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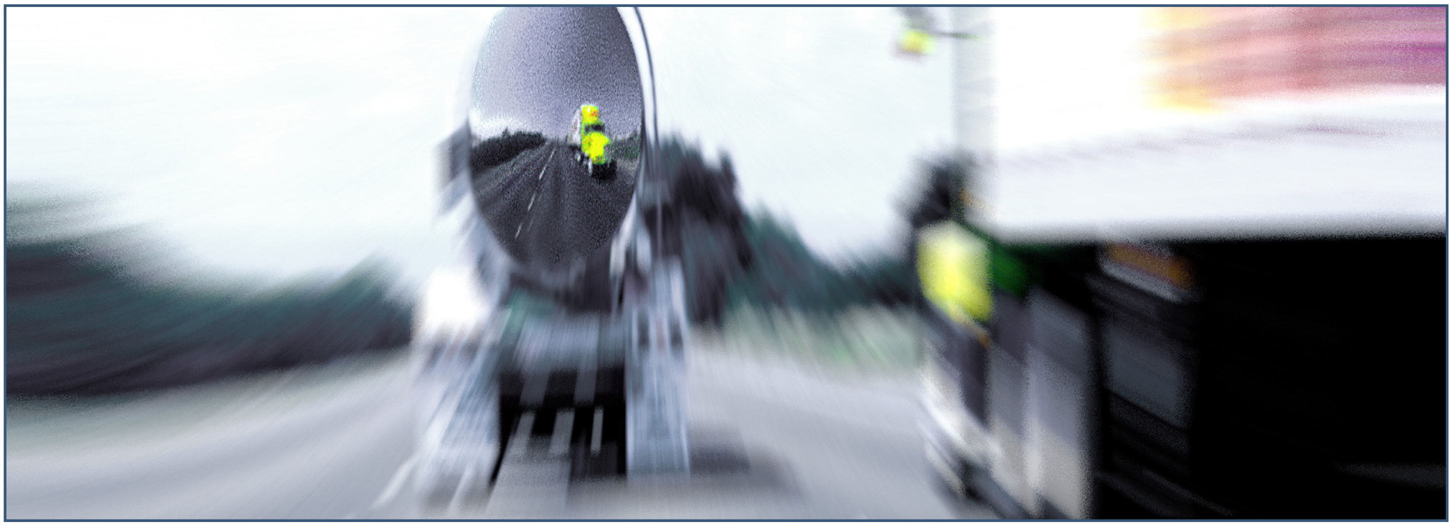
Wyoming Freight Movement System Vulnerabilities and ITS



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WYOMING FREIGHT MOVEMENT SYSTEM VULNERABILITIES AND ITS

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1. INTRODUCTION

This report summarizes the work performed during the second phase of a two-phase research project. The first phase focused on two main areas: freight safety and wind vulnerability, and the identification of critical infrastructure. Phase I also tackled another major but less defined task in bringing together information from numerous sources to provide agencies in Wyoming with a general understanding of freight movement in the state. The results from the first phase can be found in the report entitled “Wyoming Freight Movement and Wind Vulnerability,” published by the Mountain-Plains Consortium (Young et al. 2005).

The objectives of the second phase were to continue the efforts on freight safety with respect to high wind conditions and to propose a system utilizing intelligent transportation system technology to mitigate high wind hazards. These two tasks are summarized in Section 2, High Wind Freight Crashes in Wyoming, and Section 3, Use of ITS for Operation of Roadway Segments in High Wind Conditions.

2. HIGH WIND FREIGHT CRASHES IN WYOMING

This section develops a quantitative model that correlates overturning freight vehicle crash records in Wyoming to measured wind speeds at nearby weather stations. The database consists of 14,700 truck crashes from 1994 through 2003 and wind speed and gust information from 21 weather stations. A binary logit model was estimated from the data to determine if there was significant correlation between weather station wind data and the likelihood that the crash was of the overturning type. While it is reasonably known that local wind speeds at the crash location are critical in predicting overturning truck crash likelihood, it was not known if distant weather station data were an adequate predictor of these crash types. The results from this work indicate that weather station data can be used as a predictor of overturning crashes. This work provides the necessary first step for the development of operational rules for roadway sections that run a high risk of overturning truck crashes in high wind conditions.

2.1 Introduction

In the United States, large trucks (vehicles with a gross vehicle weight greater than 10,000 pounds) account for about 3% of the vehicle fleet, 7% of the total vehicle miles traveled, and are associated with 12% of the total fatality count (Cerrelli 1998). This role that trucks play in fatal crashes has led to significant research into the factors behind large truck crashes (Miaou 1994; Campbell 1991; Joshua and Garber 1990; Saccomanno and Buyco 1988; Chirachavala and Cleveland 1985). Considerable work has also been done in the area of large trucks and crash severity factors (Khorashadi et al. 2005; Chang and Mannering 1999; Alassar 1988; Shao 1987; Chirachavala et al. 1984).

Large vehicle crashes, in particular freight vehicles, are critical for agencies to consider both due to the high likelihood of resulting injuries and the disruption to the transportation system these crashes cause. One type of large truck crash is the overturning crash where a single truck is overturned due to geometric alignment, steep embankments, or high wind conditions. The latter condition is a situation that cannot be remedied by roadway design modifications, and the most promising countermeasure is the development of operational guidelines for the facility that consider the risk level of various wind conditions.

This article analyzes the number of overturning truck crashes that occurred during high wind conditions and develops a model to determine if a correlation of measured wind speeds at weather stations and overturning truck crashes exists. While it is understood that the wind speed at the crash location is a factor in the crash, it is not known if the measured wind speed at a remote weather station is an adequate predictor of the crash occurrence. If the correlation between the measured wind speed and crash occurrence is found, a model could be developed for predicting the probability of trucks being overturned by high winds given the measured wind speed at the weather station. This information will help transportation agencies faced with operating roadways in high wind conditions in making better decisions regarding when the road should be closed because of hazardous wind conditions, in particular rules for closing the roadway to large trucks.

2.2 Literature Review

Work performed at the University of Manitoba Transport Institute used a computer simulation model of gusting winds to analyze the instability of large vehicles under varying wind speeds, loading situations, and road surface conditions (Summerfield and Koiser 2001; Koiser 1989). The study found that fluctuating winds produced more instability than steady winds and that resonance was an important factor. The study also found that empty or lightly loaded truck and trailer combinations became exponentially more unstable as the wind speeds increased.

The Nevada Department of Transportation (NDOT) performed a study to determine the critical wind values that trigger vehicle instability (Saiidi and Maragalas 1995). The single trailer truck was determined to be the most vulnerable to overturning and sliding during high wind conditions. (Note, the sliding condition is a concern when high winds and slippery road conditions coincide.) The equations derived in this research yielded a critical wind speed of 40 mph for the overturning condition and 29 mph for the sliding condition for the single trailer truck (assuming a 45-foot by 14-foot vehicle profile). Considerable work on the effects of wind and vehicles has also been done by Baker (1991a, b, c). This research derives an analytic framework for understanding the aerodynamic forces and movements on vehicles. Baker's work includes wind tunnel testing, computer simulation software, and a full-scale calibration on crash data from a severe wind storm in 1990 (Baker 1992). The calibration study concluded that overturning crashes were the most frequent type of wind-induced accident, accounting for 47% of the crashes during the storm event. Course deviation accidents were the second most frequent, accounting for only 19% of the total. This research also concluded that traffic should be restricted if wind gust speeds exceeded 17 to 20 meters per second (38 to 45 miles per hour).

Edwards (1996; 1998) investigated the relationship between accident severity and a variety of recorded weather conditions. The research found the wind related effects to be inconclusive in that in some locations, high wind speeds resulted in lower severity crashes while in others, higher severity crashes were found during high wind conditions.

This prior work is important for the development of operational rules, but all previous work utilizes localized wind forces. If the correlation between the crash site conditions and measured wind speeds at potentially distant weather stations cannot be made, no scientifically based operational rule can be developed since it is impossible at this time to measure wind speeds along entire roadway segments.

2.3 Data Description

This research effort utilizes two main data sources. One is the crash records for all crashes involving heavy vehicles in the state of Wyoming for a 10-year period and the other is weather data from the 21 weather stations located throughout the state.

The crash data were obtained from the Highway Safety Program at the Wyoming Department of Transportation (WYDOT) and consisted of 14,700 crashes that involved a truck from 1994 to 2003. The crash database maintained by WYDOT consists of all reported crashes occurring in the state regardless of the jurisdiction of the roadway the crash occurred on. The crash file contained information related to the crash, such as date, time, county, highway number, milepost, number of vehicles involved, number of people injured and killed, road, weather, and lighting conditions, and type of crash. The vehicle file contained information for each truck involved, such as vehicle make and year, trailer type, and cargo type. During the 10-year period, 14% (2,095) of 14,700 crashes were of the overturning type.

Crashes are required to be reported if they incur more than $1,000 in damage or if an injury occurs. As with all work utilizing crash data, the issue of underreporting of crashes is a concern. Typically, underreporting of crashes is higher for low damage crashes. In this research, it is unlikely that overturning crashes would have a large number of unreported crashes because of the type of crash and the level of damage and delay that occurs. The other types of crashes in the dataset, on the other hand, may be more susceptible to underreporting issues.

