# Characterization of Blowover Risk in the Wyoming Highway System



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# Contents

## Problem Statement

Rollover crashes by severe crosswind is a common problem on Wyoming highways as well as in the rest of the United States. The objective of this study is to fill the gap between the existing operational practices utilizing weather data from RWIS and the risk available from high resolution modeled data and the high frequency gust wind observation system. The physical process of rollover crashes has been well documented mainly through computational fluid mechanics (CFD) and wind tunnel experiments, yet the occurrence in the real world has rarely been analyzed since field gusts data are either lacking or are sporadic. Characterization of wind gusts using a high frequency wind monitoring at a known hotspot (such as I-25, mp 4) is essential for the prediction and prevention of the rollover crashes. The proposed roadside wind observation system includes a three-dimensional sonic anemometer (CSAT3B-NC) to evaluate the effect of local topography to the gust wind direction and the rollover crashes. The vehicle rollover analysis will integrate the wind data by the high frequency observation system, the RWIS and the WRF model. Figure 1 illustrates the proposed activities in this project. **Better understanding of wind, vehicle speed, load weights, and road geometry characteristics for rollover crashes will improve operational practices related to weather responsive road management** such as the current Wyoming connected vehicle (CV) pilot project. Specifically, this project aims to quantify the recommended vehicle speed and the load weight for rollover crash during strong wind periods. Thus, this research is aligned with one of the WYDOT strategic goals to improve safety on the state transportation system through education, engineering, enforcement, and other innovative methods.

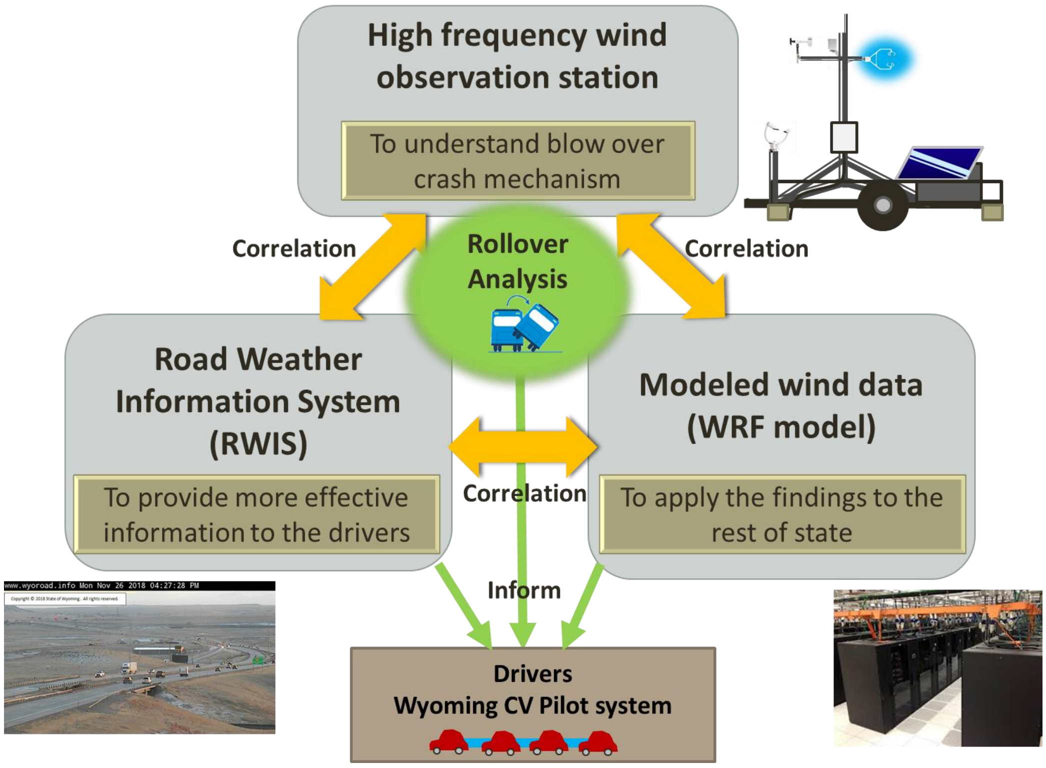


**Figure 1 - Diagram of the proposed activities**

## Background Statement

Wyoming has by far the largest number of truck and bus crashes per population in the US (U.S. Department of Transportation, 2018). On November 20, 2017, for example, wind gusts toppled 14 tractor-trailers along Interstate 25 (I-25) in southern Wyoming and northern Colorado (e.g. Kull, 2017 Wyoming Tribune Eagle). The road managers closed I-25 in both directions between Wellington, Colorado, and Cheyenne, Wyoming, due to these crashes. Additionally, a Wyoming Highway Patrol cruiser was devastated on February 7, 2017, when a semi-truck rolled onto it on I-80 near Elk Mountain, Wyoming. The accident was filmed by a police dash camera of another parked patrol car (https://www.youtube.com/watch?v=r_wnG_iW9So). Figure 2 shows the blowover crashes reported in 2012-17 period. There were 316 blowover crashes reported in six years in Wyoming (52.7 incidents/year). Truck rollover crashes due to strong crosswind often resulted in long road closure (WYDOT 2016). Blowover or rollover crashes by gusting wind is clearly a considerable problem for travelers on the Wyoming sections of the national major corridors such as I-25 and I-80.

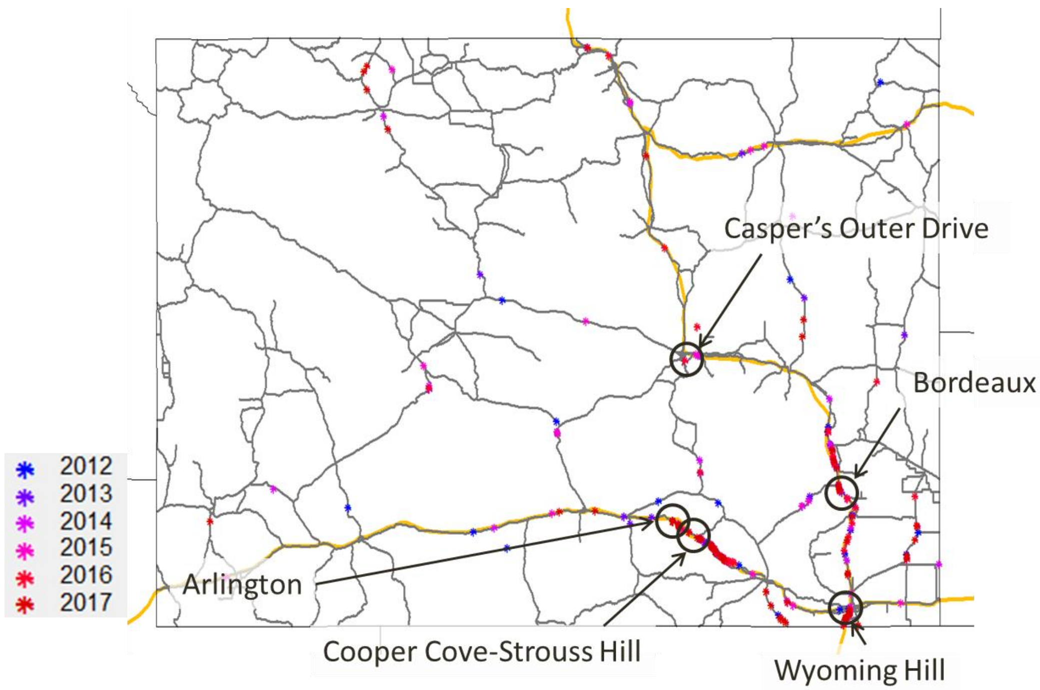


**Figure 2 – Reported blowover crashes in Wyoming during 2012-17 (WYDOT database)**

The state of Wyoming is often windy during the winter months as wind speeds reach 30 to 40 mph with wind gust speeds of 50 or 60 mph (Curtis & Grimes, 2004). Liesman (2005) identified the hazardous locations in the state with high frequencies of overturning truck crashes using three models in GIS (Grid Model, Sliding Scale Model and Advanced Grid Model) based on the record from January 1994 to June 2007. They were:

