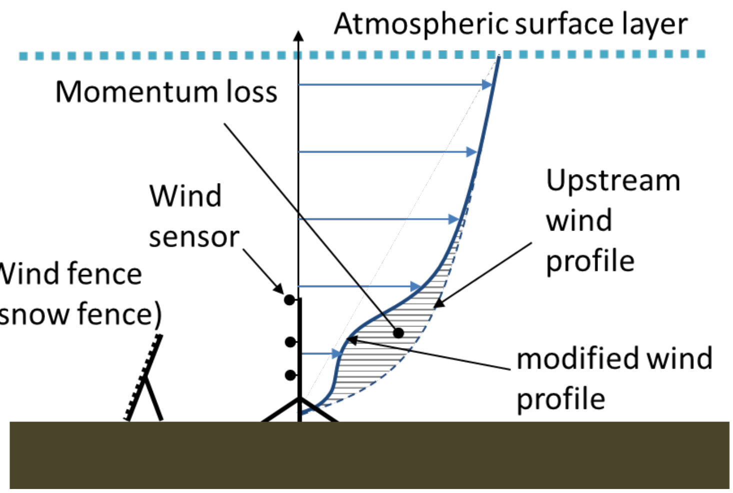
Evaluation of blow-over risk reduction by wind fences using wind profile measurements



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A proposal submitted to
Wyoming Department of Transportation
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Problem Statement

The risk of blow-over crashes caused by gusty winds represents a major concern for travelers on the Wyoming sections of national major road corridors such as the I-25 and I-80. The state of Wyoming has acted to address this problem by improving dynamic message signs (DMS) for drivers and increasing the penalties for drivers of light, high-profile vehicles ignoring road closures (Mullen, 2023; "Better signs, bigger penalties: Legislature, WYDOT take on blow-over crashes", WyoFile, Link). However, no physical mitigation measures for blow-over crashes have been implemented to date because it is challenging to assess the effectiveness of such approaches. Wind fences have been reported as an effective measure in certain situations; however, there are still key discrepancies between real-world implementations and the idealized conditions present in computational fluid mechanics (CFD) simulations and wind tunnel experiments. The objective of this study is to quantify the blow-over risk reduction by a wind fence using a comprehensive wind profile measurement system in the wide median of the I-80 near milepost (MP) 332. The proposed wind profile observations include a 12 sonic anemometer to evaluate the effect of wind modification by the existing wind/snow fence. This program of research is aligned with one of the strategic goals of the Wyoming Department of Transportation (WYDOT), i.e., to improve safety on the state transportation system through education, engineering, enforcement, and other innovative methods.

Background Statement

Wyoming experienced 316 blow-over crashes in six years (2012–2018), corresponding to an average of 52.7 crashes per year (WYDOT); therefore, blow-over crashes caused by strong wind are a major problem on Wyoming's highways. For example, wind gusts blew over 14 tractor-trailers along the I-25 in southern Wyoming and northern Colorado on November 20, 2017 (e.g., Kull, 2017, Wyoming Tribune Eagle). The road managers closed the I-25 in both directions between Wellington, Colorado, and Cheyenne, Wyoming, due to these crashes. Truck blow-over crashes due to strong crosswinds often result in long road closures for debris cleaning.

The proposed research is based on earlier efforts at the University of Wyoming (UW) that investigated the operation of roadway segments in high wind conditions. Young et al. (2005) examined truck movements and safety and follow-up research investigated the relationship between crash occurrences and the measured wind speed at nearby weather stations (Liesman, 2005; Young & Liesman, 2007a). These studies demonstrated that weather station-measured wind speed data were sufficient to characterize crashes. Young et al. (2010) developed guidelines for the WYDOT Traffic Management Center to operate the Bordeaux corridor during high wind conditions. Recently, the Principal Investigator Ohara and his team completed a project on blow-over risk evaluation with a focus on temporal risk variability during strong wind periods (Neupane et al., 2023; Ohara et al., 2023). Their study revealed an explicit relationship between the wind field and vehicle blow-over risk considering the temporal variability of wind gusts.

