COMPARATIVE EVALUATION OF AUTOMATED WIND WARNING SYSTEMS

Showcase Evaluation #15

Technical Memorandum 3: Safety Benefits

By

Christopher Strong, P.E.
and
Manjunathan Kumar, P.E.
Western Transportation Institute
College of Engineering
Montana State University

Prepared for the

Research and Innovative Technology Administration
U.S. Department of Transportation

in cooperation with the

California Department of Transportation
Division of Research and Innovation

and the

Traffic Engineering and Operations Section
Oregon Department of Transportation

March 2006

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ACKNOWLEDGMENTS

The authors are thankful for the support of the Rural California/Oregon Advanced Transportation Systems (COATS) Steering Committee through this project, and are hopeful that the results will be useful as they work to improve the safety and efficiency of the rural transportation system in northern California and southern Oregon.

The authors would like to thank the U.S. Department of Transportation Research and Innovative Technology Administration for their funding of this study, and the California and Oregon Departments of Transportation, who are partners in the California/Oregon Advanced Transportation Systems (COATS) Showcase project. The authors would also like to thank the Highway Safety Information System (HSIS) Laboratory for providing and helping with the data.

GLOSSARY OF ABBREVIATIONS

AWWS	Automated Wind Warning Systems
Caltrans	California Department of Transportation
CMS	Changeable Message Sign
COATS	California/Oregon Advanced Transportation Systems
FHWA	Federal Highway Administration
HSIS	Highway Safety Information System
ITS	Intelligent Transportation Systems
MOE	Measure of Effectiveness
MP	Mile Post
NB	North Bound
ODOT	Oregon Department of Transportation
RWIS	Road Weather Information Systems
SB	South Bound
VMS	Variable Message Sign
VMT	Vehicle-Miles of Travel

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

One challenge facing rural travelers is weather hazards that produce adverse driving conditions at isolated locations. One such hazard is sustained high winds that can cause high-profile vehicles such as recreational or commercial vehicles to overturn, and lower-profile vehicles to leave their lanes, jeopardizing motorist safety. Since wind conditions and patterns are defined significantly by local topography, there is limited ability to mitigate the impacts of wind through improved roadway design. Warning the drivers of impending cross winds well in advance and measures to reduce operational speeds are other options explored by transportation professionals.

To address localized high cross wind challenges, the Oregon and California Departments of Transportation (ODOT and Caltrans, respectively) have used intelligent transportation systems (ITS) installations to alert motorists of dangerously windy conditions automatically. The warning messages are displayed to drivers at locations where they can stop and wait until the winds die down or where they can decide to take a longer alternate route. Three systems have been deployed in the rural California/Oregon Advanced Transportation Systems (COATS) study area, at the following locations:

- Between Port Orford and Gold Beach, Oregon on US Route 101 between mileposts (MP) 300.10 and 327.51 ("South Coast System")
- On the Yaquina Bay Bridge (US Route 101) between mileposts 141.27 (SB) and 142.08 (NB) in Oregon
- On Interstate 5 in Siskiyou County, California between postmiles 13.2 (Weed) to 45.3 (Yreka)

As these automated wind warning systems (AWWS) represent innovative applications of ITS in a rural environment, a project through COATS Showcase was initiated to evaluate their effectiveness. The evaluation focused on the two Oregon systems, because these two systems were fully automated and operational prior to the high wind season of 2003-04 (i.e. November 2003 – March 2004). The AWWS on Interstate 5 in California is not expected to be fully automated before December 2005. The goals of the automated wind warning systems (AWWS) deployed in Oregon are threefold:

- Improve the safety and security of the region's rural transportation system
- Provide sustainable advanced traveler information systems that collect and disseminate credible, accurate "real-time" information
- Increase operational efficiency and productivity focusing on system providers

In this COATS Showcase research project, the automated wind warning systems in Oregon are being evaluated against the measures of effectiveness (MOE) shown in Table 1-1. The ones that are focused on the overall evaluation of these systems are as follows:

1. Reduction in wind induced accident frequency and severity
2. Traveler awareness of these systems
3. Traveler perception of the usefulness of these systems
4. Traveler perception of the reliability of the system

5. System accuracy
6. Other operational cost savings

The purpose of this technical memorandum is to assess the systems' safety benefits (MOE 1). Chapter 2 provides further background on the AWWS deployed in the COATS region. Chapter 3 reviews the safety impacts of high cross winds as summarized in the literature, and specifically through the two US Route 101 sites in Oregon. Since information on the presence of high winds is not routinely collected by Oregon crash investigators, it was necessary to look at other states where this information is recorded. Chapter 4 examines this data to determine of the extent of wind-influenced crashes and identify "typical" wind-influenced crashes in these other states. Finally, Chapter 5 offers conclusions on this analysis with safety recommendations.