1. On I-80 approximately 35 miles west of Laramie near Arlington
2. On I-25 north of Cheyenne about 10 miles south of Wheatland (Bordeaux)
3. On I-80 west of Evanston
4. At the I-80 and I-25 interchange in Cheyenne

Among these sections, Young (2010) found the most hazardous section to be between Milepost 70.00 and Milepost 71.00 along I-25. Additionally, WYDOT (2016) empirically identified common blowover "hot spots" in Wyoming as follows:

1. Wyoming Hill (I-25, District 1, mp 3-5)
2. Bordeaux (I-25, District 2, mp 60-80)
3. Arlington (I-80, District 1, mp 272-274)
4. Cooper Cove-Strouss Hill (I-80, District 1, mp 278-284)
5. Casper's Outer Drive (Hwy 258, District 2, near I-25)

Many of these spots are situated downwind of mountain gaps where the Bernoulli Effect (mountain gap wind effect) often takes place. However, according to the recent blowover crash record (Figure 2), crashes can happen in other than these hotspots. Therefore, it is important to improve our understanding of the rollover crash for better risk management.

## Mitigation in practice

There is general agreement that lowering driving speed is effective in lowering the accident risk (e.g. Chen and Cai, 2004, Young, 2010). Setting suitable driving speed limit is important to decrease the likeliness of accident occurrence.

The Nevada DOT applied a high wind warning system on a seven-mile section of US Route 395 because this highway segment was subjected to high speed crosswinds. 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. Both wind speed and wind gust speed were used as decision factors, and the threshold value of wind gust speeds to prohibit high profile vehicles on the road was 40 mph. Another motorist warning system has been implemented by Idaho DOT on a100-mile section of Interstate 84 in southeast Idaho and northwest Utah (Kyte, Shannon, & Kitchener, 2000).

Young (2010) pointed out that 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) than Nevada and Idaho. Chen and Cai (2004) stated that extremely high wind speed inevitably causes overturning for high-sided vehicles, like trucks and tractor-trailers. However, Young & Liesman (2007) found that speed limit reductions improved safety only when wind speeds where above 37 mph. They outlined four-levels of operational strategies in the high wind warning system (Young & Liesman, 2007), 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, lightweight vehicles.

On the other hand, ground-based facilities such as wind fences were reported to be effective. Imai (2002) demonstrated the effect of wind fences and embankment against wind hazards on train operations in 1996 along the Nemuro Line, Japan. Alonso-Estébanez et al. (2017) demonstrated the effectiveness of the wind fence and embankment system using the Reynolds-averaged Navier–Stokes (RANS) equations along with the k-ω SST turbulence model

## General characteristics of truck rollover

There are several mathematical models available, such as: PHASE-4 (Perera et al., 1990); University of Michigan Transportation Research Institute model (Bedard, 1986); Linear yaw plane model (Wong & El-Gindy, 1986, El-Gindy & Wong, 1987); TBS model (Wong & El-Gindy, 1986, El-Gindy & Wong, 1987), and Static roll (Baker, 1986). Fundamentally, the drag force acting on a vehicle can be evaluated by,

$$D = \frac{1}{2} C_D \rho U^2 A \tag{1}$$

where, $\rho$ is the mass density of air at normal air pressure, D is the drag force (N), U is the wind speed in (m/s), and $C_D$ is the drag coefficient. This general formula has been used in many existing models with some variations. Also, the lift force due to an airfoil effect can be computed by,

$$L = \frac{1}{2} C_L \rho U^2 A \tag{2}$$

where L is the lift force and $C_L$ is the lift coefficient. Baker (1986) quantified the aerodynamic coefficients (drag and lift coefficients) as functions of relative wind yawing angle for a Leyland Atlantean bus (a double-decker bus).

Balsom et al. (2006) used the Data Acquisition System (DAS) (Figueredo, 2004) to confirm that wind enhances the lateral accelerations experienced by a truck. Studies by Baker (1994) and Chen and Cai (2004) showed that the driver behavior is important for an accurate simulation of the accident risks. Chen and Cai (2004) defined the critical driving speed as “accident driving speed”. Their study concluded that the accident driving speed generally decreases with the increase in wind speed. Young (2010) verified through analyses that the chance of an overturning crash was strongly correlated to the wind speed. However, it is interesting that trucks are more likely to have overturning crashes on dry road conditions than on wet road conditions. These crashes start when the vehicle starts to turn over when the moment of the wind-induced forces around the point of rollover exceeds the resisting moment due to gravity. However, the shift of the point of rollover center due to a slippery road surface actually prevented a rollover. In fact, Nevada DOT categorized two crash modes: overturning mode and sliding mode (Saiid & Maragalas, 1995).

Young (2010) found that the average wind speed of the loaded overturned truck was 51 mph, whereas the average wind speed of the empty overturned truck was 38 mph. This suggested the importance of the truck weight parameter related to overturning crashes as it could lead to different strategies for the High Wind Warning System. Therefore, it is important to consider the uncertainty in the parameters in the vehicle overturning model.

The road geometry and wind direction are both important factors for rollover crashes. In the case of a truck traveling around a curve, a strong gust of wind from the inward side (coming from the center of the curve) may provide the extra force required at the critical moment to cause the overturning forces to exceed the resisting forces, resulting in rollover (Balsom et al. 2006). Conversely, safety is increased when the wind is blowing at the back of the vehicle with increasing vehicle speed (Snaebjörnsson, Baker & Sigbjörnsson, 2007). Chen and Cai (2004) pointed out that vehicles on the bridge are more vulnerable to accidents than on the road.

There are few studies focusing on the weather pattern causing hazardous conditions. Misu and Ishihara (2012) assessed the gust frequency along the Tohoku line railroad in Japan, using wind record and a model simulation. They also found significant agreement between mean wind direction and gust wind direction. Misu and Ishihara (2012) modeled the gust strength proportional to the mean wind speed as a function of turbulence intensity.  These characteristics are useful to interpolate the gust and wind fields between the wind monitoring sites using model-based weather variables.

## High-resolution Reconstructed Weather data in Wyoming

Previous work (Ohara, 2017) provided continuous weather data to help in designing snow fence systems in the areas where wind and precipitation data are hard to obtain.  The dataset prepared by Ohara (2017) provides a unique opportunity to evaluate the vulnerability of truck rollover risk as well as blowing snow because it has high temporal (half hourly) and spatial (4 km or 2.5 miles) resolutions with 50 major historical blowing snow events during the 34 year-long-period (1981-2014).  Moreover, the continuous historical weather simulation at 9km (5.6 mile) resolution will enable evaluating the road surface condition prior to the gust event.  The reconstructed wind fields with complete spatial coverage in Wyoming are clearly useful to quantify crash risks under adverse weather conditions and to potentially improve winter travel in Wyoming.