This proposed study aims to quantify how a wind fence can reduce the blow-over probability. Existing studies based on CFDs, wind tunnel experiments, or field measurements may not be directly applicable to this problem due to discrepancies between idealized experimental conditions and real-world conditions. As Principal Investigator Ohara actively operates a blow-over risk model based on the force balance acting on a vehicle, the efficiency of possible wind fence design can be evaluated using the proposed wind profile measurement system. Specifically, the force reduction by a wind fence for light, high-profile vehicles can be directly evaluated based on the mean and gust airflow momentum loss. To achieve this, we propose to install multiple wind towers upstream and downstream of the existing snow fence in the wide median of the I-80 near MP 332. The quantified wind momentum reduction will then be analyzed using the integrated blow-over risk evaluation model.

Literature Review

Blow-over crashes are not a Wyoming-specific problem; in fact, the US Department of Transportation (2020) reported that overturn (rollover) incidents comprised 4 percent of all fatal crashes involving large trucks in the US and 2 percent of all nonfatal crashes involving large trucks. Not all the reported rollover crashes were caused by strong winds; however, blow-over crashes can occur in many parts of the US Highway system when the conditions are met. Moreover, the ongoing climate change seems to make the environment windier (Ohara, 2017; Pryor et al., 2020). Ohara et al. (2021) estimated that approximately 42.6 percent of Wyoming's highways have a considerable blow-over risk based on the historical maximum wind speed. Thus, Wyoming, as one of the windiest states (Curtis and Grimes, 2004), represents an ideal location to study wind-related hazards and develop mitigation methods.

Blow-over crash risk is affected by many factors, including road geometry, wind speed, wind gusts, wind direction, vehicle weight, vehicle travel speed, and driver's skill. In the case of a truck traveling around a curve, a strong gust of outward wind (originating 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). However, using their static blow-over model, the UW team showed that both inward and outward winds can result in high blow-over risk depending on the superelevation, design vehicle speed, and travel speed (Ohara et al., 2021; Ohara et al., 2023). For example, when a vehicle travels slower than its design speed, inward wind can result in higher blow-over risk due to the superelevation. Additionally, since headwinds also contribute lift force (Neupane et al., 2023), winds blowing at the back of a vehicle can reduce the blow-over risk (Snaebjörnsson, Baker & Sigbjörnsson, 2007). Chen and Cai (2004) identified that vehicles on bridges are more vulnerable to blow-overs than those on the road. Young (2010) found that loaded trucks overturn at an average wind speed of 51 mph, whereas empty trucks overturn at an average wind speed of 38 mph. This finding highlights the importance of the truck weight parameter in the context of overturning crashes. These observations were subsequently verified by the recent UW study by the Principal Investigator (Ohara et al., 2021; Neupane et al., 2023; Ohara et al., 2023).

The effect of wind fences on vehicle stability has previously been studied using CFD models. El Gindy and Wong (1987) evaluated CFD models for vehicle stability, while Zhang et al. (2020) used detailed aerodynamic coefficients (e.g., drag coefficient) to quantify the behavior of a heavy tractor semi-trailer under crosswinds using the CFD model. Chen et al. (2012) quantified the shelter effect of a deflector-porous fence based on the velocity magnitude, turbulence magnitude, and pressure distributions of the triangular prism placed behind the fence. Alonso-Estébanez et al. (2017) analyzed the effect of perforated wind fences in cross-wind environments using a CFD model based on the Reynolds-averaged Navier–Stokes (RANS) equations. Their study found that wind fences with circular holes are more effective than those with rectangular slits. They also found that the effect of distance on the rollover coefficient depends on the fence height, although they only analyzed the distance effect up to 5 m from the fence.

Additionally, the effect of the accumulation of snow and ice should also be considered for wind fence design (Alonso-Estébanez et al., 2017, Tabler, 2005).

