AvgSpeed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	28	2624.28791	93.72457	1.47	0.0690
Error	187	11895.47135	63.61215		
Corrected Total	215	14519.75926			

R-Square	Coeff Var	Root MSE	AvgSpeed Mean
0.180739	10.50845	7.975722	75.89815

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LowWindSpeed	1	117.9089361	117.9089361	1.85	0.1750
HighWindSpeed	11	708.3444982	64.3949544	1.01	0.4371
LowWindSp*HighWindSp	11	603.4201956	54.8563814	0.86	0.5783

SAS OUTPUT FOR THE AVERAGE SPEED OF TRUCKS

The GLM Procedure

Class Level Information

Class	Levels	Values
HighWindSpeed	17	30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 47

Number of Observations Read 170
Number of Observations Used 170

The GLM Procedure

Dependent Variable: AvgSpeed

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	30	3738.26477	124.60883	1.70	0.0215
Error	139	10184.88817	73.27258		
Corrected Total	169	13923.15294			

R-Square	Coeff Var	Root MSE	AvgSpeed Mean
0.268493	13.15485	8.559940	65.07059

Source	DF	Type III SS	Mean Square	F Value	Pr > F
LowWindSpeed	1	230.394497	230.394497	3.14	0.0784
HighWindSpeed	13	1492.335282	114.795022	1.57	0.1018
LowWindSp*HighWindSp	13	1801.775688	138.598130	1.89	0.0359

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Appendix E: Survey to Trucking Companies

- High Wind Warning System Survey
- High Wind Hazards Survey

High Wind Warning System Survey

High Wind Warning System to Prevent Overturning Truck Crashes on Interstate-25 in the Bordeaux Area

The I-25 corridor known as Bordeaux (~Milepost 70.0) between Cheyenne and Casper has frequent high wind events and is a known hazard area for overturning truck crashes due to high winds. The Wyoming Department of Transportation and the University of Wyoming are developing a high wind warning system to address safety concerns in this area. This work will result in a warning system that may also be deployed at other high wind hazard areas.

1. Please describe your association with the trucking industry.

Other, please specify
- ☐ Driver
- ☐ Dispatcher
- ☐ Trucking Company Representative
- ☐ Check all that apply.

2. Have you traveled I-25 in the Bordeaux area of Wyoming (I-25, milepost 70)?

○ Yes ○ No

3. If you answered yes to the previous question, please describe the frequency at which you travel the Bordeaux area?

- ○ Less than once per month
- ○ 1-2 times per month
- ○ 3-4 times per month
- ○ 2-3 times per week
- ○ Daily or more

4. Have you traveled I-25 in the Bordeaux area of Wyoming (I-25, milepost 70) in what you would consider high wind conditions?

○ Yes ○ No

5. Please describe the type of trips you typically make?

- ☐ Short Haul
- ☐ Intermediate Haul
- ☐ Long Haul
- ☐ Mixed

High Wind Warning System

The research team is looking for feedback on the proposed High Wind Warning System. The survey is divided into three parts: Information sources (how), information locations (where), and type of information (what). Survey responses can be based on experience with the Bordeaux area of Wyoming (I-25, Milepost 70) or with other high wind hazard areas.

6. There are several ways WYDOT can provide high wind warning information to travelers. Which of the following methods do you currently use to receive road condition and/or weather information?

Check all that apply.

- ☐ WYDOT Traveler Website (www.WyoRoad.info)
- ☐ 511 (1-888-WYOROAD) Phone Service
- ☐ 511 Notify Text Message Service
- ☐ Roadside Dynamic Message Signs
- ☐ Highway Advisory Radio
- ☐ Broadcast Radio
- ☐ Television
- ☐ Other, please specify

7. From the sources listed in the previous question what is your preferred source of information?

-- None --

8. As part of the proposed high wind warning system at the Bordeaux area (I-25, Milepost 70),WYDOT is consider adding additional information sources. Below are traveler information sources being considered? Please indicate which information source(s) would be of use to you as you travel this specific corridor.