One of the research outcomes was a trend towards increase in the adverse winter weather occurrences over the last three decades in Wyoming.  The number of days that wind speed exceeds 5.4 m/s (12 mph, the threshold for blowing snow (Tabler, 2003)) was computed for every five-year period from 1980 through 2014, as shown in Figure 3.  The analysis revealed that in recent years Wyoming has roughly 20-30 more windy days than in the 1980s.  The time series of the computed Wyoming average wind speed showed a slight upward trend in the average wind speed with a rate of 0.138 m/s per decade (0.31 mph per decade).  According to the WRF simulation based on the NARR data, Wyoming has gotten windier over the last three decades.  It may be inferred that the increase of wind speeds and number of windy days is likely due to the climate change.  As the past is considered the best predictor of the future, the rollover risk of semi-trailer trucks due to winter gust wind will likely remain problematic, at least for the next few decades.  Thus, it is possible that the risk of truck rollover crash may also increase (Ohara, 2017).

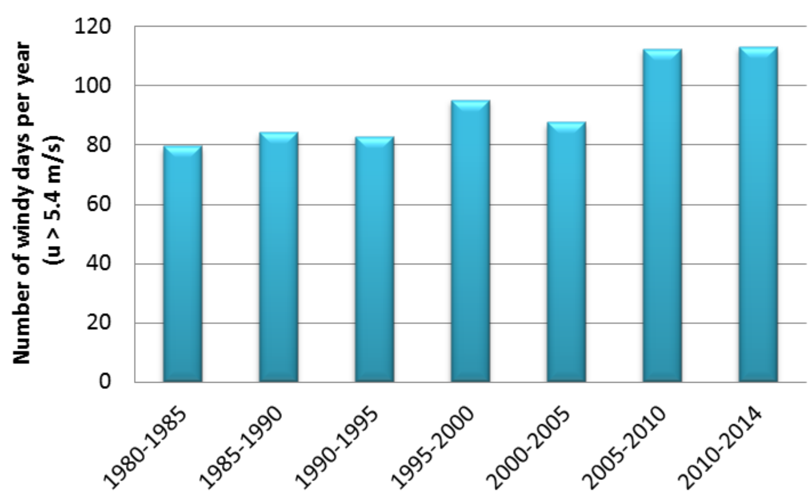


**Figure 3 - Frequency of windy days (wind speed > 5.4 m/s (12 mph)) during the last three+ decades based on the reconstructed Wyoming average wind speed for 1980 – present**

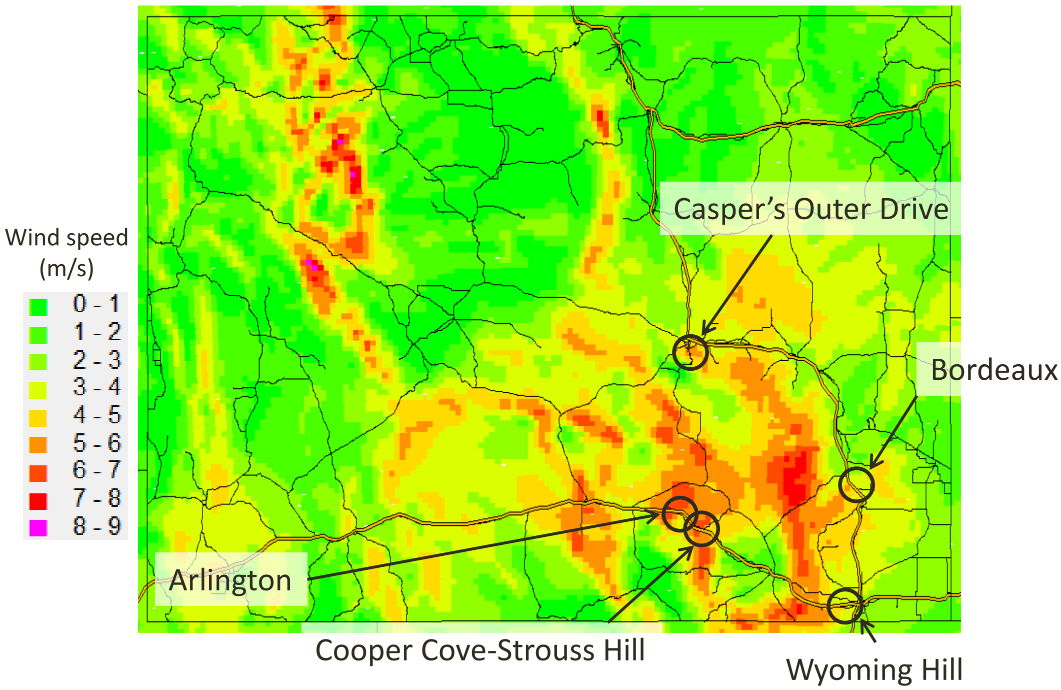


**Figure 4 - Mean wind speed (m/s) of the winter storm period, 1980-2014, and the empirical blowover hot spots**

This model-simulated wind field identified most of the common blowover "hot spots" presented in the background statement section. Figure 4 shows the average wind speeds computed at every 4 km (2.5 mi) node during the winter storm period, 1980-2014. It can be seen that the combination of wind speed and direction defines these places as blowover hotspots. The dataset prepared for the previous project provides a unique opportunity to evaluate the wind-induced crash vulnerability of high-profile vehicles in Wyoming.

## Pikalert® System

Weather information including wind gust condition has been incorporated into the connected vehicle (CV) pilot project. Pikalert, for example, is an information integrating system developed by NCAR with support of the USDOT as part of the FHWA's Road Weather Management Program (NCAR, 2018). A sub module of the Pikalert system, the Vehicle Data Translator (VDT), was implemented to collect, quality-check, and disseminate weather observations from vehicles as well as road condition data since 2008 under the IntelliDrive℠ initiative (Mahoney et al., 2010). The system was demonstrated in the experiments involving 9 to 11 vehicles in the Detroit, MI area in 2009 (Anderson et al., 2012) and 2010 (Drobot et al., 2010). The VDT can identify hazardous road conditions from the combined vehicle and weather observations (Drobot et al., 2012) based on the Road Weather Forecasting System (RWFS) to provide a 72-hour forecast as well as current hazard conditions. Pikalert is being integrated directly into WYDOT's system in the Wyoming CV Pilot project.

The Wyoming CV Pilot uses the blowover risk algorithm based on the fuzzy-logic (Young et al., 2018) to address the safety concerns over freight vehicle crashes. The algorithm involves four sets of fuzzy logic (Mcneill, D and Freiberger, P., 1993) weights and functions using RWIS wind gust speed, sustained wind speed, and orientation of wind direction relative to the road segment. The system uses sustained wind speed to compute wind gust differential, which is the difference between wind gust speed and sustained wind speed. Fuzzy logic is more appropriate than a decision tree because of the complicated and overlapping blowover factors including vehicle weight and height profile dependent logic. The CV Pilot system will provide vehicle-dependent alerts based on the vehicle onboard unit which has information on the height and weight parameters of the individual vehicles. However, good understanding of the truck blowover mechanism is essential to reduce uncertainty or error in the fuzzy-logic-based alert system.