As an alternate approach, wind tunnel experiments have also been used to evaluate the efficiency of fences. Zhang et al. (2010) investigated the shelter effect of a scaled 4 cm-high porous wind fence using a wind tunnel experiment. The fence's effect was found to decay monotonically in the leeward region and became very small (<10 percent of sand transport) downstream of x/H=3, where H is the height of the fence and x is the distance from the fence. In addition, Dong et al. (2010) showed that the shelter effect of porous fences may occur across a much larger area (x/H = ~15–30) by visualizing the wind speed and turbulent kinetic energy for various fence porosities (H = 2 cm). They concluded that the optimum fence porosity for the wind shelter effect is 0.2, which differs from the optimum porosity (~0.5) for snow capture efficiency (Tabler, 2003). Edamoto et al. (1999) performed a 1/10 scale wind tunnel experiment with seven different wind fence configurations (15–20 cm high). They found a substantial wind reduction over a sufficient distance to cover the roadway (scaled distance equivalent to ~30 m real distance). However, it is debatable whether these scaled experiments can accurately represent real-world conditions despite meeting the Reynolds law of similitude.

Wind fences for blow-over risk reduction have been incorporated in the railway design regulations in Japan, especially for bridges in windy regions (e.g., Imai et al., 2002). These regulations were initiated by the Amarube Bridge accident in 1986, in which seven passenger cars of a train were blown from a bridge 41.5 m (136 ft) in height (Fujii et al., 1999). This incident also led to various studies on the aerodynamic forces acting on trains in cross winds (e.g. Suzuki et al., 2003; Tanemoto et al., 2013). Hibino et al. (2010) developed a detailed overturning model for a train under strong cross winds incorporating the wind oscillation effect. Otobe et al. (2017) evaluated the shelter effect of wind fences on a bridge at various wind angles by performing wind tunnel experiments at a 1/40 scale. Their study demonstrated that the shelter effect generally increases with higher fences and at closer distances; however, they also observed that certain wind directions (wind azimuth angles of 30–70º) can result in a negative shelter effect, particularly in the case of wind-fenced high bridges. Although these studies demonstrated the effectiveness of wind fences, the influence of wind field variations remains unclear.

Several studies have focused on the weather pattern causing hazardous strong wind conditions. The gust factor, which describes the gust strength as proportional to the mean wind speed, is a well-accepted metric (e.g. Sherlock, 1956; Mitsuta, 1962; Davis and Newstain, 1968; Paulsen & Schroeder, 2005). In addition, Misu and Ishihara (2012) identified a significant agreement between the mean wind direction and gust wind direction using wind records and a model simulation. The UW team (Neupane et al., 2023; Ohara et al., 2023) incorporated wind speed variability into their blow-over risk assessment system using statistical techniques. However, the shelter effect for wind gusts under highly variable wind direction remains largely unknown. To date, no study has investigated the shelter effect of wind fences based on actual field observations with a consideration of the distance from the fence and wind field variations.

Objectives

This study aims to establish the fundamental understanding and technology for wind fence design based on field monitoring and the stochastic blow-over risk model.

The objectives of this work are as follows:

1. Characterization of mean and gust wind profiles based on field monitoring around an existing snow fence (I-80 MP332, Wyoming).
2. Quantification of the local wind momentum loss due to the fence for both mean and gust winds at different downstream distances in response to various wind directions.
3. Quantification of the blow-over risk reduction by the fence using the existing UW blow-over risk model (Neupane et al., 2023; Ohara et al., 2023).
4. Development of recommendations for potential wind fence installation design and anticipated blow-over risk reduction.

Benefits

The key benefit of this study will be the provision of the information needed to design wind fences for blow-over risk mitigation for high-profile lightweight vehicles under different high wind conditions. Specifically, the deliverables from this project will be:

- Wind force reduction data for a wind/snow fence based on the field-measured wind profiles.
- Quantification of the expected blow-over risk reduction depending on the distance from the wind/snow fence.
- Visualization of the blow-over crash risk reduction of the existing snow fence system.

The proposed research also has strong ties to the following WYDOT strategic goals:

- Keep people safe on the state transportation system.
- Serve our customers.