Table 1-1: Goals, Objectives and Measures of Effectiveness

Goal	Objective	Potential Measures of Effectiveness	Data Source
Improve the safety and security of the region's rural transportation system	Improve the safety of high profile vehicles	▪ Crash frequency for high profile vehicles ▪ Crash severity for high profile vehicles	Crash Data
	Improve safety of lower profile vehicles	▪ Crash frequency for all vehicles ▪ Crash severity for all vehicles	Crash Data
Provide sustainable traveler information systems that collect and disseminate credible, accurate "real-time" information	Improve the motorist information on severe weather conditions	▪ System usage by motorists ▪ Awareness of system among motorists	Motorist Survey
	Improve motorist acceptance and perception	▪ Sign clarity ▪ Message credibility and reliability	Motorist Survey
Increase operational efficiency and productivity focusing on system providers	Improve staff operations efficiency	▪ Savings in personnel time ▪ Reduction in the time to post a message	Maintenance Logs
	System reliability	▪ Number of full system outages ▪ Number of partial system outages	Maintenance Logs
	Improving emergency response	▪ Information sharing	Kick Off

2. SYSTEM DESCRIPTION

This chapter provides more detail on the wind warning systems which are being evaluated in this project along with – for completeness – the system under development in northern California.

2.1. South Coast System

This part of U.S.highway 101 from Port Orford to Gold Beach has been identified as a high wind area. The ODOT ITS Unit designed a system that uses a local wind gauge (anemometer) to monitor wind speeds in the critical wind speed location (i.e. near Humbug Mountain).

Prior to implementation of the system, when high winds were detected, maintenance staff drove to Gold Beach (MP 330) and Port Orford (MP 300) to flip up folded signs that read "CAUTION HIGH WINDS NEXT 27 MILES WHEN FLASHING" and turn on a flashing beacon to warn traffic about windy conditions. The employee would patrol the highway until the winds subsided, and then manually turn off each sign. This system had a high maintenance cost, required a 60-mile round trip to Gold Beach, and was not timely enough. One of these signs is shown in Figure 2-1.

Figure 2-1: Static Sign with Flashing Beacon at Gold Beach

This process has now been automated. Currently, this system consists of an anemometer that provides continuous input to the controller connected to a flashing beacon on static warning signs located at either end of the corridor. Communication to the two warning signs is automated and is provided using dial-up telephone links. Motorists are informed when average winds of speeds higher than 35 mph are recorded over a given time interval (e.g. 2 minutes). This enhancement has also enabled an automated creation of an instance of severity 0 (zero) incident (for wind speeds between 35 and 80 mph) or a severity two incident (for wind speeds greater than 80 mph) in Oregon's Highway Travel Conditions Reporting System (HTCRS). This incident in HTCRS is then verified by the Traffic Operations Center (TOC) staff. When verified by the TOC staff, the HTCRS warning is posted on ODOT's TripCheck web site.

Project implementation was motivated by the many potential benefits, including equipment cost savings, elimination of unnecessary and possibly unsafe travel by ODOT personnel, and more rapid detection and notification of high-wind conditions, which would improve safety in the corridor.

2.2. Yaquina Bay Bridge System

The second AWWS in Oregon was installed on Yaquina Bay Bridge (US Route 101) between mileposts 141.27 (SB) and 142.08 (NB). ODOT had a manual process for measuring gusts in the vicinity of the bridge and providing warnings to the public. When gusts or sustained high winds were present, an employee went to the site with a portable anemometer and, if windy conditions were verified, unfolded static warning signs on either end of the bridge. Crossing the bridge to reach the other sign (and then coming back) presented a safety risk for the employee charged with this task.

To avoid the safety risks and to improve operations, ODOT has automated the posting of high-wind warnings. The proposed system originally consisted of a local wind gauge connected to small variable message signs (VMS) located at either end of the corridor with different levels of warning. Due to lack of available funding, the current system uses a static sign that reads "Caution High Winds on Bridge When Flashing" and flashing beacons installed on top of the signs. The signs are located to provide sufficient warning for drivers to be able to turn around on existing roads under either end of the bridge. Although the current signs display a fixed message, the system records two different warning levels. Proposed warnings for each range of sustained wind speeds are shown in Table 2-1. This system also defines the severity of the incident. This severity is automatically recorded in HTCRS, and is then verified by the Traffic Operations Center (TOC) staff. When verified and accepted by TOC staff, a warning message is automatically posted on ODOT's TripCheck Web site. Faxes are also sent manually to other agencies, and maintenance staff are also notified automatically via pager and / or email. The sign is deactivated when the average wind speed goes below 25 mph. This system will archive data including wind speed, and date and time of warning postings.

Table 2-1: Warning Messages for Yaquina Bay System

Average Wind Speed Range	Warning Message	HTCRS Severity Level
35 to 80 mph	Pending Closure	1
Over 80 mph	Closure	2

2.3. Interstate 5 System

Caltrans has installed a set of changeable message signs (CMS) on Interstate 5 in Siskiyou County between postmiles 13.2 (Weed) to 45.3 (Yreka). Currently there are static signs with no flashing beacons at both the locations indicated above. The static signs are not responsive to real-time weather conditions and they make less of an impression on the drivers, because they display a message of caution irrespective of wind speeds.