## Objectives

The main goal of this study is to quantify the blowover crash risk associating with vehicle speed, load weight, wind field, and road geometry. One high-frequency wind monitoring tower will characterize the wind condition around the 2017 multiple rollover crash site (I-25 milepost 3-5), one of the known hotspots identified by WYDOT (2016). This field-observed wind speed data during gust events will improve the understanding of the rollover crash mechanism under adverse weather conditions. The field data and the high-resolution modeled data will be used to fill the gap between the RWIS and the rollover crash risk. The field-observed wind data will also be used for the rollover analysis for the prediction and prevention of such crashes in Wyoming.

The rollover crash model, using the statewide WRF model weather data, will extrapolate the rollover crash risk along the major highways in order to set more localized vehicle speed limit, set a truck load weight recommendation, and identify the most effective locations of wind hazard mitigation facilities for semi-trailer-truck safety. This research will extract useful gust wind statistics to compute vulnerability indicators (such as critical vehicle velocity and load weight) along the Wyoming highways from the reconstructed weather conditions using the WRF model employed in the previous project. The proposed activities in this project are mapped in Figure 1. The rollover analysis integrates all collected data to improve the driver information system.

The rollover risk (e.g. threshold vehicle speed and load weight) at every tenth of a mile will be quantified by the analytical rollover model based on the wind speed, wind direction, and road geometry. This project will assess the risk of rollover crash for high profile vehicles, such as a semi-trailer truck, on Wyoming highways using the simulated winter weather conditions prepared in the previous study -- Historical Winter Weather Assessment for Snow Fence Design using a Numerical Weather Model (FHWA-WY-17/03F). The assessed risk associated with the existing roadside weather monitoring system can be adapted in the Wyoming CV Pilot system.

## Benefit

Every year, the 402-mile Wyoming I-80 corridor has experienced 700 commercial vehicle crashes and over 1,500 hours of road closures. This proposed work will correlate wind data from the 3-D gust wind monitoring tower in the selected hotspot, the statewide regional climate model, and the Road Weather Information System (RWIS). Then, the rollover risk of semi-trailer-trucks will be quantified using the model-based wind field and road geometry with support of the hotspot wind tower. Wind related truck rollover crash risk in Wyoming will be computed in terms of critical gust wind speed and threshold vehicle speed by the modeled wind field in the historical period (1981-2014) at very high spatial resolution. The benefits of this research are listed below:

- Analysis on the historical rollover crashes, including a better understanding of the 2017 incidents
- Improved understanding of the gust wind characteristics for the blowover risk algorithm in the Wyoming CV Pilot system

- Quantification of the **recommended load weight** and **vehicle travel speed** when high wind warning is effective
- Improved risk-based traveler information for vehicles during high wind conditions based on current or forecasted wind conditions and road geometry
- Recommendations for the potential wind break locations

## Applicable Questions

No potential barrier to project implementation has been identified to date. The P.I. will communicate closely with the project manager and sponsors when any issue emerges. The requirements for this project will be met by the P.I., who has extensive experiences in data analysis, model operation, and field climate monitoring through various national and international projects.

## Statement of Work

### Work Schedule

The project is scheduled for 24 months, beginning in July of 2019 and ending in June of 2021, in order to include several gust wind events. Here are the tasks in this project.

1. Install the high frequency wind observation station around the 2017 multiple rollover crash site in the Wyoming Hill area (I-25, District 1, mp 3-5).
2. Acquire the roadside weather data including Road Weather Information System (RWIS) data.
3. Develop gust wind statistics based on the reconstructed weather data at every 0.1 mile of the highways.
4. Correlate the wind data from the high frequency wind observation system, the WRF model, and the RWIS.
5. Perform the rollover crash risk analysis.
6. Perform the risk assessment of critical rollover crash at every road segment along highways in Wyoming.
7. Review the Pikalert blowover risk algorithm parameters based on the computed rollover risk.
8. Make recommendations for the advised truck load and travel speed during high wind warnings, and potential wind break locations.

| | Months | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tasks | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Installation of a wind observation system (I-25) | | | | | | | | | | | | | | | | | | | | | | | | |
| Acquire the roadside weather data | | | | | | | | | | | | | | | | | | | | | | | | |
| Gust wind statistics | | | | | | | | | | | | | | | | | | | | | | | | |
| Correlation of the wind data (I-25, RWIS, WRF) | | | | | | | | | | | | | | | | | | | | | | | | |
| Rollover crash risk analysis | | | | | | | | | | | | | | | | | | | | | | | | |
| Risk assessment of rollover crash in Wyoming | | | | | | | | | | | | | | | | | | | | | | | | |
| Review of Pikalert blowover risk algorithm parameters | | | | | | | | | | | | | | | | | | | | | | | | |
| Recommendations | | | | | | | | | | | | | | | | | | | | | | | | |
| Reporting | | | | | | | | | | | | | | | | | | | | | | Final report | | |

The technical details of the proposed work are presented below.

## High Frequency Wind Observation System

One high-frequency wind monitoring tower will be installed near the 2017 multiple rollover crash sites in the Wyoming Hill area (shown in Figures 2 and 4). The specific location of the instrumentation will be determined through discussions with the WYDOT and Wyoming Highway Patrol. The system will be installed on a trailer and deployed to the designated site in order to reduce the roadside work time and to add flexibility in the site location, as illustrated in Figure 5. The tower will be equipped with a 3-D sonic anemometer (CSAT3B-NC), a mechanical anemometer (05108-45-L15-PT), a visibility sensor (CS125-PT), and a temperature and humidity sensor (CS215-L3-PT). A snow flux meter (FlowCapt) may be added as needed. The detailed cost estimation (quote from Campbell Scientific) is attached in the end of this document. The collected data will verify the wind gust statistics that were found elsewhere, such as: sub-hourly gust frequency, proportionality to mean wind speed, and wind direction character (e.g. Misu and Ishihara, 2012). The 3-D sonic anemometer will provide wind direction and speed at excellent temporal resolution (e.g. 1 Hz, every second). The data will support the rollover crash risk model and the model-based wind field data.

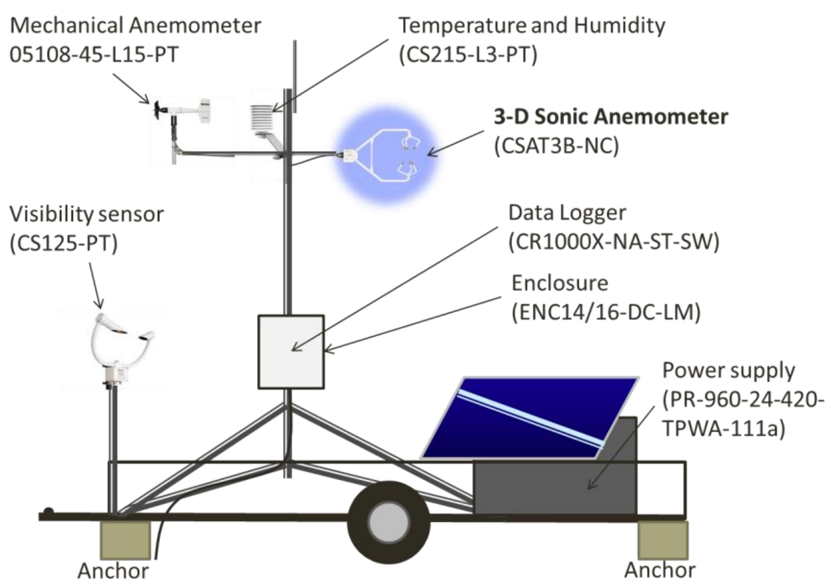


**Figure 5 – Proposed high frequency wind monitoring system installed on a trailer**

## Wind Gust Statistics

It is well-known that wind is generally strong during the winter in Wyoming while highly dependent on time of day, weather, and time scale of data sampling (e.g. Curtis & Grimes, 2004; Cook and Gruenbacher, 2008; Ohara, 2017). Therefore, wind load on structure has typically been estimated based on wind gust probability (e.g. Ellingwood et al., 1999). This study will take advantage of the recent improvement in numerical weather prediction (NWP) model for historical wind field reconstruction.