Applicable Questions

No potential barrier to project implementation has been identified to date. The Principal Investigator will communicate closely with the project manager and sponsors if any issues emerge. The requirements for this project will be met by the Principal Investigator, who has extensive experience in data analysis, blow-over model development and operation, and field wind monitoring through various national and international projects, as well as previous WYDOT RAC projects.

Statement of Work

Work Schedule

The project is scheduled for 36 months, beginning in July 2024 and ending in June 2027. The key tasks of this research program are listed below.

1. Wind profile monitoring system installation around an existing snow fence (I-80 MP332).
2. Wind profile data collection using the 12 sonic wind sensor for continuous mean and gust wind characterization.
3. Wind profile modification characterization based on the local wind momentum loss due to the fence using a curve fitting exercise.

4. Blow-over risk reduction estimation using the existing UW model (Neupane et al., 2023; Ohara et al., 2023).
5. Project reporting, including recommendations for potential wind fence installation sites and anticipated blow-over risk reduction.

	Year 1				Year 2				Year 3			
Tasks	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Wind profile monitoring system installation												
Wind profile data collection												
Wind profile modification characterization												
Blowover risk reduction												
Reporting												

Wind profile monitoring system installation and data collection

The proposed wind profile monitoring site lies within the wide median of I-80 near milepost MP332, which is a WYDOT right-of-way. This site is occupied by relatively flat grassland with minimum influence of other topographic features. Figure 1 shows aerial images and a landscape photograph of the proposed site. This area is accessible through the access road for the nearby Historical Site, “Tree in The Rock”. We expect a minimal snowdrift effect compared to the surrounding snow fence areas based on an examination of historical satellite imagery taken in April 2017 (lower right panel of Figure 1). However, we anticipate that some adjustments will be required in the analysis due to surface elevation variations. Additionally, once we collect sufficient wind profile data for one wind/snow fence configuration, we plan to discuss possible fence modifications with the WYDOT sponsors and the project manager.