In order to quantify the overturning truck problem more fully, a one-tenth mile grid analysis was performed for the overturning truck crashes throughout the state of Wyoming. This entailed using a Geographic Information System (GIS) to overlay a map of the overturning crash locations with a grid and counting how many crashes occurred within each tenth mile cell. The results of this analysis are shown in Figure 2.1. This map shows the locations with the frequencies of five or more overturning crashes for a 10-year period from 1994 to 2003. As is shown in the figure, there are five locations in the state with high frequencies of overturning truck crashes: I-80, approximately 35 miles west of Laramie near Arlington (82 crashes); I-25, north of Cheyenne and about 10 miles south of Wheatland (64 crashes); I-80, 4 miles west of Evanston (11 crashes); US-30, approximately 3 miles east of Kemmerer (8 crashes); and at the I-80 and I-25 interchange in Cheyenne (17 crashes). The overturning crashes near Evanston occurred at the port of entry/rest area and appear to be related to roadway geometry since none of the crashes occurred during strong winds or ground blizzards. Likewise, the crashes near Kemmerer did not occur during windy conditions and all occurred on a curve. The crashes at Cheyenne also appear not to be wind related, but rather due to the tight curves on the ramps at the cloverleaf interchange at the junction of I-80 and I-25. That leaves only the Arlington and the south Wheatland locations as areas where strong wind conditions are likely causing high hazard areas with respect to overturning truck crashes. This result led to the development of models for the Arlington and south Wheatland weather stations in addition to a statewide model. The dataset for the two regional models are those crashes that are associated with the respective weather stations. This association is described in greater detail in Section 2.4.

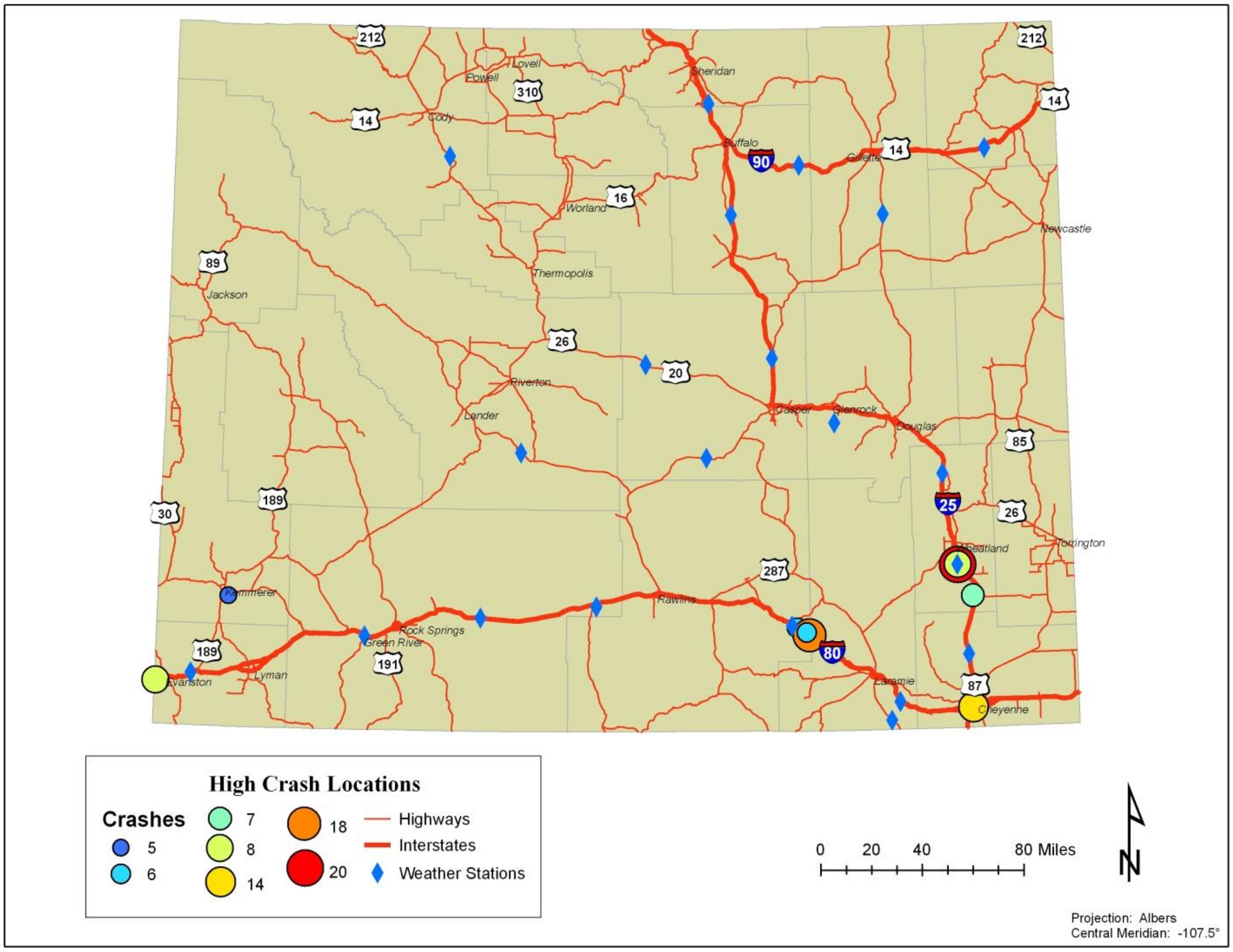

Figure 2.1 Overturning truck crashes in Wyoming, 1994-2003

Several binary variables were created using information in the crash file that was considered likely to be associated with overturning truck crashes. The first is the response variable OVERTURN. This variable was set to 1 if the crash type was overturning and 0 otherwise. The other crash types include angle collisions, head on, left or right turn collisions, rear ends, sideswipes, and unknown. A variable SLICK was created to account for road surface condition at the time of the crash and was set to 1 if the road was icy, snowy, or slushy and 0 otherwise. Other roadway conditions include dry, muddy, or unknown. The last variable created from the crash records was STRAIGHT. This variable was set to 1 if the crash occurred on the straight section of the road and 0 if the roadway was curved or unknown.

Wind Data

In order to determine if a relationship existed between measured wind speed and trucks overturning, wind data from around the state were needed in sub-hourly intervals. These data were obtained from the Wyoming State Climate Office for the 21 weather stations across the state. Data from these stations were available from 1994 through October 2002 in approximately 15-minute intervals, resulting in over six million records. Weather data for 2003 were not yet available.

The truck crashes were then associated with the closest weather station using GIS and the straight line distance between the reported crash location and the weather stations. Once the nearest weather station to each crash was known, the wind data for the reported time of the crash was added to the crash database records. Before any of the weather data were linked to the crash data, the weather time data were changed from Greenwich Mean Time to Mountain Standard Time, and the wind speed data converted from knots to miles per hour. Macros were written in Microsoft Excel using Visual Basic for Applications (VBA) to link the weather data. The macro code looped through the crash database to find a crash that was associated with the current weather station. It would then loop through the weather data to find the date of the crash. After the date of the crash was found, the macro would check the time of each weather data entry until the difference between the crash time and the weather time started to increase after initially decreasing.

A minimum difference between the two times ensured the closest correlation between the weather crash data. The macro finished by adding the wind speed, gusts, and direction, as well as the time of the observation to the crash database. The average difference in time between the observed weather time and the time of the crash was 20 minutes. Any crash record that did not contain wind data was excluded from the model estimation process. Of the 14,700 truck crashes throughout the state, 14% (2,095) were overturning crashes. A total of 9,281 crashes (1.397; 15% overturned) had the associated wind data and were able to be used in the analysis.

This process added four wind variables to the crash database: wind speed, wind gust, wind direction, and distance of the crash from the weather station. The wind direction was given in degrees from north, which can be difficult to interpret as a coefficient since both 0° and 360° refer to the same direction. This numerical discrepancy in wind direction was corrected by creating binary indicator variables that have a value of one if the wind is coming from that direction or zero otherwise. The directions used were east, south, and west. North was not used to avoid multicollinearity.

According to the previous literature on wind effects on large vehicles from wind tunnel experiments, the critical condition is a large difference between wind speeds and wind gusts. To account for this, a variable was created that took the difference between measured wind gusts and measured wind speeds. This variable was called WindGust_WindSp.

To summarize, Table 2.1 is a list of the eight variables considered in the modeling process. For the initial variables, the mean, median, standard deviation, minimum, and maximum values of the variables are given for the three data sets. Note that the Arlington and Wheatland datasets are subsets of the statewide data.