To utilize the hourly model reconstructed wind field, we need to establish the relationship between the mean wind speed and the gust wind speed. Sherlock (1952) first defined gust factor $G$ as follows;

$$G = U_{max}/\overline{U} \tag{3}$$

$\overline{U}$ = mean wind speed
$U_{max}$= peak gust speed

Although there are a few other alternatives (e.g. Doran and Powell, 1982), this simple proportionality has been widely used in practice. Cook and Gruenbacher (2008) demonstrated that this relationship holds for strong wind range using the data from the weather station networks in the US. Mitsuta (1962) proposed an experimental formula for the gust factor.

$$G = \left(\frac{s}{D}\right)^{-p} \tag{4}$$

$s$ = average time of gust (>1.5 second)
$D$ = sampling duration
$p$ = constant depending on the measurement height $z$ (0.050-0.083)

It has been recognized that wind speed distribution within 10 minutes can be fitted by a Gaussian distribution (Mitsuta and Tsukamoto, 1989; Cao et al., 2009). Based on the Gaussian approximation, the gust factor can be expressed as:

$$G = 1 + k\sigma_u/\overline{U} \tag{5}$$

where $\sigma_u$ is the standard deviation of U within the time window. There are a few formulas available for the peak factor k (Brook and Spillane, 1970). Alternatively, the relationship between gust factor and turbulence intensity has been commonly utilized for wind gust analysis. Cao et al. (2009) combined the formulas proposed by Ishizaki (1984) and Choi (1984) into the following expression for the gust factor relating to the turbulent intensity:

$$G = 1 + k_1 I_u^{k_2} \ln\frac{T}{t} \tag{6}$$

$k_1$ $k_2$ = coefficients ($k_1$ = 0.5, and $k_2$ = 1.15, Cao et al., 2009)
$T$ = The averaging time of the mean
$t$= average time of gust
$I_u$ = turbulence intensity ≡ $u'/U$
$u'$ = root-mean-square of the turbulent velocity fluctuations
$U$ = Reynolds averaged mean velocity

The distribution of maximum wind speeds is often fitted by extreme value distributions (Revfeim and Hessell, 1984). Imai et al. (2009) used Weibull distribution for the data when wind speed was over 15 m/s, for example. Wind gust frequency analysis using general extreme value (GEV) distribution was discussed by Lin (2003). The site specific gust wind statistics will be developed and discussed in the proposed study using the observed data as well as the simulated wind field data prepared in the previous project.

**Gust wind direction**

Gust wind direction statistics have not been documented as much as the intensity, because it might be considered to be obvious and less interesting. In fact, the 1-minute average wind direction typically well represented the maximum wind direction in the period (Misu and Ishihara, 2012). Cao et al. (2009) analyzed the wind record during the extreme weather event of Typhoon Maemi in 2003. They also found significant agreement between the gust wind direction and the average wind direction during the very windy period. As such, the gust wind direction may be assumed to be same as the mean wind direction in this project unless we obtain different results from the field site in the Wyoming Hill (I-25, mp 3-5).

These wind gust statistics will be used to estimate the gust wind field from the simulated hourly or half-hourly mean and maximum wind speed data. This study will initially adopt the wind gust characteristics available in the literature. However, the choice of the statistical distribution and its parameters will be eventually determined by the field observation in Wyoming.

## Correlation among the wind data

We will correlate following three main wind datasets.

1. Field-observed high-frequency wind data at the Wyoming Hill site
2. RWIS data including Wyoming Hill station
3. Historical reconstructed wind data by the WRF model

RWIS is often located some distance from a road and at an elevation far above a road to a wind speed profile at the road. Therefore, it is necessary to establish the correlation between the RWIS data and the roadside data since they provide the real-time weather information to the drivers. Additionally, any available wind data such as the PWIS of the Winter Research will be utilized.

The product of the recent project, Historical Winter Weather Assessment for Snow Fence Design using a Numerical Weather Model (FHWA-WY-17/03F), will be utilized for the extrapolate the findings to the rest of the state. This dataset provides seamless wind field and snow precipitation data under adverse winter storm conditions using a numerical weather prediction model, the Weather Research and Forecasting (WRF). The boundary conditions were prepared using the North American Regional Reanalysis (NARR) data and the model outputs, especially snow precipitation, were assimilated to the compiled historical observed data (PRISM data, PRISM Climate Group, Oregon State University). The simulated wind field maps were verified with the existing manually-observed wind data by Dr. Tabler (Tabler data, e.g. Tabler, 2003). Additional wind events will be searched including summer periods and re-simulated for this project.

## Rollover Crash Risk Analysis

A static stability analysis (Kunieda, 1972; Baker, 1986; Hibino and Ishida, 2003) will be customized for the rollover crash in this proposed study.

The lift forces by the headwind and the crosswind can be computed as,

$$L_x = \frac{1}{2} C_{Lx} \rho A_x (V + U_x)^2 \tag{7}$$

and

$$L_y = \frac{1}{2} C_{Ly} \rho A_y U_y^2, \tag{8}$$

respectively.

$C_{Lx}$= Lift coefficient for headwind
$C_{Ly}$ = Lift coefficient for crosswind
$\rho$ = Density of air (kg/m$^3$)
$A_x$ = Reference area from front (m$^2$)
$A_y$ = Reference area from side (m$^2$)

$V$ =Vehicle travel speed (m/s)
$U_x$ =Headwind speed (m/s)
$U_y$ =Crosswind speed (m/s)

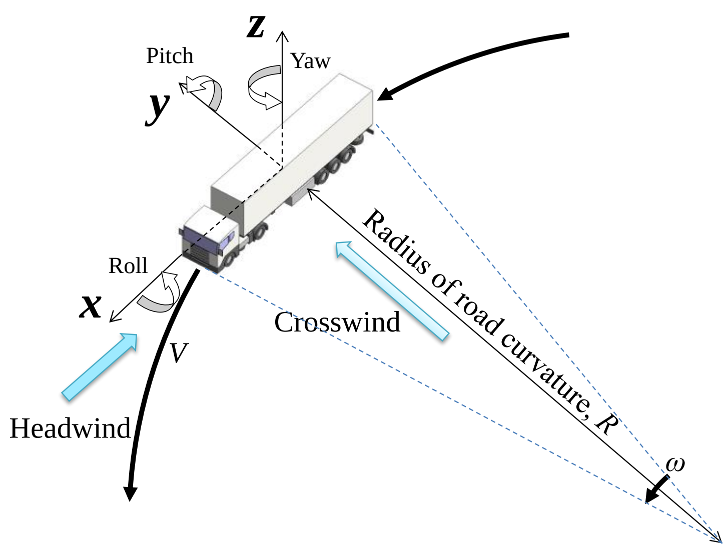


**Figure 6 - Definitions of axes in the static rollover analysis**

The drag force by the wind acts on the vehicle horizontally; therefore, only the crosswind component is effective. The drag force $D_y$ by the crosswind may be written as:

$$D_y = \frac{1}{2} C_D \rho A_y U_y^2. \tag{9}$$

$C_D$ = Drag coefficient for crosswind

The centrifugal force due to the road geometry $F_C$ can be computed as:

$$F_C = MR\omega^2 = \frac{MV^2}{R}. \tag{10}$$

$\omega$ = Vehicle angular velocity
$R$ = Radius of curve (m)
$M$ = Mass of vehicle (kg)