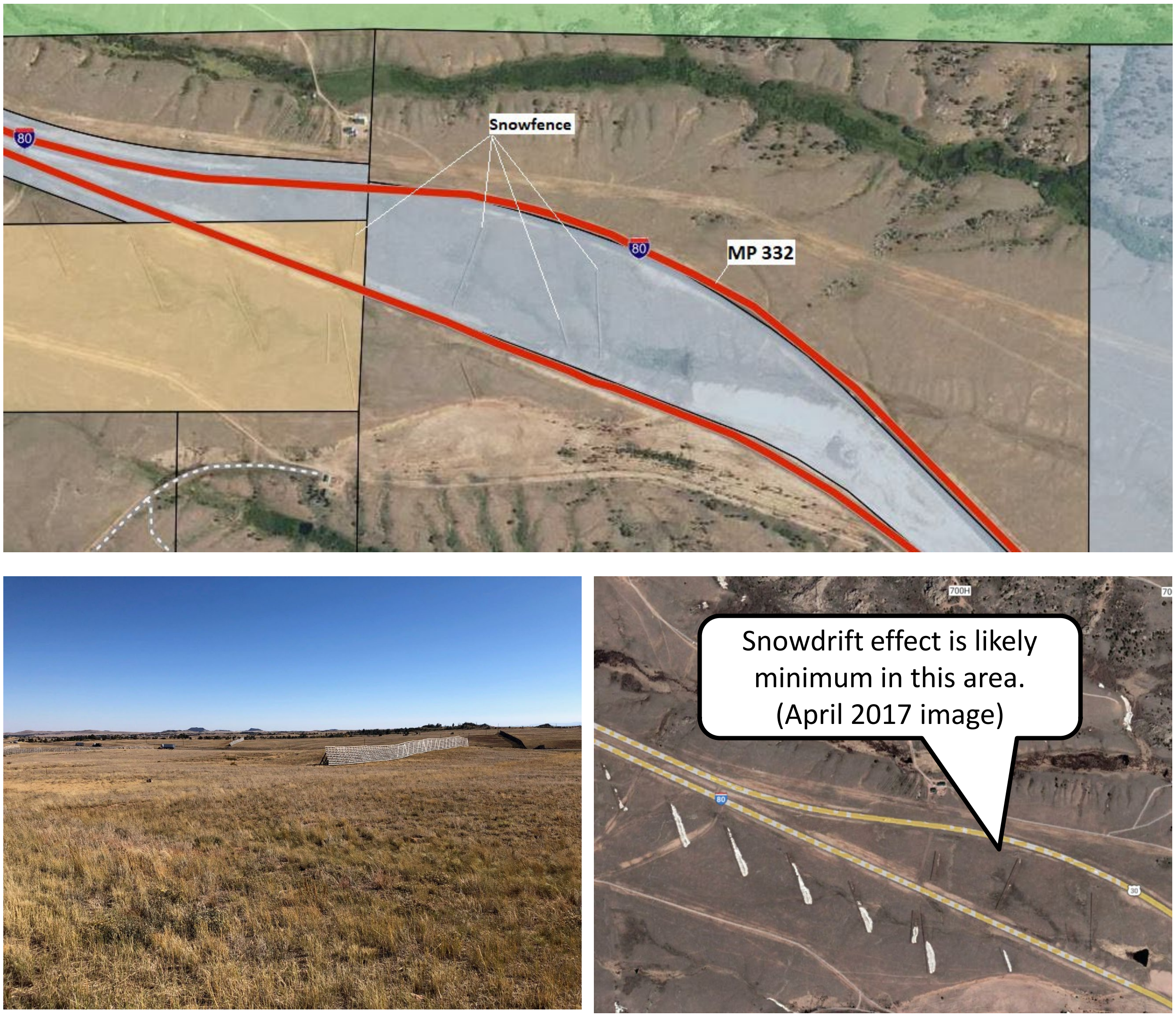

Figure 1: Map, landscape photograph, and springtime satellite image of the proposed site in the wide median of I-80 near MP 332.

Wind profile modification characterization

We propose four independent wind profile towers in the upstream and downstream areas of the wind fence, as illustrated in Figure 2. Each tower will be equipped with three sonic anemometers.

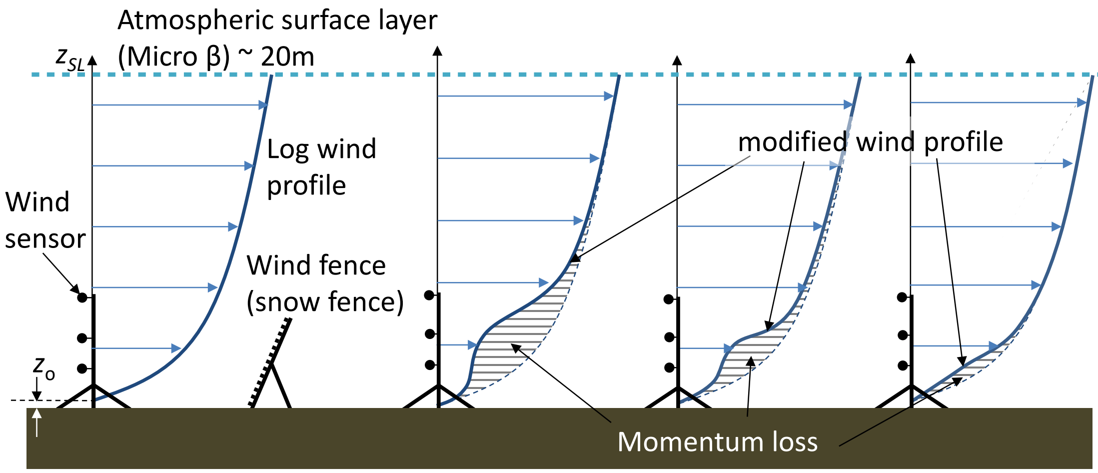

Figure 2: Schematic illustration of the proposed wind profile monitoring system. The wind speed reduction with respect to the downstream distance will be characterized.