Caltrans has been providing high wind warning messages through two CMS: one just south of the Yreka interchange (PM 45.3) and the other at the Abrams Lake over-crossing (PM 13.2) for the southbound and northbound traffic, respectively. There is a weather station installed at the northbound Weed Safety Roadside Rest Area at PM 25.7 to make the system responsive to conditions on a real-time basis. Caltrans is in the process of automating the activation of warning messages through these CMS signs. The CMS also allow greater flexibility in message sets, including the ability to report specific levels of warning, or the actual wind speed.

Table 2-2 summarizes the different characteristics of these three systems. All three systems are currently active. The two systems on US 101 in Oregon are automated, while the system on Interstate 5 in California is operational but not fully automated.

Table 2-2: Summary of Wind Warning System Characteristics.

Charactersitics of the System	AWWS at Yaquina Bay Bridge, OR	AWWS at South Coast, OR	5, Siskiyou County, CA
Flashing/Non-Flashing	Flashing	Flashing	CMS
Static/Dynamic	Static (to be upgraded to CMS)	Static	Dynamic (CMS)
Message sent to sign (manual / automated)	Automated	Automated	Manual (To Be Automated in 2005)
Message posted on Web (manual / automated)	Semi - Automated	Semi - Automated	N/A
Archiving of the Wind Data	Yes	Yes	No
TOC notification of sign activation (manual / automated)	Automated	Automated	To be Automated
TOC notification of wind data (manual / automated)	Automated	Automated	Automated
Location of signage	US Route 101, MP 141.27 (SB) and 142.08 (NB)	US Route 101, MP 300.10 to 327.51	Interstate 5, PM 13.2 to 45.3, Siskiyou County

3. REVIEW OF HIGH WIND SAFETY CHALLENGES

The AWWS on US Route 101 were implemented to automate processes that were used to warn drivers of high winds. These locations were selected based on a combination of the frequency of high-wind conditions, the exposure of vehicles to safety challenges, and the potential consequences of crashes on user safety and corridor delay. As such, it is valuable to document how high wind conditions affect safety, on a general basis as well as in this specific corridor. In this chapter, previous studies on the effects of high wind on safety are reviewed. This is followed by a review of crash statistics in the AWWS locations and user perceptions of safety challenges in the area.

3.1. Literature Review

High winds across highways can cause high-profile vehicles to overturn and make vehicle control difficult for passenger cars. Some of the noted difficulties caused by high cross winds are serious safety concerns.

Perry and Symons (1) describe three types of effects of cross winds on vehicles. The first type of effect is direct interference with a vehicle through the force of the wind, at a minimum making steering difficult or, with sufficient wind strength, overturning the vehicle or pushing it off the road or into the path of another vehicle. The second effect is described to be winds causing obstruction by blowing snow, sand or other material into the highway, blowing down trees, parts of buildings and other debris. Thirdly, the cross winds can also indirectly affect the travelers by causing build-up of snow, creating conditions for avalanches, danger to bridges, etc.

Perry and Symons further explain that the forces exerted by wind are proportional to the square of the wind speed and to the area of the vehicles facing the wind direction. So, high-profile vehicles experience more force than lower profile vehicles. Stability of all vehicles in motion is a complex problem in dynamics because of the sideways overturning moment, oscillatory forces at the rear of the vehicle and turbulent nature of low-level airflow and the induced eddies by the traffic itself. The sudden gusts induced by the moving traffic may exacerbate the situation.

In their study, Perry and Symons found that overturning accidents were the most common type of wind-induced accidents. In one windstorm in Great Britain in 1990, 66 percent of accidents involved high-sided commercial vehicles or vans, while only 27 percent involved cars. At the interface between atmosphere and the ground surface, friction reduces the wind speeds and makes the air turbulent, showing itself in sharp fluctuations in wind speed and changes in wind direction. Added to all these hazards, the sharp transitions in velocity which occur at highway features like tunnels and bridges can result in frequent risks to the stability of high profile vehicles, caravans, RVs and motorcycles.

In response to high wind conditions, the British Transport Commission developed two tiers of wind warnings: Tier 1, where wind gusts are in excess of 70 mph; and Tier 2, where wind gusts exceed 50 mph. Perry and Symons recommended countermeasures such as fixed or permanent precautions (e.g. slatted fences), information and warnings (e.g. electric signs that can display warnings) and road closures to all or certain classes of vehicles to reduce the wind hazard, apart from decisions related to roadway design.

Perry and Symons concluded that many wind-related accidents occurred due to a failure to foresee the possible consequences of conditions which themselves may have been accurately forecast. Therefore, they advocated continuous wind monitoring, preferably with automatic recording and warning devices, for operational purposes. This could be facilitated through broad scale installation of road weather information systems (RWIS).