Finally, the resisting gravitational force W can be calculated by:

$$W = Mg. \tag{11}$$

The rollover stability condition can be written by the moment equation around x axis at the edge of the wind leeward tires as follows:

$$y_W W \geq \alpha\left[y_L\left(L_x + L_y\right) + h_D D_y + h_C F_C\right]. \tag{12}$$

$\alpha$ = Safety factor
$b$ = Width of vehicle (m)
$h_D$ = Center height of drag force (m)
$h_C$ = Center height of centrifugal force (m)
$y_L$ = Center location of lift forces (m)

$y_W$ = Center location of gravitational force (m)

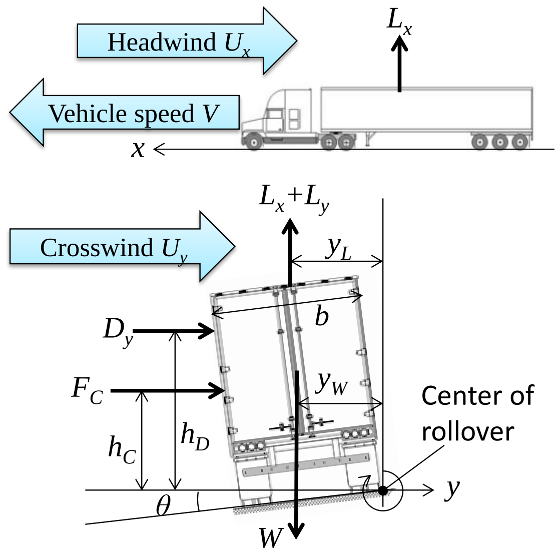


**Figure 7 - Definitions of the forces acting on the vehicle in the static rollover analysis**

The cross slope (or cant angle) of road $\theta$ will adjust the locations of the forces acting, $y_L$ and $y_W$. This means that a traveler with a high profile vehicle will likely experience a rollover crash if they exceed the critical vehicle travel speed. Also, the lighter the vehicle is, the higher the rollover crash risk is. Obviously, the critical vehicle travel speed $V_{crt}$ is dependent on the gust wind field, the road geometry, and the vehicle weight. This project will quantify the $V_{crt}$ that corresponds to the gust occurrence probability (frequency) so that the vulnerability to the wind rollover risk can be identified in the highway network. Through this project we will be able to say, for example, that this site has a critical vehicle travel speed of 54 mph with once-in-50-year frequency. This rollover analysis will quantify the effect of load weight in the vehicle to the rollover crash risk.

### Risk assessment of rollover crash in Wyoming

Rollover risk will be characterized by the field data as well as the climatological gust wind field and road geometry. Wind related truck rollover crash risk in Wyoming will be mapped by model simulated wind field in the historical period (1983-2012) at very high spatial resolution. The rollover risk (threshold vehicle speed and corresponding load weight) at every tenth of a mile will be quantified by the analytical rollover model based on the wind speed, wind direction, and road geometry. Moreover, the blowover risk algorithm (Young et al., 2018) in the Wyoming CV Pilot system will incorporate this rollover crash condition through correlating to the wind speed of the RWIS.

Finally, a recommendation will be made for the advised vehicle travel speed and load weight during the strong wind periods based on the rollover risk analysis.

## Budget

The total request amount for this project is $119,762 as shown in the table below.

**PROJECT TITLE: Characterization of Blowover Risk in the Wyoming Highway System**

| **Project total** | **Request** | **UW share** | **Total** | |
|---|---|---|---|---|
| **A. Senior Personnel** | | | | |
| 1. Noriaki Ohara | $12,180 | $0 | $12,180 | 3/4 month salaries for |
| 2. Rhonda Young | $10,150 | $0 | $10,150 | both PI each year |
| **(A) Total Senior Personnel** | $12,180 | $0 | $12,180 | |
| **B. Other Personnel** | | | | |
| 1. One (1) Graduate Student | $32,691 | $0 | $32,691 | Stipend for one MS |
| **(B) Total Other Personnel** | $32,691 | $0 | $32,691 | student for 2 years |
| **C. Fringe Benefits** | | | | |
| 1. Senior Personnel (43.3% for fuculty) | $5,549 | $0 | $5,549 | Fringe benefit is 43.3 % |
| **(C) Total Fringe Benefits** | $5,549 | $0 | $5,549 | |
| **D. Operating Expenses** | | | | |
| 1. Computer Usage and Service | $0 | $2,000 | $2,000 | We use the existing |
| 2. Communication | $400 | $0 | $400 | computing system at the |
| 3. Field and office Supplies | $2,500 | $1,000 | $3,500 | UW. $2500 is requested |
| **(D) Total Operating Expenses** | $2,900 | $3,000 | $5,900 | for field and office supply. |
| **E. Technology Transfer** | | | | |
| 1. Field visits | $1,500 | $700 | $2,200 | We will have 10 field visits |
| 2. Presentation at TRB Conference | $1,400 | $0 | $1,400 | every year. One trip to |
| 3. Reporting (final report and progress reports) | $600 | $0 | $600 | the TRB conference (DC) |
| **(E) Total Technology Transfer** | $3,500 | $700 | $4,200 | is inculded. |
| **F. Equipment** | | | | |
| 1. Tower and datalogger | $2,542 | $0 | $2,542 | Solar powered high |
| 2. Wind Anemometers (05108-45) | $1,595 | $0 | $1,595 | frequency wind |
| 3. Temperature and RH sensor | $9,524 | $0 | $9,524 | monitoring system is |
| 4. 3-D Sonic Anemometer (CSAT3B) | $7,035 | $0 | $7,035 | included. One existing |
| 5. Visibility sensor (CS125-PT) | $4,176 | $0 | $4,176 | snow flux sensor will be |
| 6. Power supply | $9,524 | | | added. |
| 7. Snow flux sensor (FlowCapt) | $0 | $5,000 | $5,000 | |
| 8. Trailer | $1,500 | | | |
| **(F) Total Equipment** | $26,735 | $0 | $26,735 | |
| **G. Total Direct Costs (A through F)** | $83,555 | $8,700 | $92,255 | |
| **H. Indirect Costs (Specify Rate and Base)** | | | | |
| 1. Indirect Costs (20%) | $16,711 | $3,872 | $20,583 | Indirect cost was |
| **(H) Total Indirect Costs** | $16,711 | $3,872 | $20,583 | computed using 20% |
| **I. Tuition and Fees** | | | | |
| Tuition and Fee | $19,496 | $0 | $19,496 | Tuition for one MS |
| **(I) Total Tuition and Fees** | $19,496 | $0 | $19,496 | student for 2 years |
| **J. Total Direct and Indirect Costs (G+H+I)** | **$ 119,762** | **$12,572** | **$132,334** | |

## Implementation

Better understanding of the rollover crash mechanism will enhance the risk-based traveler information to vehicles during high wind conditions. The model-based rollover risk map will also be useful for the variable speed limit determination as well as the load weight recommendation to drivers. The blowover risk algorithm based on the fuzzy-logic (Young et al., 2018) used in the Wyoming CV Pilot system will be reviewed based on the wind monitoring data and the computed rollover risk. Recommendations for the potential wind break locations together with the rollover risk maps will be provided to the WYDOT. Finally, this project will provide fundamental information to determine the recommended **truck load weight** and **vehicle travel speed** when high wind warning is effective.