Blow-over force reduction F_{red} may be computed as the decrease in the airflow momentum p within the atmospheric surface layer ($z < z_{SL}$).

$$F_{red} = \frac{\Delta p}{\Delta t} = \frac{p_{in} - p_{out}}{\Delta t}$$

where Δt is the time increment, p_{in} is the incoming airflow momentum and p_{out} is the outgoing airflow momentum. The airflow momentum within the atmospheric surface layer can be estimated as

$$p = \int_{z_o}^{z_{SL}} \rho_{air}\, u(z)^2\, dz$$

where $u(z)$ is the wind speed at height z, and ρ_{air} is the density of air. The difference can be evaluated by

$$\Delta p = \rho_{air} \int_{z_o}^{z_{SL}} [u_{in}(z)^2 - u_{out}(z)^2]\, dz.$$

In theory, the wind profile within the atmospheric boundary layer may be expressed as

$$u_{in}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_o}\right)$$

where κ is the von Kármán constant, and u_* is the friction velocity. The upstream wind sensor will determine the aerodynamic roughness length z_o and the friction velocity u_*. To do so, we will test various mathematical functions to model the deviation from the logarithmic wind profile caused by the wind/snow fence. Accordingly, the force reduction by the wind fence will be evaluated using the airflow momentum loss derived from measurements made using multiple sensors.

Blow-over risk reduction estimation

In our previous study (Ohara et al., 2022, Neupane et al., 2023; Ohara et al., 2023), we developed a stochastic blow-over model (the UW model) for a tractor-trailer truck which has provided useful information for road managers in Wyoming (Mullen, 2023). The static vehicle stability model integrates the major influencing factors of blow-over crashes, such as wind speed, gust speed, wind direction, travel speed, vehicle weight, and road geometry. As shown in Figure 3, this model can directly incorporate the force reduction by the wind fence estimated using the field method described above.

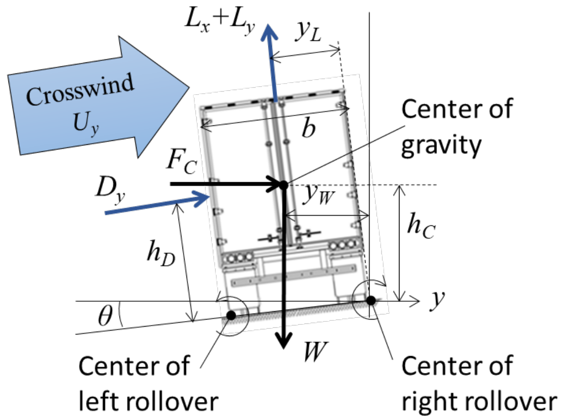

Figure 3: Diagram of the force balance acting on a vehicle.

The stochastic model based on this force balance can then be used to quantify the blow-over probability (Neupane et al., 2023). For instance, frequency histograms of computed critical vehicle speeds within the typical time interval (~15 min–1 hour) can be modeled using a statistical distribution. Figure 4 illustrates a schematic of the modeled critical vehicle speed with and without the wind fence.

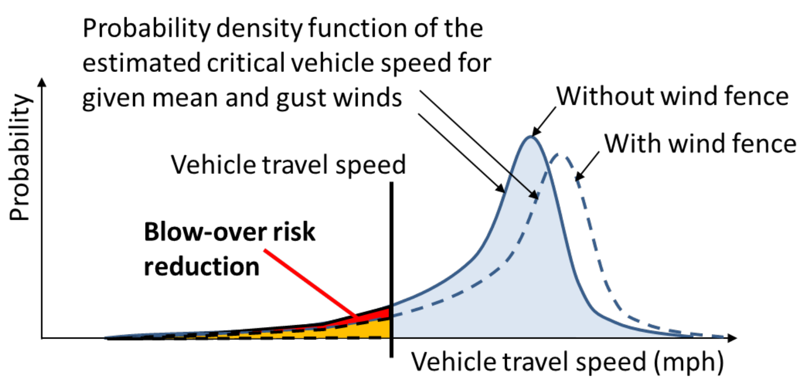

Figure 4: Schematic visualization of blow-over risk reduction by the wind/snow fence

The estimated distribution can be applied to quantify the probability of blow-over risk for a high-profile lightweight vehicle by specifying the travel speed. Determining the blow-over risks with and without the wind fence can then be used to quantitatively assess the effectiveness of the wind/snow fence, which may otherwise be difficult to estimate based on the limited available crash records.