Edwards (2) examined wind-related accidents in England and Wales between 1980 and 1990, with specific interest in identifying the effects of wind on accident occurrence. The proportion of time of recorded high winds over a given time period was compared to the percentage of total accidents occurring in high winds over that same period. The proportion of accidents occurring in high winds was almost double the percentage duration of high winds. This study also attempted to demonstrate, using severity ratios, that the presence of high winds at the scene of an accident largely determines accident severity. After working around small sample size issues, there were inconclusive findings regarding the effect of high winds on accident severity unlike other weather hazards, such as rain (where there is a decrease in accident severity) and fog (which results in an increase in the severity of an accident).

Baker and Reynolds (3) analyzed wind-induced accidents in Great Britain. The objective of this study was to determine which vehicles are most at risk during windy periods and the likely values of critical wind speeds through analysis of the data from a major storm in 1990. This study determined that the most common type of wind-induced accidents is overturning accidents, which accounted for 47 percent of the total. Course deviation accidents and accidents involving trees comprised 19 and 16 percent, respectively.

Khattak (4) analyzed the direct and indirect effects of high-risk factors in single-large truck rollover crashes using Highway Safety Information System (HSIS) data for North Carolina. This study found that truck exposures to roadways that have dangerous geometry (particularly more curves) to be one of the high-risk factors along with post-crash fires and dangerous truck-driving behaviors.

3.2. Review of Oregon Crash Data

Crash frequency and crash rates for the two AWWS locations in Oregon are shown in Table 3-1 and Table 3-2. Crash data for years between 1997 and 2003 were used for this analysis. It should be noted that the two systems were fully or partially automated by January 2004; before this, both systems had the capability of being manually activated from a remote location. Historically, there have always been warnings and road closures provided to enhance the safety of the traveling public. Therefore, while there is a clear time line definition for “before AWWS” and “after AWWS”, a “before-after” safety benefit assessment was not performed as part of this study. However, with the AWWS providing more reliable and prompt wind warnings, fewer vehicles will be exposed to high wind events, which consequently should reduce crash risk.

Table 3-1: Crash Rate for Wind Season for South Coast System

Year	Number of Crashes		Crash Rate (per million VMT)	
	Wind Season	Total	Wind Season	Total
1997	10	21	1.20	0.83
1998	3	12	0.36	0.46
1999	3	10	0.35	0.37
2000	3	12	0.37	0.44
2001	6	21	0.68	0.74
2002	6	14	0.68	0.48

Notes:
Includes crashes on US Route 101 from Mileposts 300.10 to 327.51.
Wind Season includes months of January, February, March, November, and December.

Table 3-2: Crash Rate for Wind Season for Yaquina Bay Bridge System

Year	Number of Crashes		Crash Rate (per million VMT)	
	Wind Season	Total	Wind Season	Total
1997	6	8	3.33	1.59
1998	4	8	2.07	1.46
1999	3	5	1.54	0.93
2000	2	3	0.96	0.94
2001	1	1	0.53	0.18
2002	0	0	0.00	0.00
2003	1	1	0.48	0.18

Notes:
Includes crashes on US Route 101 from Mileposts 141.27 to 142.08.
Wind Season includes months of January, February, March, November, and December.

The crash rates during the high wind months – November through March – were consistently higher for the Yaquina Bay Bridge system and usually higher for the South Coast location than the annual rates at these locations. The months of high wind season are also the winter months at these locations and a higher crash rate can not solely be attributed to high cross winds. Moreover, because the Oregon crash reporting form does not list “high winds” as a contributing factor to a crash, it is uncertain how many of these crashes were caused by high winds.