## Technology Transfer

Technology transfer will be done through dialog with the Wyoming Department of Transportation and other stakeholders throughout the entire project. Results will be disseminated through a final report, peer-reviewed publication(s), and technical presentations at national conferences such as the annual meeting of the Transportation Research Board. The results will be transferable to other agencies operating roads subject to high wind conditions.

## Data Management Plan

The rollover data will be stored on WYDOT servers and will be made available to persons, programs, and departments as needed. The Wyoming CV Pilot system at the WYDOT office will incorporate the project outcomes.

## References

Alonso-Estébanez, A., Díaz, J. D. C., Rabanal, F. Á., & Pascual-Muñoz, P. (2017). Performance analysis of wind fence models when used for truck protection under crosswind through numerical modeling. *Journal of Wind Engineering and Industrial Aerodynamics*, *168*, 20-31.

Anderson, A. R. S., M. Chapman, S. D. Drobot, A. Tadesse, B. Lambi, G. Wiener, and P. Pisano, (2012). Quality of mobile air temperature and atmospheric pressure observations from the 2010 Development Testbed Environment experiment. *J. Appl. Meteor. Climatol*., **51**, 691–701, https://doi.org/10.1175/JAMC-D-11-0126.1 .

Baker, C. J. (1986). A simplified analysis of various types of wind-induced road vehicle accidents. *Journal of Wind Engineering and Industrial Aerodynamics*, *22*(1), 69-85.

Baker, C. J. (1994). The quantification of accident risk for road vehicles in cross winds. *Journal of Wind Engineering and Industrial Aerodynamics*, *52*, 93-107.

Balsom, M., Wilson, F., & Hildebrand, E. (2006). Impact of wind forces on heavy truck stability. *Transportation Research Record: Journal of the Transportation Research Board*, (1969), 115-120.

Bedard, J. T. (1986). Vehicle Rollover Threshold Evaluation: An Assessment of Computer Simulation Models. Vehicle Weights and Dimensions Study.

Brook, R. R., & Spillane, K. T. (1970). On the variation of maximum wind gusts with height. *Journal of Applied Meteorology*, *9*(1), 72-78.

Chen, S. R., & Cai, C. S. (2004). Accident assessment of vehicles on long-span bridges in windy environments. *Journal of Wind Engineering and Industrial Aerodynamics*, *92*(12), 991-1024.

Choi, C. C. (1984). *Wind Loading in Hong Kong: Commentary on the Code of Practice on Wind Effects Hong Kong, 1983*. Hong Kong Institution of Engineers.

Cook, K. R., & Gruenbacher, B. (2008). Assessment of methodologies to forecast, wind gust speed national weather service. *Wichita Kansas. National Weather Service*. (https://www.weather.gov/ict/windgust)

Curtis, J., & Grimes, K. (2004). *Wyoming Climate Atlas.* Laramie, Wy: Office of the Wyoming State Climatologist.

Doran, J. C., & Powell, D. C. (1982). Gust structure in the neutral surface boundary layer. *Journal of Applied Meteorology*, *21*(1), 14-17.

Drobot, S., M. B. Chapman, A. Anderson, B. Lambi, P. A. Pisano, and G. Guevara, 2012: Tomorrow's forecast: Informed drivers. *Transportation Research Circular,* **E-C162**, 560–572, http://www.trb.org/Publications/Blurbs/167060.aspx.

Drobot, S., M. Chapman, E. Schuler, G. Wiener, W. Mahoney III, P. Pisano, and B. McKeever, 2010: Improving road weather hazard products with vehicle probe data. *Transportation Research Record: Journal of the Transportation Research Board*, **2169**, 128-140, https://doi.org/10.3141/2169-14 .

El-Gindy, M., & Wong, J. Y. (1987). A comparison of various computer simulation models for predicting the directional responses of articulated vehicles. *Vehicle System Dynamics*, *16*(5-6), 249-268.

Ellingwood, B. R., & Tekie, P. B. (1999). Wind load statistics for probability-based structural design. *Journal of structural engineering*, *125*(4), 453-463.

Hibino, Y., & Ishida, H. (2003). Static analysis on railway vehicle overturning under crosswind. *RTRI Report*, *17*(4), 39-44.

Imai, T., Araki, K., & Fukuhara, T. (2009). A Method to Estimate the Probability of a Train Encountering Gusts in an Operating Section. *Quarterly Report of RTRI*, *50*(4), 222-226.

Imai, T., Fujii, T., Tanemoto, K., Shimamura, T., Maeda, T., Ishida, H., & Hibino, Y. (2002). New train regulation method based on wind direction and velocity of natural wind against strong winds. *Journal of wind engineering and industrial aerodynamics*, *90*(12-15), 1601-1610.

Ishizaki, H. (1984). Wind profiles, turbulence intensities and gust factors for design in typhoon-prone regions. In *Wind Engineering 1983, Part 3A* (pp. 55-66).

Kunieda, M. (1972). Theoretical study on the mechanics of overturn of railway rolling stock. *Railway Technical Research Report*, *793*, 1-15.

Kyte, M., Shannon, P., & Kitchener, F. (2000). *Idaho Storm Warning System Operational Test.* Idaho Deparment of Transportation.

Liesman, J. S. (2005). An analysis of Wyoming truck crashes. In *Masters Abstracts International* (Vol. 45, No. 06).

Lin, X. G. (2003). Statistical modelling of severe wind gust. In *International congress on modelling and simulation, Townsville* (Vol. 2, pp. 620-5).

Mahoney, B., S. Drobot, P. Pisano, B. McKeever, and J. O'Sullivan. (2010). Vehicles as mobile weather observation systems. *Bull. Amer. Meteor. Soc.*, **91**, 1179–1182, https://doi.org/10.1175/2010BAMS2954.1 .

Mcneill, D and Freiberger, P., 1993: *Fuzzy logic: The Revolutionary Computer Technology that is Changing Our World.* Simon and Schuster, 319

Misu, Y., & Ishihara, T. (2012). Prediction of Strong Gust Frequency in a Control Section for Train Operations Based on Onsite Measurement and CFD. *Journal of Wind Engineering*, *37*(1), 11-24.

Mitsuta, Y. (1962). Gust factor and analysis time of gust. *Journal of the Meteorological Society of Japan. Ser. II*, *40*(4), 242-244.