Table 2.1 Descriptive Statistics for Model Variables

Statewide Model (N = 9,281)					
Variable	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**
Overturn	0.1505	0.3576	0	0	1
Straight	0.2131	0.4095	0	0	1
Slick	0.4635	0.4987	0	0	1
Wind_Speed (mph)	16.7642	12.0782	14.0000	1.0000	77.0000
WindGust_WindSp (mph) [wind gust – wind speed]	3.2279	2.4132	3.0000	0	26.0000
Dist_Miles	19.9332	19.2794	16.5726	0.0049	130.6181
W_Wind_DIR	0.4883	0.4999	0	0	1
E_Wind_DIR	0.1424	0.3495	0	0	1
S_Wind_DIR	0.1695	0.3752	0	0	1
Arlington Model (N=1,255)					
Variable	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**
Overturn	0.2175	0.4127	0	0	1
Straight	0.2080	0.4060	0	0	1
Slick	0.6638	0.4726	1.0000	0	1
Wind_Speed (mph)	27.5143	15.5541	28.0000	1.0000	77.0000
WindGust_WindSp (mph) [wind gust – wind speed]	4.9760	2.9850	4.6000	0	26.0000
Dist_Miles	46.2486	32.4275	38.2602	0.0162	128.8903
W_Wind_DIR	0.8159	0.3877	1.0000	0	1
E_Wind_DIR	0.1243	0.3301	0	0	1
S_Wind_DIR	0.0136	0.1156	0	0	1
Wheatland Model (N=258)					
Variable	**Mean**	**Std Dev**	**Median**	**Minimum**	**Maximum**
Overturn	0.3876	0.4882	0	0	1
Straight	0.2636	0.4414	0	0	1
Slick	0.1473	0.3551	0	0	1
Wind_Speed (mph)	28.0186	18.8608	24.5000	1.0000	73.0000
WindGust_WindSp (mph) [wind gust – wind speed]	5.1196	3.7611	4.0000	0	20.0000
Dist_Miles	19.4560	16.0994	14.6067	0.0211	45.7681
W_Wind_DIR	0.6240	0.4853	1.0000	0	1
E_Wind_DIR	0.1279	0.3346	0	0	1
S_Wind_DIR	0.1047	0.3067	0	0	1

2.4 The Model

To analyze whether the wind speed was correlated to an overturning crash type, a model that could predict discrete outcomes was needed. A binary model was needed since there were only two possible outcomes—overturned or non-overturned crash type. To accommodate the binary model, the response variable OVERTURN was created, containing a one if the crash type was overturned and zero otherwise. The general form for the logistic model used in this work is shown in Equation 1 below:

$$P = \frac{e^{\underline{\beta}}}{1 + e^{\underline{\beta}}} \qquad (1)$$

$$\underline{\beta} = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k$$

As β becomes larger in a positive sense, *P* would approach one, which indicates that the probability of a success (in this case, a truck overturning) increases. This equation calculated the probability of a truck crash being an overturning event given the fact that a truck crash occurred since the data set contained reported crashes. The statistical software program *SAS* with the *Logistic* procedure was used to estimate the maximum likelihood probability function.

Variable Associations

Prior to estimating the logit model, the associations between all the variables discussed in Section 2, including the response variable, were investigated by determining the correlation among the variable pairs. For comparison of continuous variables, the Pearson *r* was calculated. For continuous – dichotomous pairs, the Point-Biserial correlation, r_{pb}, was calculated. And finally, for dichotomous variable pairs, the Phi coefficient, φ, was calculated. The correlation and significant level for all variable pairs is reported in Table 2.2.

Table 2.2 Variable Correlation Results

	Overturn	Straight	Slick	Wind_ Speed	Windgust_windsp	Dist_Miles	W_Wind_DIR	E_Wind_DIR
Straight	-0.1098 (<0.001)							
Slick	-0.1188 (<0.001)	0.01643 (0.1135)						
Wind_ Speed	0.17530 (<0.001)	0.00369 (0.7220)	0.18397 (<0.001)					
Windgust_windsp	0.16528 (<0.001)	0.01359 (0.1906)	0.08237 (<0.001)	0.75369 (<0.001)				
Dist_Miles	0.00341 (0.7423)	0.04593 (<0.001)	-0.18159 (<0.001)	-0.18591 (<0.001)	-0.14187 (<0.001)			
W_Wind_DIR	0.07826 (<0.001)	-0.01257 (0.2260)	0.05286 (<0.001)	0.35627 (<0.001)	0.26587 (<0.001)	-0.13991 (<0.001)		
E_Wind_DIR	-0.04137 (<0.001)	-0.00207 (0.8420)	0.00879 (0.3972)	-0.16446 (<0.001)	-0.13104 (<0.001)	0.03365 (0.0012)	-0.39813 (<0.001)	
S_Wind_DIR	-0.02230 (0.0317)	0.01105 (0.2871)	-0.13196 (<0.001)	-0.20364 (<0.001)	-0.16145 (<0.001)	0.05935 (<0.001)	-0.44130 (<0.001)	-0.18411 (<0.001)

In each cell, the numbers give the correlation results (r, r_{pb}, or φ) and the significance level, respectively.

At the 0.05 significance level, the response variable OVERTURN is associated with all other variables except the distance variable. STRAIGHT is only associated with the response variable and the distance variable. Other than the SLICK and east wind direction variable, all other variable pairs were also found to have significant association.

Of the significant associations between variable pairs, OVERTURN and the wind speed variables (Wind_Speed and WindGust_WindSp) had positive associations, as would be expected. The association between OVERTURN and STRAIGHT, and the east and south wind direction variables were negative.

Binary Logit Model Development

The model was developed by putting all eight variables discussed in Section 2 into the model at the beginning of the analysis and removing variables one at a time that were not found to be significant. A variable was considered significant if its coefficient is statistically different from zero. This was accomplished by testing the null hypothesis of H_0: $\beta_j = 0$, where β_j was the coefficient of the j^{th} variable. The model output included the associated p-value for each test. The p-value is a measure of the probability of the hypothesis test being true. The hypothesis tested in this situation is that the coefficient is not statistically different from zero, which was used as a decision rule to decide whether the variable should stay in the model. A p-value of 0.05 was chosen to serve as the criteria by which a variable would remain in the model. Therefore, any variable with a p-value less than 0.05 ensures that less that 5% of the observations would indicate that the coefficient should be zero.

Using this decision rule, any variables with a p-value greater than 0.05 were removed from the model and any with a p-value less than 0.05 remained. Variables were removed by selecting for removal the one with highest p-value above 0.05. The model was then rerun and the next variable with the highest p-value above 0.05 would be removed. This process was repeated until all the variables had a p-value below 0.05. The four weather variables in the crash database include wind speed, wind gust, wind direction, and distance of the crash to weather station.

Model Results

Three models were developed (Statewide, Arlington, and Wheatland) to determine whether the wind speed measured at the weather station is correlated to overturning truck crashes. When the coefficient β_i is positive, the corresponding x_i will increase the probability of an overturning crash as x_i increases. Conversely, if β_i is negative, an increase in the variable x_i will reduce the probability of an overturning crash. For model coefficient interpretation, it is important to remember that β_j represents the change in the *logit* of the probability associated with a unit change in the *k*-th predictor when all other predictors are held constant and not the direct change in probability.

The statewide model used the full 9,281 crash records that had wind data associated with them. All eight variables (see Table 2.1) were estimated in the initial model. As discussed in Section 3.2, the variables with the highest p-values were then removed one at a time until all the remaining p-values were below 0.05 for the final model. Table 2.3 shows the initial and final model coefficient and p-value results.

For the Arlington model, 1,255 crash records were analyzed and of these, 273 (22%) were overturning crashes. All 16 variables listed previously were placed in the model at the beginning of the analysis. The area for the station south of Wheatland had 348 truck crashes and 34% (119) of these overturned. Weather data were available to analyze 258 (100; 39% overturned) of these crashes.

Table 2.3 Logit Model Results

STATEWIDE	Initial Model		Final Model	
Variable	**Coeff.**	**p-value**	**Coeff.**	**p-value**
INTERCEPT	-2.4305	<.0001	-2.3385	<.0001
SLICK	-0.9018	<.0001	-0.9172	<.0001
WIND_SPEED	0.0363	<.0001	0.0375	<.0001
WINDGUST_WINDSP	0.0300	0.0254	0.0298	0.0251
STRAIGHT	0.7144	<.0001	0.7170	<.0001
DIST_MILES	0.0071	0.2635		
E_WIND_DIR	-0.0055	0.9616		
S_WIND_DIR	0.0430	0.6844		
W_WIND_DIR	0.1262	0.1449		
ARLINGTON	**Initial Model**		**Final Model**	
Variable	**Coeff.**	**p-value**	**Coeff.**	**p-value**
INTERCEPT	-0.6835	0.0850	-1.0408	<.0001
SLICK	-1.2684	<.0001	-1.2552	<.0001
WIND_SPEED	0.0226	0.0020	0.0220	0.0024
WINDGUST_WINDSP	0.0919	0.0048	0.0937	0.0039
STRAIGHT	0.0754	0.6740		
DIST_MILES	-0.0049	0.0404	-0.0049	0.0406
E_WIND_DIR	-0.4678	0.2634		
S_WIND_DIR	-0.6740	0.3641		
W_WIND_DIR	-0.8858	0.0233	-0.5115	0.0368
WHEATLAND	**Initial Model**		**Final Model**	
Variable	**Coeff.**	**p-value**	**Coeff.**	**p-value**
INTERCEPT	-2.6502	0.0018	-2.5643	<.0001
SLICK	-1.6485	0.0071	-1.6771	0.0053
WIND_SPEED	0.0381	0.0730	0.0552	0.0035
WINDGUST_WINDSP	0.2139	0.0207	0.2063	0.0256
STRAIGHT	1.3117	0.0040	1.2759	0.0040
DIST_MILES	-0.0460	0.0013		
E_WIND_DIR	-0.7724	0.5290		
S_WIND_DIR	0.1835	0.8401		
W_WIND_DIR	0.8081	0.2728		

The SLICK variable that accounts for the road surface conditions was significant in all three models and was negative in all cases, most likely due to the lower speeds and more cautious driving that occurs when the roadway is icy. The coefficient for STRAIGHT, which accounted for the geometric conditions of the roadway at the accident location, was significant in the statewide and Wheatland models and were positive in these cases. The positive influence on overturning crashes is likely due to the fact that on straight roadway segments the trucks can be lined perpendicular to the wind forces for longer periods of time.