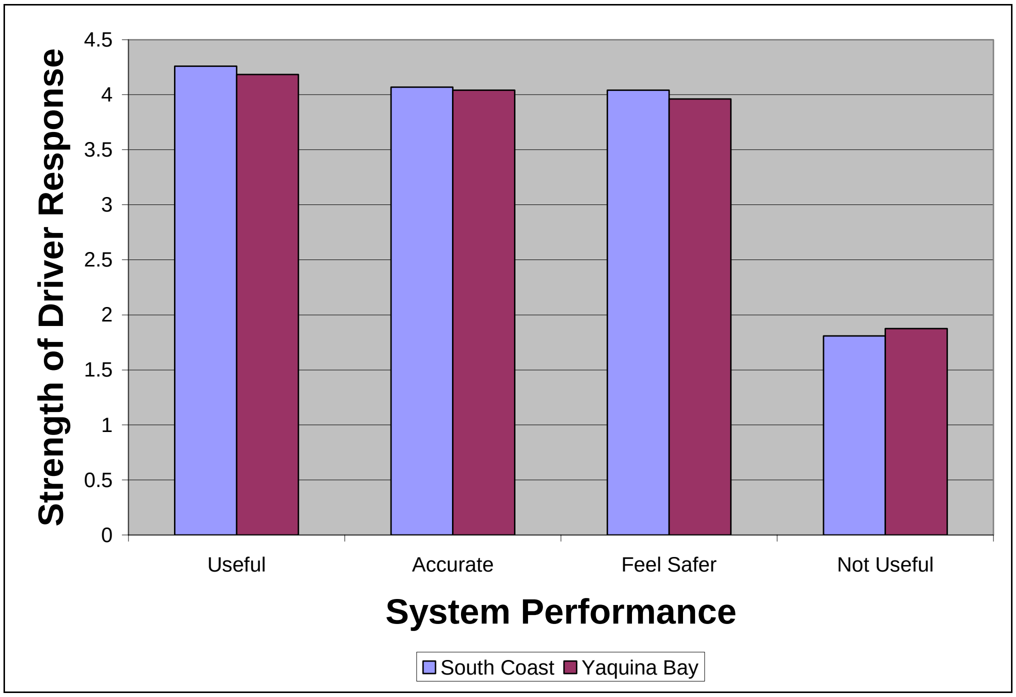
This ambiguity led to the exploration of wind influenced crashes as recorded in an enhanced crash data set from HSIS for the states of California and Minnesota. The objective of this analysis was to gain a better understanding of the wind-influenced crashes in terms of types of crashes, type of collision and severity of collision. These findings are explored later in this technical memorandum.

3.3. Driver Perception of AWWS Safety

The absence of direct reporting of high winds on crash investigation forms and the relatively infrequent number of wind-influenced crashes at each location would require a significant number of assumptions in order to estimate potential safety benefits attributable to AWWS. With some simplifying assumptions, the safety benefits associated with reducing crashes appear small, because of the relative infrequency of wind-related crashes. The average crash rates over the wind season are estimated to be 0.67 and 1.27 crashes per million vehicle-miles of travel (VMT) for the South Coast and Yaquina Bay Bridge systems, respectively, based on the crash data shown in Table 3-1 and Table 3-2. Annual crash rates are estimated to be 0.57 and 0.75 per million VMT for these locations. From an operational perspective, it is assumed that full automation of the wind warning process would result in earlier notification of high-wind conditions – perhaps an hour earlier – which would reduce the number of vehicles exposed to high-wind conditions (5). Using these crash rates, it was determined that the reduction in crash exposure for the driving public from one less hour of exposure to high winds would be 0.0017 crashes per hour and 0.00037 crashes per hour for the South Coast and Yaquina Bay Bridge systems, respectively. In other words, by providing warning of high wind conditions an hour earlier, it would take hundreds or thousands of high-wind events to reduce the number of expected crashes by one. In both locations, however, a crash will not only affect the safety of people directly involved in the crash, but will also likely close the road, causing potentially significant delays. These benefits are realizable, but are not quantified because of the numerous assumptions required.

Nevertheless, safety is an important consideration for motorists through these areas. If they perceive high winds to be a challenge, they would be inclined to heed the warnings. Therefore, a motorist survey conducted as part of this evaluation asked local residents to score their agreement with the statement "I would feel safer driving this road knowing the system is in place" on a 1-to-5 ordinal rating scale, with 1 representing strongly disagree, and 5 representing strongly agree. The mean rating of respondents for this statement is shown in Figure 3-1 along with ratings for other statements on system performance. The response on the agreement to this statement received an average rating of about 4 (i.e. "somewhat agree") for both the systems. More details on the driver perception of the usefulness and safety enhancement can be found in Technical Memorandum 1 (6).

Figure 3-1: Perception of AWWS Safety Benefit



4. ANALYSIS OF WIND-INFLUENCED CRASHES

High wind condition across roadways is a weather phenomenon which significantly impacts highway safety. In general, high winds are rare and site-specific, often catching drivers unaware and resulting in unsafe driving conditions. While crashes may occur directly or indirectly as a result of high cross winds, there has been limited investigation into the specific nature of crashes which occur during high cross wind conditions. Moreover, the relative infrequency and localized nature of heavy cross wind events often result in statistically inconclusive results when safety analysis studies are conducted. The nature of crashes caused by high winds is not well understood, which makes safety analysis and countermeasure development more complicated.

To understand this phenomenon better, data received from the Highway Safety Information System (HSIS) database was analyzed to determine the "typical" characteristics of crashes that have been recorded as wind-influenced. The Federal Highway Administration (FHWA) has developed HSIS as a database for nine states for use in safety analysis studies. Minnesota and California were selected, because the crash data from these states listed wind as a contributing factor or recorded whether the crash occurred in high wind conditions. These states also had a significant number of rural highways. To make data requirements more manageable, this analysis used HSIS data from California and Minnesota for years between 1997 and 2003. The HSIS data set consists of three interrelated subsets: accident, vehicle and occupant. For this analysis, the focus was on the accident and vehicle components of the data set.