Mitsuta, Y., & Tsukamoto, O. (1989). Studies on spatial structure of wind gust. *Journal of Applied Meteorology*, *28*(11), 1155-1160.

National Center for Atmospheric Research. *Pikalert®.* Accessed July 17, 2018 at https://ral.ucar.edu/solutions/products/pikalert%C2%AE

Ohara, N. (2017). *Historical Winter Weather Assessment for Snow Fence Design using a Numerical Weather Model* (No. FHWA-WY-17/03). Wyoming. Dept. of Transportation.

Perera, H. S., Ross Jr, H. E., & Humes, G. T. (1990). Methodology for estimating safe operating speeds for heavy trucks and combination vehicles on interchange ramps. *Transportation Research Record*, (1280).

Revfeim, K. J. A., & Hessell, J. W. D. (1984). More realistic distributions for extreme wind gusts. *Quarterly Journal of the Royal Meteorological Society*, *110*(464), 505-514.

Saiid, M., & Maragalas, E. (1995). Identification of Trigger Wind Velocities to cause Vehicle Instability. Nevada Department of Transportation.

Sherlock, R. H. (1952). Variation of wind velocity and gusts with height. In *Proceedings of ASCE* (Vol. 78, No. 126).

Snaebjörnsson, J.Th., Baker, C.J. & Sigbjörnsson, R. (2007). Probabilistic Assessment of Road Vehicle Safety in Windy Environments. *Journal of Wind Engineering and Industrial Aerodynamics 95, pgs. 1445-146.*

Tabler R.D. (2003). Controlling Blowing and Drifting Snow with Snow Fences and Road Design. Final Report NCHRP Project 20-7 (147) Tabler & Associates, Laramie, Wyoming. 345 pp.

U.S. Department of Transportation (2018) *Large Truck and Bus Crash Facts 2016*. Federal Motor Carrier Safety Administration, Analysis Division.

Wong, J. Y., & El-Gindy, M. (1986). A Comparison of Various Computer Simulation Models for Predicting the Lateral Dynamic Behaviour of Articulated Vehicles. Canroad Transportation Research.

WYDOT (2016) "Understanding Wyoming's High Winds" (https://www.youtube.com/watch?v=dIql3dWIRB4) WYDOT videos on YouTube.

Young, R. K., & Liesman, J. (2007). Estimating the relationship between measured wind speed and overturning truck crashes using a binary logit model. *Accident Analysis & Prevention*, *39*(3), 574-580.

Young, R. K., Welch, B. M., and Siems-Anderson, A.R., 2018: Generating Weather Alerts Including High Wind Blowover Hazards Using PikAlert® for the Wyoming Connected Vehicle Pilot Project, TRB, under review.

Young, R., Liesman, J., Lucke, D., & Schieck, S. (2005). Wyoming Freight Movement and Wind Vulnerability. *University of Wyoming*.

Young, R., Offei, E., & Dai, Q. (2010). *High Wind Warning System for Bordeaux, Wyoming* (No. FHWA-WY-10/05F).

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| Quoted By | Collin Daly |
| Customer Number | 71418 |
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| Li | Model | Part | Description | Qty | UM | Unit Price | Ext. Price |
|---|---|---|---|---|---|---|---|
| | ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~<br>Pricing reflects a 4% educational discount on applicable items.<br>~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ | | | | | | |
| 1 | UT10-NJ | 33042-3 | 10ft Tower w/Base, Adjustable Mast, & Grounding Kit<br>-NJ w/No J-Bolt Kit<br>-Hinged Base | 1 | EA | 556.80 | 556.80 |
| 2 | CR1000X-NA-ST-SW | 33268-2 | Measurement & Control Datalogger<br>-NA No Additional Coms<br>-ST -40 to +70C<br>-SW Standard 3yr Warranty | 1 | EA | 1,584.00 | 1,584.00 |
| 3 | ENC14/16-DC-LM | 30708-74 | Weather-Resistant 14 x 16 inch Enclosure<br>-DC 2 Conduits for Cables<br>-LM CM1xx Leg Mounting | 1 | EA | 401.28 | 401.28 |
| 4 | 05108-45-L15-PT | 32126-13 | RM Young Heavy Duty Wind Monitor, Alpine<br>15ft cable per sensor<br>-PT w/Tinned Wires | 1 | EA | 1,595.25 | 1,595.25 |
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| Li | Model | Part | Description | Qty | UM | Unit Price | Ext. Price |
|---|---|---|---|---|---|---|---|
| 5 | | 17953 | 1 x 1 inch Nurail Crossover Fitting | 1 | EA | 28.80 | 28.80 |
| 6 | CSAT3B-NC | 30330-1 | 3-D Sonic Anemometer w/Integrated Electronics -NC No Carrying Case | 1 | EA | 6,672.00 | 6,672.00 |
| 7 | CSAT3BCBL3-L15-RJ | 30322-71 | CSAT3B CPI/RS-485 Cable 15ft per sensor cable -RJ w/RJ45 Connector | 1 | EA | 135.12 | 135.12 |
| 8 | CSAT3BCBL2-L15-PT | 30321-9 | CSAT3B Power Only Cable 15ft per sensor cable -PT w/Tinned Wires | 1 | EA | 97.80 | 97.80 |
| 9 | CM204 | 17904 | Sensor Crossarm w/one CM210 Mounting Kit, 4ft | 1 | EA | 86.40 | 86.40 |
| 10 | CM210 | 17767 | Crossarm-To-Pole Mounting Kit *Used as second mount point for CM204 cross-arm. Will reduce cross- | 1 | EA | 44.16 | 44.16 |
| | | | | | | Continued | |

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| Li | Model | Part | Description | Qty | UM | Unit Price | Ext. Price |
|---|---|---|---|---|---|---|---|
| | | | arm length by 1ft. | | | | |
| 11 | CS125-PT | 30501-1 | CSL Present Weather Sensor (-25 to +60C), 16.4ft (5m) Cables -PT w/Tinned Wires | 1 | EA | 4,176.00 | 4,176.00 |
| 12 | CS215-L3-PT | 18007-57 | CSL Temperature/RH Probe 3ft cable per sensor -PT w/Tinned Wires | 1 | EA | 242.13 | 242.13 |
| 13 | RAD06 | 31543 | METSPEC 6-Plate Solar Radiation Shield | 1 | EA | 120.00 | 120.00 |
| 14 | | NOTE | ************************ Sunwize Solar Power Supply | 1 | EA | 0.00 | 0.00 |
| 15 | | SPECIAL-POWER | PR-960-24-420-TPWA-111a Load: 60 W @ 24 Vdc Load: 1.3 W @ 12 Vdc 5.7 Days of Autonomy NOT CANCELABLE OR RETURNABLE PRODUCT | 1 | EA | 9,420.00 | 9,420.00 |
| | | | | | | Continued | |

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| Li | Model | Part | Description | Qty | UM | Unit Price | Ext. Price |
|---|---|---|---|---|---|---|---|
| 16 | CABLEPCBL-L25-PT | 21969-29 | 2-Conductor 16AWG Power Cable<br>25ft per cable<br>-PT w/Tinned Wires | 1 | EA | 75.32 | 75.32 |
| | | | | | | SUBTOTAL | $25,235.06 |
| | | | | | | TAX | $0.00 |
| | | | | | | FREIGHT | TO BE ADDED |
| | | | | | | TOTAL | $25,235.06 |

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