Regarding wind variables, which was the principle focus of the research, wind speed and the difference between wind gust and wind speed variables were significant in all three models. In all cases, the estimated coefficients were positive, indicating that higher speeds and higher differences lead to higher likelihood of overturning crashes. While this was an expected result, the importance of the research is in determining that these measured values were found to be significant in the model.

The distance to the weather station variable was only found to be significant in the Arlington model. This weather station has been identified by the transportation agency as being poorly located for the weather concerns in that area. The significance of this variable appears to confirm that. Plans are underway to relocate the weather station closer to the overturning crash locations.

Of the binary wind directional variables, only W_Wind_Dir was found to be significant for the Arlington model. Table 2.3 shows that, of all three models, the wind direction in the Arlington dataset is more consistently from the west than the data for the other two models. The Arlington model is most likely picking up on this consistency and that is why this is the only model where this variable was found to be significant.

Second Order Interactions

The last step in the model development was to test for second order interactions in the wind variables. All three models were re-estimated with two new interaction variables, wind speed squared, and the difference between wind gust speed and wind speed squared. The initial and final model estimations for the three models are shown in Table 2.4. All three final models include one or both of the new second order variables. Wind speed squared was a significant variable in all three models. The difference variable between wind gust and wind speeds squared variable was significant in the statewide and Wheatland models but not in the Arlington model.

Table 2.4 Logit Model Results with Second Order Wind Interactions

STATEWIDE	**Initial Model**		**Final Model**	
Variable	**Coeff.**	**p-value**	**Coeff.**	**p-value**
INTERCEPT	-1.8753	<.0001	-1.8005	
SLICK	-0.7842	<.0001	-0.8038	<.0001
WIND_SPEED	-0.0278	0.0028	-0.0255	0.0009
WINDGUST_WINDSP	-0.00237	0.9510		
STRAIGHT	0.6992	<.0001	0.7026	<.0001
DIST_MILES	0.00242	0.1209		
E_WIND_DIR	-0.0713	0.5327		
S_WIND_DIR	0.0105	0.9210		
W_WIND_DIR	0.1239	0.1545		
$WIND\_SPEED^2$	0.00120	<.0001	0.00118	<.0001
$WINDGUST\_WINDSP^2$	0.00471	0.0829	0.00454	0.0002
ARLINGTON	**Initial Model**		**Final Model**	
Variable	**Coeff.**	**p-value**	**Coeff.**	**p-value**
INTERCEPT	-0.4739	0.2569	-0.9240	0.0001
SLICK	-1.1510	<.0001	-1.0936	<.0001
WIND_SPEED	-0.0462	0.0465	-0.0484	0.0062
WINDGUST_WINDSP	0.1167	0.1792	0.0914	0.0057
STRAIGHT	0.0806	0.6545		
DIST_MILES	-0.00432	0.0728		
E_WIND_DIR	-0.2456	0.5607		
S_WIND_DIR	0.6266	0.3961		
W_WIND_DIR	-0.3357	0.4220		
$WIND\_SPEED^2$	0.00104	0.0015	0.00110	<.0001
$WINDGUST\_WINDSP^2$	-0.00149	0.7514		
WHEATLAND	**Initial Model**		**Final Model**	
Variable	**Coeff.**	**p-value**	**Coeff.**	**p-value**
INTERCEPT	-2.4344	0.0224	-2.8909	<.0001
SLICK	-1.4611	0.0193	-1.6240	0.0071
WIND_SPEED	-0.0717	0.2844		
WINDGUST_WINDSP	0.6587	0.0040	0.6289	0.0022
STRAIGHT	1.3030	0.0051	1.3021	0.0044
DIST_MILES	-0.0468	0.0016	-0.0467	0.0014
E_WIND_DIR	-1.0078	0.4222		
S_WIND_DIR	0.0393	0.9660		
W_WIND_DIR	0.8955	0.2293		
$WIND\_SPEED^2$	0.00146	0.1386	0.000643	0.0419
$WINDGUST\_WINDSP^2$	-0.0267	0.0254	-0.0257	0.0187

It is also interesting to note if the new interaction variables removed the original non-squared wind variables from the models. In the statewide model, the original difference variable (wind gust minus wind speed) was not found to significant, and in the Wheatland model, wind speed was not found to significant. The only change that occurred in the non-wind variables was the distance variable was included in the final model for Wheatland (Table 2.4) when it was not found to be significant in the earlier final model (Table 2.3).

2.5 Conclusions

This research effort merged crash data with weather station records to develop models relating wind conditions and the probability of overturning truck crashes. Two notable results emerged from this effort. The first is that wind variables such as wind speed and the difference between measured wind gust speed and average wind speed were found to be significant in the estimated models. Prior to this research, it was believed by some that wind conditions were too localized for weather station data to be adequate predictors of crash hazards.

The second notable result is the difference between models estimated for different areas. This work estimated models using the entire statewide data set and also at two regional sub-areas. The included variables and estimated coefficient results for each of these models were different enough that it is unlikely a single model could be developed that would be applicable to different roadway segments.

From the model results presented in Section 3, it is believed that wind data from weather stations can be used to estimate the probability of truck crashes being an overturning crash. The models showed that weather station data are promising for use in predicting risk for overturning crashes. Once again, these models were only developed to test the significance of the measured wind in predicting overturning crashes; they are not intended for use for making operational decisions at this time but instead are promising results that operational models will be able to be developed. The value of this research is in providing the foundation for developing site-specific operational guidelines based on weather station data and historic crash records.

3. USE OF ITS FOR OPERATION OF ROADWAY SEGMENTS IN HIGH WIND CONDITIONS

The focus of this research is truck safety in high wind conditions, in particular the use of Intelligent Transportation System technology for operating roadway segments during high wind conditions. The high wind conditions frequently present throughout the state of Wyoming cause trucks to overturn and often cause the closure of the road, resulting in large delays, economic impacts, and a loss of system reliability. The paper examines how critical weather conditions can be identified, what the various levels of operations could be depending on these conditions, means of identifying at-risk vehicles, and the benefits of implementing an advanced system for operating these high hazard roadway segments.

3.1 Introduction

The state of Wyoming experiences frequent severe wind conditions, particularly in the southern and eastern portions of the state along Interstates 80 and 25. These facilities also carry important long-distance freight traffic with average daily traffic volumes in 2003 of 11,380 and 5,700 on I-80 and I-25, respectively, and truck percentages of 55 and 20, respectively. Closure of these facilities, for any reason, results in large delays and significant economic impacts.

During the winter months, Wyoming often experiences wind speeds that are greater than 40 mph. Between the years 1994 and 2001, the weather station near Elk Mountain, Wyoming, on the I-80 corridor (see Figure 3.1) experienced maximum wind speeds in excess of 40 mph for 10% of time between mid-October and late February and 15% of the time between mid-December and mid-January (Curtis and Grimes 2004). The Bordeaux weather station along I-25 south of Wheatland, Wyoming, showed a similar trend for the same time period. The winds at Bordeaux had maximum speeds above 40 mph for 7% of the time from November to mid-February.