Crash records for both states allow for coding of wind as a causative factor or weather condition during vehicle crashes. However, the analysis of wind-influenced vehicle crashes is difficult. In both states, wind is reported as one of many values for "weather" governing a particular accident. In Minnesota, for example, the weather field includes other values such as snow or blowing snow. Where more than one of the values is present (for example, it is both snowing and windy), the field investigator would be limited to recording one value. Therefore, the number of accidents in which wind is a causative factor would be underestimated by including only those incidents where wind is listed as the dominant weather condition.

In California's data set, wind is listed not only as a value for weather (in the accident data set), but also as a causative factor (in the vehicle data set). In some cases, investigators would record wind in both data fields, but there were many cases where it was recorded in one and not the other. For the analysis presented in this document, a crash was counted as wind-influenced even if only one of the fields (i.e. causative factor or weather) was entered as "wind". While this would ideally develop a more comprehensive set of wind-influenced crashes, there is also the subjectivity in the process that the interpretation of windy conditions is left to the crash investigator on site. A number of questions (e.g. is 30 mph a reasonable level to describe as windy?) are not answered in the standard accident reporting forms. Therefore, while this analysis is quantitative in nature, caution is urged in extrapolating the findings to estimate the safety benefits of measures that may mitigate wind-related crashes.

4.1. Extent of Wind-Influenced Crashes

In this section, the relative frequency and variation (temporal and geographic) of wind-influenced crashes is examined.

4.1.1. Frequency

Even considering potential underreporting, wind-influenced crashes are relatively infrequent. In Minnesota, 0.11 percent (244 of 228,273 crashes) of the total number of crashes was recorded as wind-influenced. The percentage was higher in California – 0.64 percent (3,228 of 501,901). The difference may be attributable to differences in reporting, but it could also be related to California's mountainous terrain, or possibly more frequent cross winds on California roadways.

4.1.2. Temporal

To look at temporal characteristics of wind-influenced crashes, an index was set up:

$$index_i = 100 \times \frac{\sum_{i=1}^{N} n_i}{\sum_{i=1}^{N} w_i} \times \frac{w_i}{n_i}$$

where w_i = the number of wind-influenced accidents in the i^{th} time period
n_i = the number of non-wind accidents in the i^{th} time period
i = the time period of interest (e.g. month of October or 12th hour of the day)
N = the number of time periods examined (e.g. 12 months for a year, 24 hours for a day)

An index value of 100 indicates no temporal abnormalities, whereas values greater than or less than 100 indicate higher-than-expected or lower-than-expected frequencies of wind-influenced crashes, respectively.

Figure 4-1 shows index values by month for each state, and Figure 4-2 shows index values for different hours of the day. As can be seen, wind-influenced crashes are more likely to occur during the winter and early spring months in both states. In Minnesota, there appears to be a trend toward increasing frequency of wind-influenced crashes during the late afternoon. There is no similar trend in the California crash data. It is suspected that time-of-day wind-influenced crash trends may be masked by the higher proportion of urban-area commute trips that occur in California compared to Minnesota.