Please check all that apply.

- ☐ Additional Dynamic Message Signs
- ☐ CB Alert System (see below)

The CB Alert System (also known as CB Wizards) would broadcast warning messages over CB Channel 19 at 30, 60 or 90-second intervals. When activated the system would select one of three prerecorded warning messages based on three alert levels for high wind conditions. The device monitors CB transmissions and only broadcasts during lulls between transmissions.

9. Other than the existing or proposed information sources are there any other methods of getting information to travelers that you would recommend for the high wind warning system?

10. Please provide any additional comments on traveler information sources.

Locations to Receive Information

11. The next series of questions deal with where it is preferable to receive the high wind warning information. For the proposed Bordeaux High Wind Warning System there are several points along the I-25 corridor in Wyoming where information could be provided for use in travel decisions. Please indicate at what points high wind warnings for the Bordeaux area would be useful.

Select all that apply.

- ☐ Immediately Prior (<0.5 miles) Hazard Area
- ☐ Interchanges Prior to Hazard Area (~2 miles, no services)

- Towns closest to Hazard Area (Wheatland and Chugwater)
- Major Cities Prior to Hazard Area (Casper and Cheyenne)
- Prior to entering Wyoming
- Other, please specify

12. When provided with high wind hazard warnings what type of actions do you typically take?

Select all that apply.

Other, please specify

- Choose a different route to avoid hazard area.
- Stop and wait out the high wind hazard.
- Drive slower.
- Do nothing.
- Other, please specify

13. General comments about where to provide high wind information and what actions you typically take with the information.

Type of High Wind Warning Information

14. What types of information are useful to receive regarding high wind conditions?

Select all that apply.

- Average Wind Speeds (MPH)
- Wind Gust Speeds (MPH)
- Wind Direction
- Wind Forecasts
- Road Surface Condition
- Other, please specify

15. Some information sources have limited ability to convey information. From the previous list, which is the most important information type?

-- None --

Other, please specify

15. Some information sources have limited ability to convey information. From the previous list, which is the most important information type?

-- None --

16. General comments about the specific information you would like to receive about high wind warnings.

17. If you would like to be contacted to discuss this project further or to be updated on the project as things develop please provide your contact information below.

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High Wind Hazards

Background

As part of the high wind hazard system project we are looking for information is in the area of High Wind Hazards and the dynamics of truck crashes due to high winds. One of the outcomes from this work is a risk model that will help further define the relationship between wind speeds, truck configurations, and truck weight. We are compiling information on recent crashes in the Bordeaux area in order to verify some theoretical models and wind tunnel results. We are looking also looking for general information from the trucking industry on hazards.

1. Please describe your association with the trucking industry.
   Check all that apply.
   - ☐ Driver
   - ☐ Dispatcher
   - ☐ Company/Owner
   - ☐ Other, please specify

2. Have you traveled I-25 in the Bordeaux area of Wyoming (I-25, milepost 70)?
   ○ Yes ○ No

3. If you answered yes to the previous question, please describe the frequency at which you travel the Bordeaux area?
   - ○ Less than once per month
   - ○ 1-2 times per month
   - ○ 3-4 times per month
   - ○ 2-3 times per week
   - ○ Daily or more

4. Have you traveled I-25 in the Bordeaux area of Wyoming (I-25, milepost 70) in what you would consider high wind conditions?
   ○ Yes ○ No

5. Have you traveled high wind hazard areas other than Bordeaux?
   ○ Yes ○ No

6. If you answered yes to the previous question please breifly describe the location of the high wind hazard area that you are familiar with.

7. Please describe the type of trips you typically make?
   - ☐ Short Haul
   - ☐ Intermediate Haul
   - ☐ Long Haul
   - ☐ Mixed

8. Have you ever been in a truck crash in the Bordeaux area where high winds were a cause or a contributing factor?*
   ○ Yes ○ No

Bordeaux High Wind Crash

The following questions are related to the crash at the Bordeaux area. There are many things unknown about the dynamics of overturning truck crashes due to high wind so this information is very valuable in quantifying the risk of vehicles in different wind conditions. If you have information on more than one crash please answer the questions for one crash at a time.