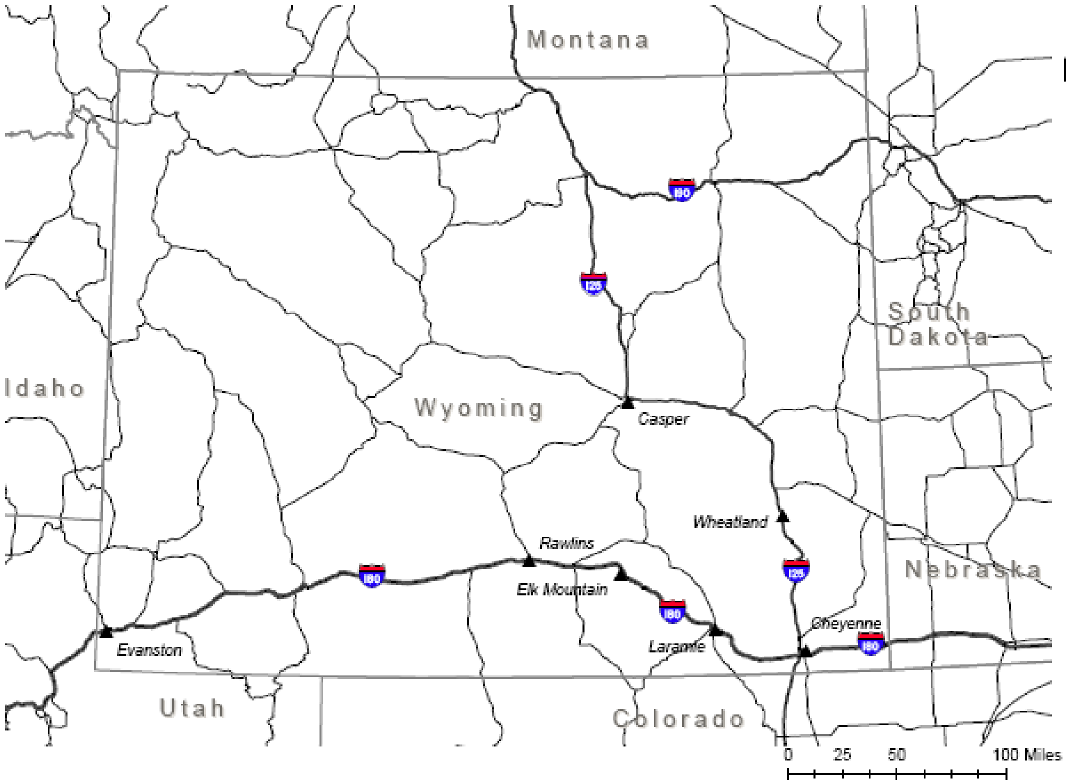

Figure 3.1 Map of Study Area

Roadway closures in the southeastern part of the state are relatively commonplace, particularly along the I-80 corridor. From April 1998 to March 2005 there were 96 days where some portion of the 200-mile segment of I-80 from Rawlins east to the Nebraska state line was closed, 29 of these closure days were wind related. The most frequent month for closures is March with 21 of the closure days during the time period. The total duration of closures for this time period was over 1,300 hours with an average closure time of eight hours.

The combination of large truck volumes and interstate closures create significant delay and economic losses, and political pressure is intense enough to keep the roadways open. Reliability is often a major concern for truckers traveling through Wyoming because of the frequency and duration of road closures, particularly along the I-80 corridor. This research looks at the development of Intelligent Transportation System (ITS) applications for minimizing the impacts to motorists while maximizing safety of roadways under high wind conditions. The research combines previous research in the area of wind forces on heavy vehicles and current research on crash risk and measured wind speeds to develop an operational framework.

3.2 Literature Review

The literature review for this research effort focused on two main areas: research on the critical wind conditions for heavy vehicles and the current operational rules for high wind conditions that were being implemented by transportation agencies.

Critical Wind Conditions

Winds can be particularly dangerous to high profile vehicles such as trucks. The study of the effects of wind on trucks is not only applicable to areas that are known for their strong wind conditions (such as Wyoming), but also in areas prone to hurricanes and other high intensity wind events. Most transportation officials currently reply on judgment to decide when the winds are too strong to continue evacuation during hurricane events.

While strong winds can overturn trucks, lighter winds with gusts may move the trailer and result in resonance and cause the trailer to move hazardously (Summerfield and Kosior 2001). This effect has been compared to a child on a swing: if pushed at the maximum extent, only a small force is needed to maintain or increase motion. The University of Manitoba Transport Institute conducted a computer simulation with gusting winds to determine the effect on large trucks (Summerfield and Kosior 2001). The criterion used was a 5° angle between the trailer and the tractor as the limit of when the truck becomes unstable and is likely to crash. It was determined that a light load and slick roads cause the truck to be more susceptible to winds, while slower vehicle speeds reduced the effect of wind.

Nevada DOT performed a study to determine critical wind values that trigger vehicle instability (Saiidi and Maragalas 1995). The study examined what wind force was necessary to cause a vehicle to overturn or slide. Two equations utilizing force equilibrium were used to determine the wind speed necessary to cause a vehicle to overturn or slide. The single trailer truck was determined to be the most vulnerable to overturning and sliding. The equations yielded a critical wind speed of 40 mph for overturning and 29 mph for sliding for the single trailer truck 45-feet long with a 14-foot profile height.

Considerable work has also been done in the United Kingdom on heavy vehicles in high wind conditions (Baker 1991a; Baker 1991b; Baker 1991c). Work by Baker derives an analytic framework for understanding the aerodynamic forces and movements on vehicles. This work includes wind tunnel testing, computer simulation software, and a full-scale calibration using crash data from a severe wind storm in 1990 (Baker 1992). The calibration study concluded that overturning crashes were the most frequent type of wind-induced accident, accounting for 47% of the crashes during the event. Course deviation accidents were the second most frequent, accounting for 19% of the crashes. This research also concluded that traffic should be restricted if wind gust speeds exceeded 17 to 20 meters per second (38 to 45 miles per hour).

Edwards (Edwards 1996; Edwards 1998) investigated the relationship between accident severity and a variety of recorded weather conditions. The research found the wind related effects to be inconclusive in that in some locations high wind speeds resulted in lower severity crashes while in others higher severity crashes were found during high wind conditions.

The previous phase of this research effort correlated measured wind speeds at weather stations and overturning truck crashes in Wyoming (Young and Liesman 2006). This work developed a probability model for these crashes utilizing variables for geometric features, road surface condition, and measured wind variables. The research found that wind speed, the difference between wind gust speed and wind speed, and in some cases wind direction were the significant wind variables in the model.

Operational Rules

Research has been done using Road Weather Information Systems (RWIS) to determine when weather conditions make traveling hazardous (Blomquist and Carson 2003). Many states and agencies have some type of RWIS; however, most are focused on precipitation, road surface conditions, and fog. The Federal Highway Administration's website listed six states with best practices of road weather management related to high winds (Goodwin 2003). Only four of the states' best practices directly relate wind speed to vehicle safety. Idaho DOT collects road, weather, and traffic conditions for 100 miles along Interstate 84 in the southeast part of the state (Goodwin 2003). This information is transmitted to a central computer that warns traffic managers when conditions are hazardous. Managers then decide what messages should be displayed on the dynamic message signs (DMS). The effectiveness of the DMS to influence driver behavior was studied between 1993 and 2000. This study found that speeds were reduced between 12% and 35% when advisory messages were displayed.

California DOT (Caltrans) relates high wind information to travelers in the Stockton-Manteca area on Interstate 5 and State Route 120 (Goodwin 2003). Information from Environmental Sensor Stations (ESS), which record weather conditions, and vehicle detection sites, which monitor traffic speed, is transmitted to three central computers at the Stockton Traffic Management Center (TMC). These computers process the data and automatically display warning messages on the DMS on the highways. When the wind speed is greater than 35 mph, the computer shows "HIGH WIND WARNING" on the DMS. Operators at the TMC have the ability to override the computer generated message, if the need arises.

Two of the states have systems in place that restrict high profile vehicles, such as large trucks, during high wind conditions. The Montana DOT monitors a 27-mile section of Interstate 90 in the Bozeman/Livingston area for high winds, and warns motorists when the wind speeds exceed 20 mph. A warning message—"CAUTION: WATCH FOR SEVERE CROSSWINDS"—is displayed on DMS when wind speeds are between 20 and 39 mph (Goodwin 2003). If the wind speeds reach 40 mph or greater, high profile vehicles are prohibited from that section of the interstate and instructed to exit. The diverted traffic is then routed through Livingston. The Montana DOT developed the wind speed criteria through their knowledge and judgment of the area (Gammon 2004).

The Nevada DOT has a high wind warning system on a seven-mile segment of US 395. Nevada measures both the average wind speed and the maximum wind gust and these values are used to determine when to display messages on DMS discouraging or prohibiting high profile vehicles from traveling on that road (Goodwin 2003). High profile vehicles are "not advised" when the average wind speed is above 15 mph or the wind gusts are above 20 mph. When the average wind speed exceeds 30 mph or the wind gusts are above 40 mph, high profile vehicles are prohibited.

A recent report by the Western Transportation Institute of automated wind warning systems evaluated three installations (Kumar and Strong 2005). One system was on US 101 between Port Orford and Gold Beach along the Oregon Coast, the second was on US 101 in Oregon at the Yaquina Bay Bridge, and the last along Interstate 5 in Siskiyou County, California. The Port Orford US 101 system uses an automated system to control flashing beacons on static signs that state “CAUTION HIGH WINDS NEXT 27 MILES WHEN FLASHING” located at either end of the corridor. Wind speeds exceeding 35 mph trigger the flashing beacons. The Yaquina Bay Bridge system utilizes variable message signs connected to a wind gauge. For winds 35 to 60 mph, “HIGH WINDS” is posted; wind speeds from 61 to 80 mph result in a “CAUTION: HIGH WINDS” message; and for speeds greater than 80 mph, the message is “CLOSED TO LARGE VEHICLES.” The I-5 system in California uses two variable message signs and one weather station. At the time of the report Caltrans was in the process of developing automated, weather responsive messages.