Figure 4-1: Relative Frequency of Wind Influenced Crashes by Month

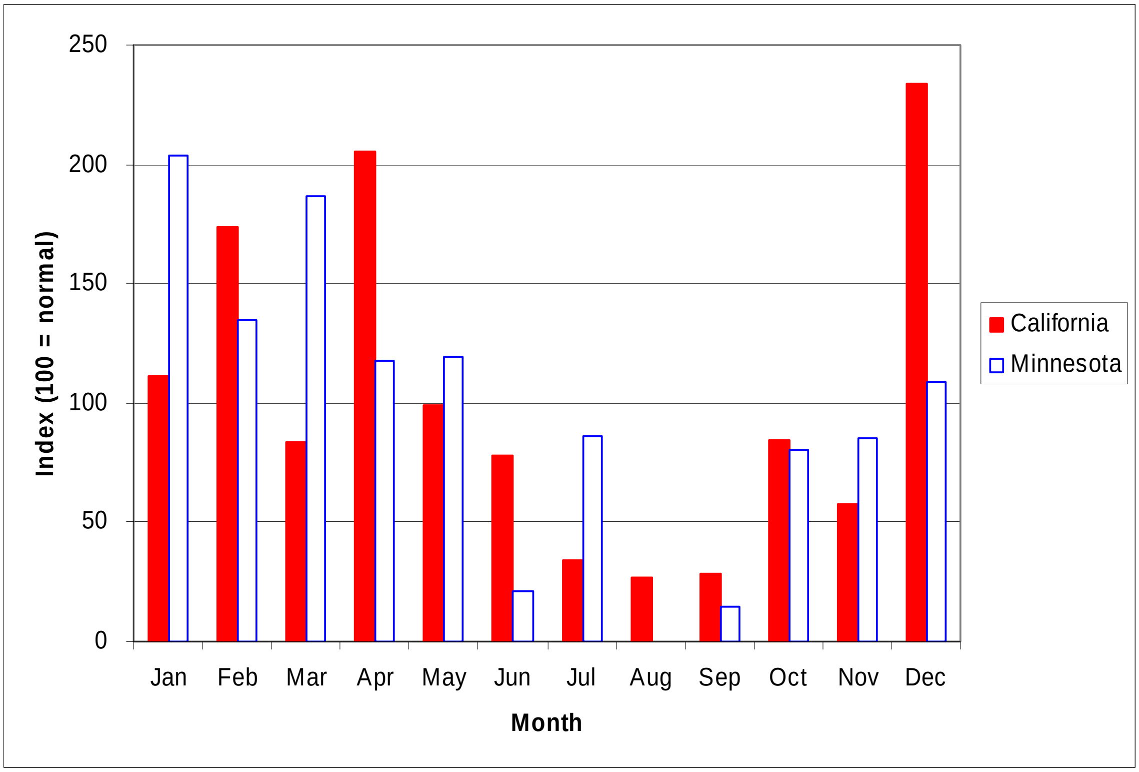
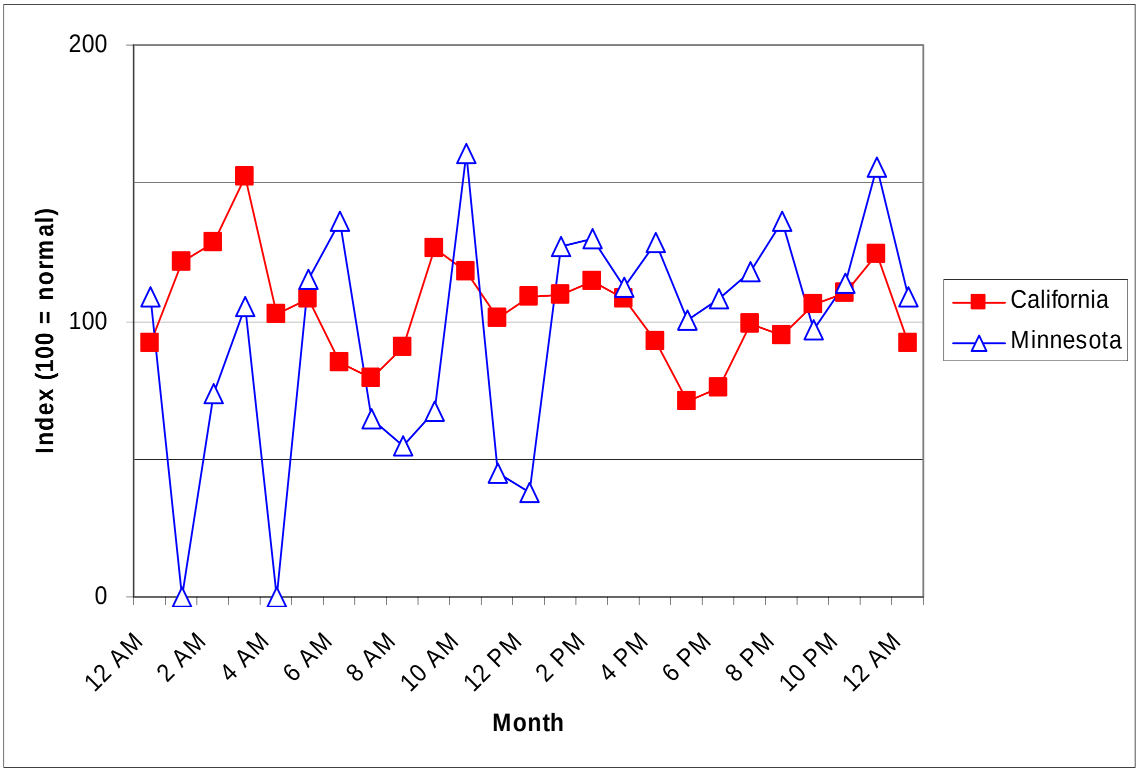


Figure 4-2: Relative Frequency of Wind Influenced Crashes by Time of Day



4.1.3. Geographical

To examine the geographic spread of wind-influenced crashes in each state, the locations of crashes were examined by county and highway, whether an area was rural or urban, and the type of highway facility.

<u>By County and Highway</u>

Wind-influenced crashes tend to be relatively localized phenomena. To demonstrate this, crashes were classified by county and highway to determine trends. In California, there are clear differences across counties in the proportion of crashes that were influenced by wind. While only 0.64 percent of crashes statewide were classified as wind-influenced, in three counties – Imperial, Inyo and Mono, all of which are located in the eastern part of the state – wind was cited as an influence in crashes at least five times more frequently. Since highway mileposts in California are consecutively numbered only within each county, the data permits ready analysis of trends on the entirety of a particular highway within a given county. At this level, there are 521 county-highway segments within the state.