Budget

Total budget of $164,138 is requested as shown in the budget table below. This cost estimation includes support for one MS student for three years, half (0.5) month summer-time commitment for the Principal Investigator Ohara every year, and one TRB presentation in Washington DC. Note that an inflation rate of 3 percent is applied for personnel cost estimations. Four wind profile towers are budgeted as major equipment ($8474 x 4 towers = $33,899). Each tower consists of three 2-D sonic wind sensor (WINDSONIC4), one data logger (CR350-NA), 15-feet tripod (CM115), an enclosure (ENC10/12), and power supply (SP10 and BP12).

PROJECT TITLE: Evaluation of blow-over risk reduction by wind fences using wind profile measurements		
Contract Period: 36 months		
A. Senior Personnel		
1. Noriaki Ohara	$17,433	0.5 mon summer
(A) Total Senior Personnel	**$17,433**	
B. Other Personnel		
1. One (1) Graduate Student	$53,379	Graduate student stipend
(B) Total Other Personnel	**$53,379**	
C. Fringe Benefits		
1. Senior Personnel	$7,130	Fringe Rates are 40.9% for faculty and 1.8% for graduate
2. Graduate Student	$961	
(C) Total Fringe Benefits	**$8,091**	
D. Operating Expenses		
1. Field supply	$1,500	Office supply includes a monitor and other accesary
2. Office Supplies	$300	
(D) Total Operating Expenses	**$1,800**	
E. Technology Transfer		
1. Presentation at TRB Conference	$1,400	One presentation in TRB conference in DC
(E) Total Technology Transfer	**$1,400**	
F. Equipment (more than $5000)		
4 wind profile towers	$33,899	See quote for two towers by Campbell Scientific
(F) Total Equipment	**$33,899**	
G. Tuition and Fees		
Tuition and Fee	$31,715	Graduate student tuition
(G) Total Tuition and Fees	**$31,715**	
H. Total Direct Costs (A through F)	**$147,717**	
I. Indirect Costs (Base: H Total direct cost)		20% of Total Direct Costs (H) - Equipment (F) - Tuition and Fees (G)
1. Indirect Costs, UW	$16,421	
(I) Total Indirect Costs	**$16,421**	
J. Total Direct and Indirect Costs (H+I)	**$164,138**	Total request

PROJECT TITLE: Evaluation of blow-over risk reduction by wind fences using wind profile measurements			
Budget Period:	Year 1	Year 2	Year 3
A. Senior Personnel			
1. Noriaki Ohara	$5,640	$5,809	$5,983
Total	**$5,640**	**$5,809**	**$5,983**
B. Other Personnel			
1. Graduate Student	$17,100	$17,784	$18,495
Total	**$17,100**	**$17,784**	**$18,495**
C. Fringe Benefits			
1. Senior Personnel	$2,307	$2,376	$2,447
2. Graduate Student	$308	$320	$333
Total	**$2,615**	**$2,696**	**$2,780**
D. Operating Expenses			
1. Field supply	$500	$500	$500
2. Office Supplies	$100	$100	$100
Total	**$600**	**$600**	**$600**
E. Technology Transfer			
1. Presentation at TRB Conference	$0	$0	$1,400
Total	**$0**	**$0**	**$1,400**
F. Equipment			
4 wind profile towers	$33,899	$0	$0
Total	**$33,899**	**$0**	**$0**
G. Tuition and Fees			
Tuition and Fee	$10,572	$10,572	$10,572
Total	**$10,572**	**$10,572**	**$10,572**
H. Total Direct Costs (A through F)	**$70,426**	**$37,461**	**$39,831**
I. Indirect Costs (Base: H Total direct cost)			
1. Indirect Costs, UW	$5,191	$5,378	$5,852
Total	**$5,191**	**$5,378**	**$5,852**
J. Total Direct and Indirect Costs (H+I)	**$75,616**	**$42,839**	**$45,683**
		Total project cost:	**$164,138**