In Japan, real-time wind speed and air and pavement temperatures are displayed on roadside signs in addition to being provided to drivers through car navigation systems (Pisano et al. 2003). Japan is also utilizing variable speed limits based on wind speed, visibility, air, and road temperature conditions.

The Wyoming Department of Transportation (WYDOT) currently makes decisions regarding interstate closures due to high wind on a case-by-case basis at the district dispatch centers with input from the state highway patrol. This is by far the most common operational practice among state departments of transportation.

As mentioned in the literature references above, the critical wind speeds and wind gusts utilized by other agencies range from 20 to 45 mph, except in the case of the Yaquina Bay system where the wind thresholds ranges from 35 to 81 mph. While the lower wind condition thresholds may work adequately for other agencies, areas like Wyoming have more frequent and more severe high wind conditions that make these thresholds unfeasible given the travel delay and economic impacts incurred by closing the road during these conditions. Based on historic measured winds (Curtis and Grimes 2004), if WYDOT were to close the interstates to large trucks every time the wind speed was above 40 mph, trucks would be prohibited from traveling these corridors at least 7% to 10% of the time during four months of the year. This is the main motivation for this research effort to develop a decision system that relies on more than just measured wind speed.

3.3 Critical conditions

The operational rules developed for this research consider three critical conditions: wind speeds, surface conditions, and vehicle type. Each of these conditions, including models used to assess risk, will be discussed in the following sections.

Wind Conditions

The first question to be addressed is what measured wind speeds should trigger a decision by the agency. The literature suggests that wind speeds as low as 20 mph should be of concern for roadway operation. A prior phase to this research developed probability models for overturning crashes (Young and Liesman 2006) based on wind conditions from RWIS stations. Figure 3.2 graphs the probability curves as a function of measured wind speed and the difference between wind gust speed and wind speed assuming dry road conditions. As expected, both increases in wind speeds and the difference between wind gust speeds and winds speeds lead to higher probability of wind crashes. This work indicates that both variables should be monitored and considered in operational rules for high wind conditions.

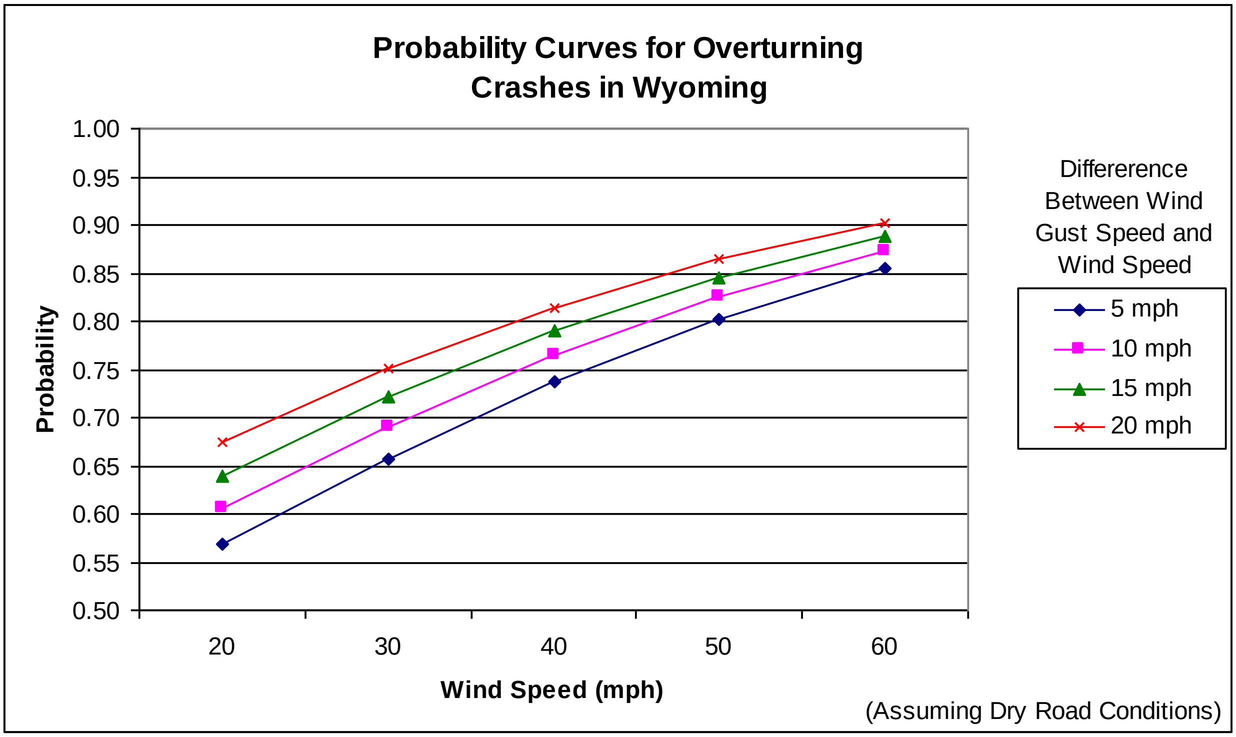

Figure 3.2 Probability Curves for Overturning Crashes in Wyoming (Dry Road Conditions)

Surface Conditions

Figure 3.3 graphs the same probability curves as shown in Figure 3.2 except the assumption is made that the roadway surface conditions are slick. (Slick was defined by the earlier research as snow, slush, or ice.) These curves were estimated using a binary variable for roadway conditions where the variable was set to one if the roadway conditions had ice, snow, or slush and zero otherwise. As shown in the figures, the probability of an overturning crash are significantly lower if the roadway conditions are slick than if they are not. The explanation for this change is that slick roadway conditions are a visible hazard to drivers and result in more cautious driving. High wind conditions alone are often deceiving since drivers are less aware of the hazards posed by this condition. This result also confirms earlier work, described in the literature review section, that lower speeds reduced the effect of wind (Summerfield and Kosior 2001).

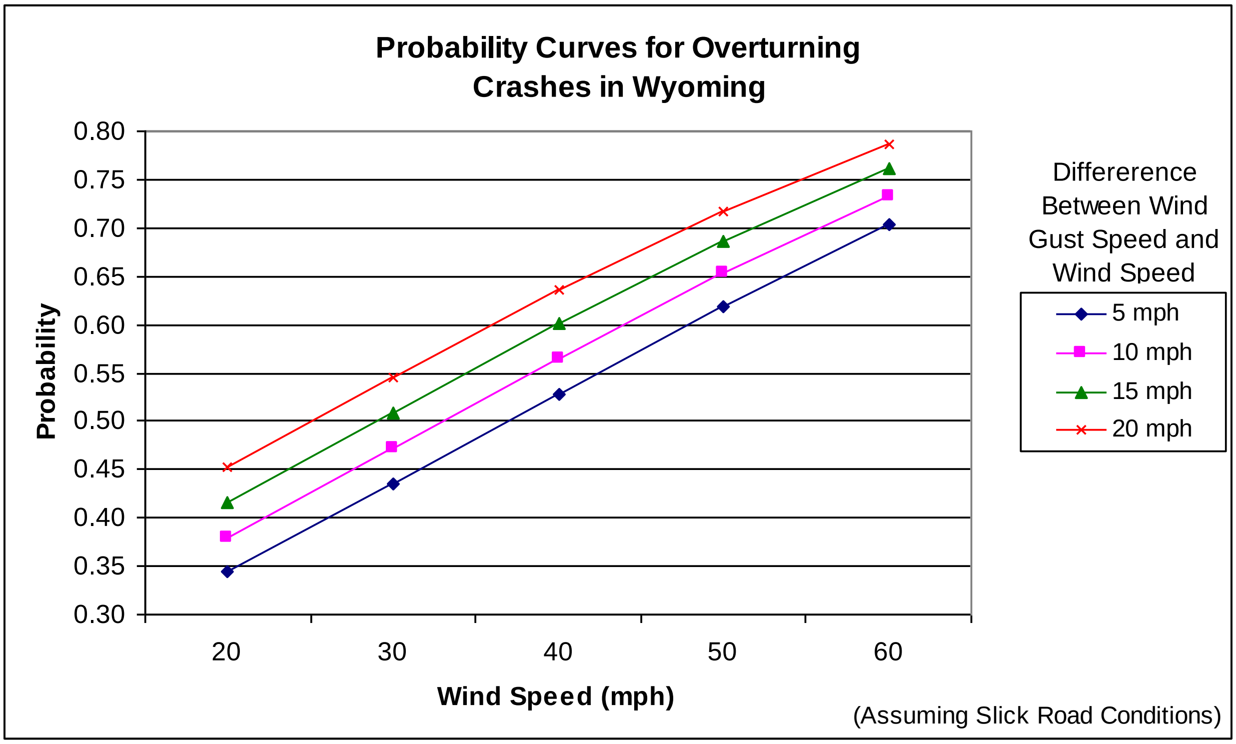

Figure 3.3 Probability Curves for Overturning Truck Crashes in Wyoming (Slick Road Conditions)