9. What was the approximate date of the crash?

Approximate date is adequate if exact dates not known.

10. What was the approximate wind speed and/or wind gust speed at the time of the crash?

If known.

11. Please describe the configuration of the truck involved in the crash. Please include a best guess for the weight of your vehicle at the time of the crash.

12. Please describe the events of the crash including things such as approximate locations, direction of travel, speed of travel, and any evasive actions taken prior to and during the crash sequence.

13. Please provide any additional information or comments about this crash event.

14. Do you have another Bordeaux crash during high wind conditions to describe?

○ Yes ○ No

Bordeaux High Wind Crash 2

The following questions are related to the crash at the Bordeaux area. There are many things unknown about the dynamics of overturning truck crashes due to high wind so this information is very valuable in quantifying the risk of vehicles in different wind conditions. If you have information on more than one crash please answer the questions for one crash at a time.

15. What was the approximate date of the crash?

Approximate date is adequate if exact dates not known.

16. What was the approximate wind speed and/or wind gust speed at the time of the crash?

If known.

17. Please describe the configuration of the truck involved in the crash. Please include a best guess for the weight of your vehicle at the time of the crash.

18. Please describe the events of the crash including things such as approximate locations, direction of travel, speed of travel, and any evasive actions taken prior to and during the crash sequence.

19. Please provide any additional information or comments about this crash event.

20. Do you have another Bordeaux crash during high wind conditions to describe?

○ Yes ○ No

Bordeaux High Wind Crash 3

The following questions are related to the crash at the Bordeaux area. There are many things unknown about the dynamics of overturning truck crashes due to high wind so this information is very valuable in quantifying the risk of vehicles in different wind conditions. If you have information on more than one crash please answer the questions for one crash at a time.

21. What was the approximate date of the crash?

Approximate date is adequate if exact dates not known.

22. What was the approximate wind speed and/or wind gust speed at the time of the crash?

If known.

23. Please describe the configuration of the truck involved in the crash. Please include a best guess for the weight of your vehicle at the time of the crash.

24. Please describe the events of the crash including things such as approximate locations, direction of travel, speed of travel, and any evasive actions taken prior to and during the crash sequence.

25. Please provide any additional information or comments about this crash event.

High Wind Truck Crashes

The project is focused on developing a high wind warning system for the Bordeaux area but is also interested in expanding the knowledge base on high wind truck crashes generally. Any information you can provide on these types of crashes is beneficial to the project.

26. Do you have a high wind crash to describe that occurred in an area other than Bordeaux?

○ Yes ○ No

High Wind Truck Crash Information

27. Please describe the location of the crash including as much detail as possible.
    Include milepost if known.

28. What was the approximate date of the crash?
    Approximate date is adequate if exact dates not known.

29. What was the approximate wind speed and/or wind gust speed at the time of the crash?
    If known.

30. Please describe the configuration of the truck involved in the crash. Please include a best guess for the weight of your vehicle at the time of the crash.

31. Please describe the events of the crash including things such as approximate locations, direction of travel, speed of travel, and any evasive actions taken prior to and during the crash sequence.

32. Please provide any additional information or comments about this crash event.

General Comments

33. What type of actions do you make when confronted with high wind conditions?
    - [ ] Select a different route to avoid hazard areas.
    - [ ] Stop and wait out the hazard condition.
    - [ ] Reduce speed.
    - [ ] Drive on shoulder to change vehicle angle relative to wind.
    - [ ] Drive adjacent to another truck to shield truck from wind forces
    - [ ] Other, please specify

34. Please provide any comments regarding defensive driving techniques (such as those listed in the previous question) during high wind conditions.

35. Please provide any additional comments and information about truck crashes in high wind conditions.

36. If you would like to be contacted to discuss this project further or to be updated on the project as things develop please provide your contact information below.

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