Implementation

This project does not involve the installation of any new wind fence at the blow-over hot spots. However, the quantified blow-over risk reduction will provide a fundamental basis for potential future wind fence installations. Furthermore, the existing snow fence system will be re-evaluated for blow-over crash reduction, which is an additional benefit, based on the findings of the field experiments.

Technology Transfer

Technology transfer will be performed via the WYDOT throughout the entire project. The results of the project 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 also be transferable to other agencies operating roads subject to high wind conditions.

Data Management Plan

The wind and corresponding blow-over risk data will be stored on the WYDOT servers and will be made available to persons, programs, and departments as required. The anticipated data include the field observed wind profiles around the wind/snow fence. The data will be stored in CSV or ASCII file format including their location and time information. Detailed data specifications will be determined by the end of the project.

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Attachment

The quote for the wind profile measurement towers is attached below. Note that it includes only two independent towers. Total equipment cost for four towers is \$16,949.64 x 2 = \$33,899.28.

Domestic Quote

Quote #: 225932 • Quoted by: Felix Zamora
Quote Date: 04 Oct 2023 • Valid Through: 03 Dec 2023

To	Ship To	Details
Noriaki Ohara University of Wyoming Civil & Architectural Eng Dept Dept 3295 1000 E University Ave Laramie, Wyoming 82071 United States	Attn: Noriaki Ohara Wyoming State Climate Office 1000 E University Ave Laramie, Wyoming 82071 United States	Credit Terms: N30 Freight Terms: N/C Incoterms: FOB Logan, UT

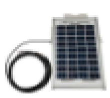
Measurements

#		Model	Part	Description	Qty	Unit Price	Ext. Price
1		WINDSONIC4-L30-PT	18456-177	2-D Sonic Wind Sensor with SDI-12 Output 30ft cable per sensor -PT w/Tinned Wires	6	$1,379.58	$8,277.48
2	↳ 	34344	34344	MetSENS-Series or Windsonic-Series Mounting Stand	6	$94.08	$564.48

Data Logging & Control

#		Model	Part	Description	Qty	Unit Price	Ext. Price
3		CR350-NA	39377-1	Datalogger (-40 to +70C) -NA No Additional Coms	2	$1,056.00	$2,112.00

Power

#		Model	Part	Description	Qty	Unit Price	Ext. Price
4		SP10-PT-SM	5278-1	10W Solar Panel, 20ft Cable -PT w/Tinned Wires -SM Std Mounting Kit	2	$213.36	$426.72
5		BP12	8065	12V Sealed Rechargeable Battery w/Mounts, 12Ah	2	$161.76	$323.52

Enclosures & Mounting

#		Model	Part	Description	Qty	Unit Price	Ext. Price

Domestic Quote

Quote #: 225932 • Quoted by: Felix Zamora
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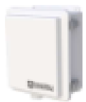
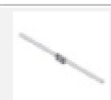
6		ENC10/12R-SC-NM	30705-24	Raised Lid Enclosure, 10 x 12 inches -SC 1 Conduit for Cables -NM No Enclosure Mounting	2	$322.56	$645.12
7		CM115	19242	Stainless Steel, 15ft Tripod w/Gnd & Guy Kit	2	$1,753.92	$3,507.84
8		19282	19282	Duckbill Standard Anchor Kit	2	$134.40	$268.80
9		CM204	17904	Sensor Crossarm w/one CM210 Mounting Kit, 4ft	6	$137.28	$823.68

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Sub Total:	$16,949.64
Tax:	$0.00
Est Freight:	$0.00
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