Saiidi's work for the Nevada DOT also considered roadway conditions (Saiidi and Maragalas 1995). This work looked at two hazard conditions in high wind: one where the winds caused overturning crashes and the other where high winds and slick roads caused a sliding crash where the vehicle was pushed off of the road due to the low wheel friction with the road surface. The single trailer truck was determined by researchers to be the most vulnerable to overturning and sliding. The dimensions used for the single trailer were the following:

- Weight (*W*): 15,000 lb
- Wheel Base (*b*): 3 ft
- Length (*l*): 45 ft
- Vehicle Height (*h*): 14 ft
- Wheel Diameter (h_2): 4 ft

For a single trailer, these equations yield a critical wind speed of 40 mph for overturning and 29 mph for sliding (Saiidi and Maragalas 1995). The sliding equation incorporates a coefficient of friction of 0.1, which is for the critical condition of snowy and icy road surfaces. It is important to note that the 40 mph critical wind speed is for empty trucks. If the weight of the truck is increased to 35,000 pounds, the formulas from Nevada's study result in a critical wind speed of 60 mph for overturning and 44 mph for sliding. This becomes important when considering selective closures for certain high risk vehicles. Figure 3.4 graphs the overturning and sliding critical wind speed equations using these earlier equations and above dimensions but varying the weight of the vehicle. Figure 3.5 looks at the relationship between critical wind speeds and vehicle height. In this graph, the dimensions above are held except for height, which is varied between 8 and 16 feet. This comes into play when considering the risk of high profile vehicles in high wind conditions.

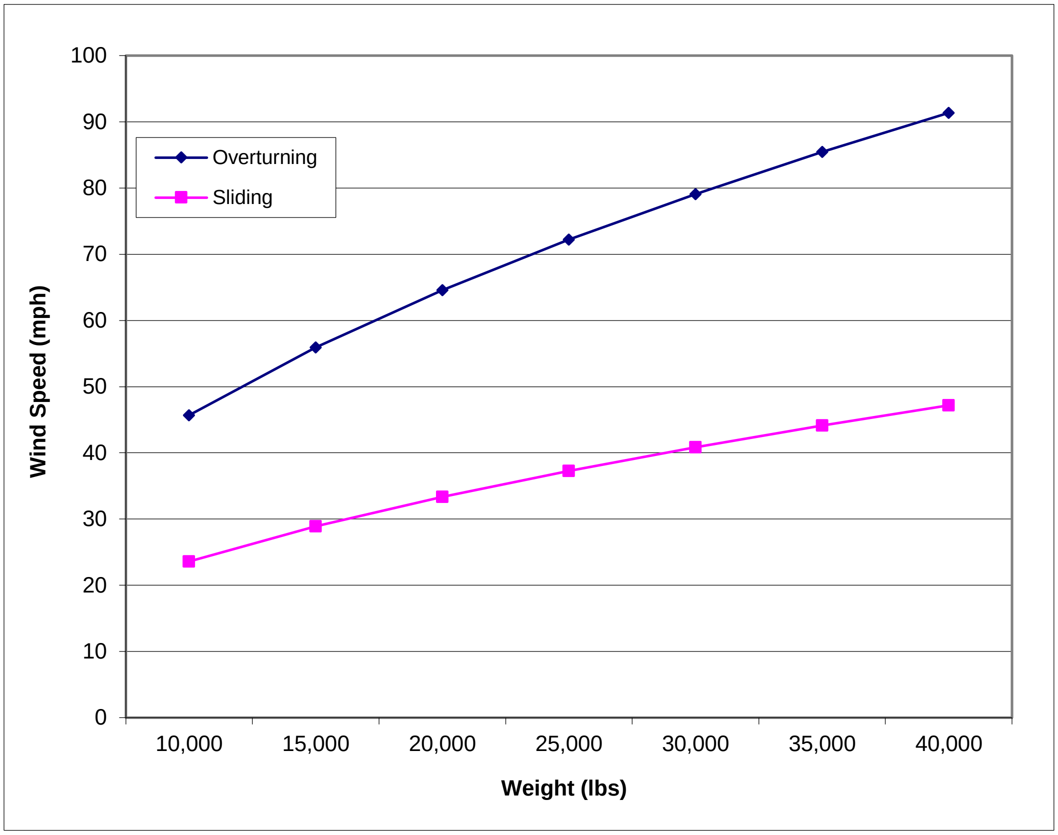

Figure 3.4 Critical Wind Speeds for Sliding and Overturning Crashes by Vehicle Weight

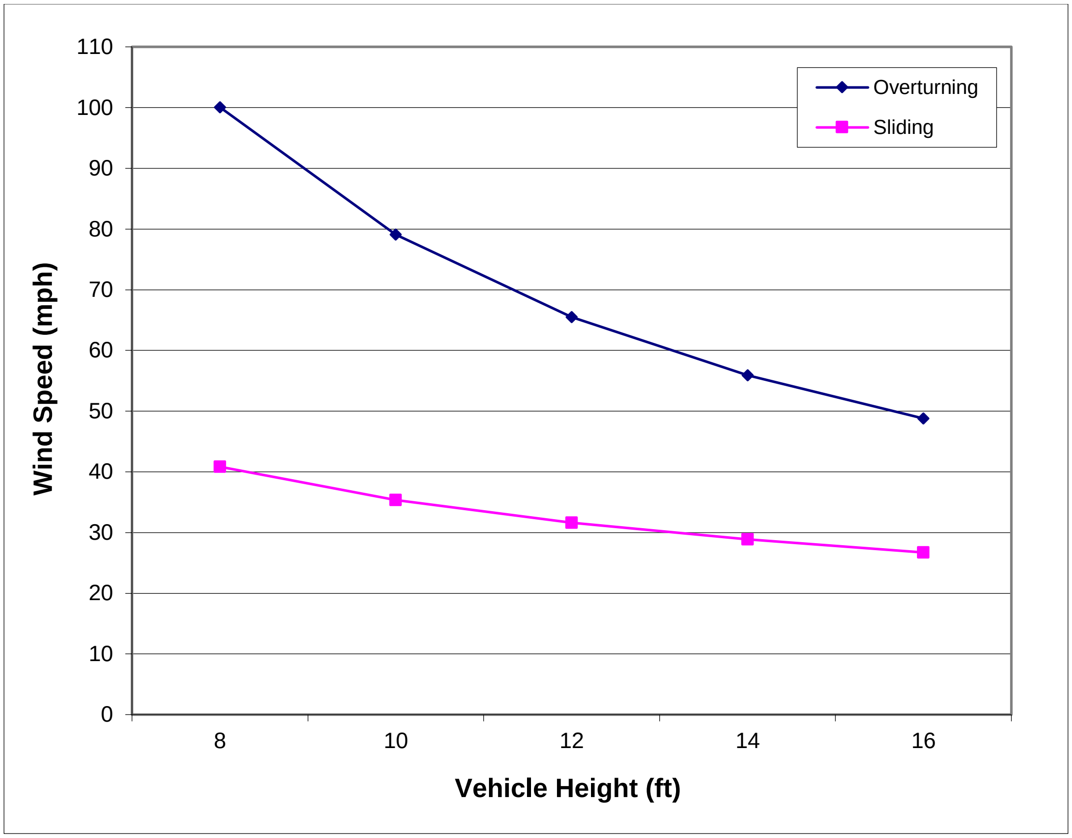

Figure 3.5 Critical Wind Speeds for Sliding and Overturning Crashes by Vehicle Height

Affected Vehicles

As mentioned in the literature review section, there have been several research efforts that look at wind effects on large vehicles. The work by Saiidi for Nevada DOT derived equations for critical wind speed for overturning and sliding conditions based on vehicle size and weight parameters (Saiidi and Maragalas 1995). From these equations, critical weight and profile characteristics of at-risk vehicles can be determined. From an operational standpoint, it may be preferable to delay a portion of the vehicle flow that is at higher risk as opposed to delaying the entire vehicle flow. The benefits of this approach will be discussed in a later section.

3.4 Operation levels

From the work discussed in the previous sections, it was determined that the critical variables for monitoring roadway segments in high wind conditions are wind speed, the difference between wind speed and wind gust speed, roadway surface conditions, and the combination of a vehicle's weight and profile characteristics. The next step was to determine levels of operational decisions. Based on the identified conditions and amount of impact to the traffic flow, the levels of operational strategies include:

- Level 1 – Wind and surface variable thresholds for advisory messages for dynamic message signs.
- 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, lightweight vehicles.

The Level 1 strategy is similar to what WYDOT currently uses although judgment is used more than fixed wind and surface condition thresholds. Currently, WYDOT officials monitor the roadway and weather conditions and, on a case-by-case basis, set the DMS messages. Consistency of the messages may be improved if guidelines based on wind threshold conditions were developed to aid officials.

The Level 2 strategy would also monitor wind and surface conditions and would set thresholds for determining road closures for all vehicles. Given the immense amount of pressure on agency officials to not close the road, this type of strategy could lead to more road closures and higher safety levels but would have large impacts on travelers and economic losses. This type of strategy does have the advantage over the current system by improving the consistency on the type of conditions warranting road closures.

The next strategy level is similar to Level 2 although the mandatory road closures would apply only to high profile vehicles such as tractor-trailers and recreational vehicles. The previous research into probability of crashes in high wind conditions obviously links vehicle profile to the likelihood of overturning or sliding crashes.

The last strategy, Level 4, utilizes technology to the greatest extent while attempting to both maximize safety and minimize delays and economic losses. For this strategy, both roadway conditions (wind and surface) as well as individual vehicle characteristics are monitored; and road closures are based on both sets of variables. If the roadway conditions warrant, individual vehicles would be monitored for both profile and weight characteristics, and the roadway would be closed to vehicles on a case-by-case basis.

As described above, as the level of operational strategy increases, the data demands for implementation increases, but the tradeoff for increased data is the lowering of delay hours and economic impact to the traffic stream, while at the same time, minimizing high wind condition hazards.

3.5 ITS Techonolgy for Implementation

Level 1 operation utilizes road weather information system (RWIS) data and dynamic message signs (DMS). A decision tree could be implemented that would recommend appropriate messages for the DMS based on surface and wind conditions. This is similar to the existing operation of the roadways but would provide a greater consistency between conditions and the displayed message, leading to more public trust in the DMS messages. It is also possible that advisories relating to vehicle profile or weight characteristics could be implemented to provide more information to at-risk vehicles. Level 2 operation utilizes the same technology as Level 1 but instead of just imposing advisory warnings, a wind and surface condition threshold would be adopted that would lead to roadway closures.

Level 3 requires the same decision tree as levels 1 and 2, with the addition of selective closures to high profile vehicles based on wind and surface condition thresholds. This partial closure would be for all vehicles of a certain height and length combination or by vehicle classification. The closure could be implemented at nearby port of entry locations or could utilize automatic vehicle classifications devices. This application would be similar to some existing weigh-in-motion applications where the vehicle is weighed and pulled over for static weighing if beyond a certain threshold. In the closure application, the vehicle classification devices would trigger vehicles to pull over to a designated parking area if identified as an at-risk vehicle given the weather conditions. Ideally, an application such as this would have information kiosks at the parking area to provide drivers with more detailed information about the conditions that warranted the closure to high profile vehicles.

Another option to vehicle classification technology would be the addition of vertical video detection. In high wind conditions, the critical vehicle variable is not axle spacing, which is what vehicle classification algorithms are based on. What is needed is vehicle length and height data. Video detection that utilizes vertical detection zones could identify vehicles that have a large enough surface area to be of concern. For this application, large vehicles either need to be funneled into one lane for separate profile detection.

Level 4 operation takes the level 3 application an additional step by identifying vehicles for partial closure based on vehicle classification and/or height and length characteristics as well as weight characteristics. For this level of operation, either weigh-in-motion or static weighing capabilities need to be provided. Weight thresholds for high profile vehicles meeting level 3 thresholds in addition to being unloaded or lightly loaded would be identified and prohibited from the roadway segment. An added challenge to Level 4 operations is the issue of enforcement, since patrol personnel would be unable to visually identify low weight vehicles. Additional weight-in-motion installations could be utilized determining low weight vehicles. Another option would be to identify vehicles at port of entry locations and enforce travel prohibitions at that point.

The Wyoming Department of Transportation is currently designing a traffic management center that will centralize its ITS operations. The centralization of ITS operations away from individual district-level dispatch centers is the ideal time to begin implementation of consistent decision rules and operational strategies as described above.

3.6 Benefits

As discussed previously, a roadway segment with frequent high wind conditions can be operated at varying levels of control. Each of these levels require increasing amounts of data and ITS technology for implementation yet result in increased safety and reduced vehicle delay. While the benefits of applying each level are site specific, an example of the potential benefits will be illustrated using a segment of Interstate 80 between Laramie, WY, and Rawlins, WY.

As mentioned previously, the average daily traffic on this segment is 11,380 with 55% trucks or approximately 6,260 trucks per day on average. Because I-80 through Wyoming is primarily used for long-distance trucking, the percentage of un- or lightly-loaded trucks is low. Data from a weigh-in-motion site using the Vehicle Travel Information System (VTRIS) reporting software on I-80 near the Wyoming-Nebraska border show 2.5% of westbound trucks and 3.4% of eastbound trucks running empty or lightly loaded according to the VTRIS W-3 report using 2004 data. Data for earlier years showed similar results. The directional split for this facility is close to a 50/50 split. so averaging these values, approximately 3% of the trucks are un- or lightly-loaded. Applying these percentages to the daily truck volumes, it is estimated that approximately 190 trucks per day are at high risk during high-wind conditions.

Level 1 operation would provide more standardized warning messages and would be expected to result in increased safety due to greater awareness of the conditions by drivers. It is also likely that some drivers would choose to voluntarily pull over for rest breaks if the severity of the conditions were known more reliably, particularly if the advisories contained vehicle profile and/or weight thresholds. While difficult to quantify due to the voluntary participation, it is likely that there would be increased safety benefits to implementation.

Level 2 operations would provide similar benefits to level 1, but in high severity wind conditions would result in roadway closures. The additional benefits to this approach would come from a likely reduction in closure time and a decrease in crash costs. Often under current operational procedures, the overturning crashes lead to road closures of long duration due to the time it takes to clear the roadway of crash debris. The current average closure time for this segment of roadway is eight hours long.

Research on the value of time for freight carriers for expected delay is estimated at around $140 to $190 per hour (Maze et al. 2005). Delay costs are increased when the delay is unexpected, as is the case for weather delays, and are estimated at around $370 per hour. These values are considered highly conservative estimates and do not account for perishable goods and the impacts due to supply chain interruptions. For lack of better data on this topic, a conservative value of $370 per hour of delay for freight vehicles will be used. In addition, the value of delay for passenger vehicles will also be ignored since they are far outweighed by the freight vehicle impacts.

For an hour of closure, approximately 600 to 900 vehicles are impacted during typical hours of the day resulting in a conservative estimate of $222 to $333 thousand in impacts. An eight-hour closure results in almost $8 to $12 million in delay costs. Any operational changes that would result in even one hour of reduced delay would have considerable benefits, particularly when considering the frequency of closures in this area.

Level 3 operations would close the roadways to high profile vehicles only, leaving the facility open to the remaining 45% of the traffic volume. As with level 2, the benefits would come in reducing the duration of the closures by avoiding the time to clear the roadway from overturning truck crashes.

Level 4 requires the largest amount of infrastructure for operation but yields the highest benefit. In this case, only the un- or lightly-loaded vehicles would be restricted from travel. As mentioned previously, this makes up about 3% of the truck traffic or around 190 trucks per day. On an hourly basis, this is between two and six vehicles per hour. The unexpected delay impacts would be around $740 to $2200 per hour. An eight-hour partial closure would between $26,000 and $80,000, far less than the $8 to $12 million for the full truck closure option.

3.7 Conclusions

This research brings together previous and current research on high wind effects on large vehicles and develops a four-level operational framework for combining wind, surface, and vehicle characteristics in order to reduce the risk of overturning truck crashes in high wind conditions and to improve travel time reliability along the corridor. While the required infrastructure to implement the higher operational levels is considerable, the benefits in terms of avoided delay to truck travel and increased reliability for travelers is substantial. This research represents a first step into implementing a framework that would allow agencies to operate roadway segments in high wind conditions more efficiently using intelligent transportation system technologies.

4. RESULTS AND CONCLUSIONS

4.1 High Wind Freight Crashes in Wyoming

This research effort merged crash data with weather station records to develop models relating wind conditions and the probability of overturning truck crashes. Two notable results emerged from this effort. The first is that wind variables, such as wind speed, and the difference between measured wind gust speed and average wind speed were found to be significant in the estimated models. Prior to this research, it was believed by some that wind conditions were too localized for weather station data to be adequate predictors of crash hazards.

The second notable result is the difference between models estimated for different areas. This work estimated models using the entire statewide data set and also at two regional sub-areas. The included variables and estimated coefficient results for each of these models were different enough that it is unlikely a single model could be developed that would be applicable to different roadway segments.

From the model results presented in Section 3, it is believed that wind data from weather stations can be used to estimate the probability of truck crashes being an overturning crash. The models showed that weather station data are promising for use in predicting risk for overturning crashes. Once again, these models were only developed to test the significance of the measured wind in predicting overturning crashes; they are not intended to be used for making operational decisions at this time, but instead are promising results that operational models will be able to be developed. The value of this research is in providing the foundation for developing site-specific operational guidelines based on weather station data and historic crash records.

4.2 Use of ITS for Operation of Roadway Segments in High Wind Conditions

This task brings together previous and current research on high wind effects on large vehicles and develops a four-level operational framework for combining wind, surface, and vehicle characteristics in order to reduce the risk of overturning truck crashes in high wind conditions and to improve travel time reliability along the corridor. While the required infrastructure to implement the higher operational levels is considerable, the benefits in terms of avoided delay to truck travel and increased reliability for travelers is substantial. This research represents a first step into implementing a framework that would allow agencies to operate roadway segments in high wind conditions more efficiently using intelligent transportation system technologies.

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