The percentage of wind-influenced crashes for each county-highway segment was calculated, and ten percent of the segments had percentages of 3.1 percent or greater. Of these segments, six each were located in Imperial, Riverside and San Bernardino counties (all of which are eastern counties) while 35 of California's 58 counties had none of the segments in the 10 percent highest proportion of wind crashes, again suggesting a geographic concentration.

Data was also analyzed by one-mile segments on each highway. Of these 13,821 segments, 85 percent of these segments reported no wind-influenced crashes, and another ten percent had only one wind-influenced crash over a three-year period. There were 182 segments which had more than one wind-influenced crash, and where at least 10 percent of crashes were wind-influenced.

In Minnesota, the relative infrequency of wind-influenced crashes makes the interpretation of statistics regarding localized concentration of crashes challenging. For example, three of the state's 87 counties have a percentage of wind-influenced crashes at least ten times the state's average frequency of wind-influenced crashes of 0.11 percent. However, these three counties combined for a total of only 12 wind-influenced crashes over the analysis period. Only four Minnesota counties reported more than 10 wind-influenced crashes over a three-year period, compared to 40 counties in California. An analysis of crashes by highway and milepost shows similar difficulties.

<u>Rural Vs. Urban</u>

Wind-influenced crashes were also analyzed by whether they occurred primarily in urban or rural areas. The California data set includes two designations which may indicate whether a crash occurred in an urban or a rural area – whether the crash occurred in an incorporated area, and the roadway classification of the highway where the crash occurred. Approximately 57 percent of wind-influenced crashes in California occurred in unincorporated areas, while only 29 percent of non-wind crashes occurred in these areas. Forty-eight percent of wind-influenced crashes occurred on highway segments classified as rural, compared to 18 percent of non-wind crashes.

Minnesota's data set provides two similar designations in each accident record to help classify crashes as rural or urban. Eighty-one percent of the wind-influenced crashes in Minnesota occurred in unincorporated areas or towns with a population of less than 1,000, as compared to 30 percent of non-wind crashes. Eighty-two percent of wind-influenced crashes occurred on highway segments classified as rural, compared to 29 percent of non-wind crashes.

While the concentration of wind-related crashes in rural areas is clear, the reasons for this are not self-evident and do not necessarily have direct traffic safety applications. For example, urbanization may tend to occur in areas with less wind. Nonetheless, it appears that wind-influenced crashes are a greater concern in rural areas than in urban areas.

<u>Type of Facility</u>

Table 4-1 shows the percentage of wind-influenced and non-wind crashes which occurred on different highway types in each state. In both states, wind-influenced crashes are relatively more frequent on two-lane roads; however, there are not any clear trends regarding freeways or multi-lane facilities. With two-lane roadways typically found in more rural areas, there may be some correlation between this finding and the previous observation that wind-influenced crashes are more frequently a rural phenomenon.

Table 4-1: Percentage of Crashes by Highway Type

Highway Type	California		Minnesota	
	Wind	Non-Wind	Wind	Non-Wind
Other	1.7%	1.0%	1.3%	3.4%
Freeway, 4 or more lanes	61.7%	69.7%	28.2%	17.5%
Freeway, less than 4 lanes	1.1%	0.4%	0.0%	0.1%
Multi-lane divided, non-freeway	15.9%	13.4%	13.7%	19.9%
Multi-lane undivided, non-freeway	3.8%	3.5%	1.3%	12.0%
Two-lane roads	15.8%	12.0%	55.6%	47.1%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**

4.2. A "Typical" Wind-Influenced Crash

As mentioned earlier, wind-influenced crashes may be underreported due to the constraints of data collection instruments used during crash investigations. Though the HSIS data may not always indicate when high winds were present or were a major causative factor in a crash, they may be useful to compare a typical wind-influenced crash versus a crash that occurs when high winds are not present. The "typical" wind-influenced crash will be classified according to the number and type of vehicles involved, the type of collision, the severity, and road surface conditions.

4.2.1. Number of Vehicles and Types of Vehicles

In both states, the average wind-influenced crash involves fewer vehicles than a non-wind-influenced crash. In California, the average number of vehicles involved in a wind-related crash was 1.69 compared to 1.99 for non-wind crashes; in Minnesota, the comparison numbers are 1.36 and 1.86, respectively. In Minnesota, 69.3 percent of wind-influenced crashes involved only one vehicle, compared to 24.7 percent of non-wind-influenced crashes. A parallel analysis for California showed that 42.7 percent of wind-influenced crashes involved one vehicle, versus 23.6 percent of non-wind-influenced crashes.

Passenger cars, pickup trucks and sport utility vehicles are the most commonly involved vehicles in crashes, irrespective of whether wind was a causative factor. However, wind influenced crashes have higher likelihood of trucks being involved than non-wind influenced crashes. In Minnesota, 28.3 percent of wind-influenced involved at least one truck, compared to 6.3 percent of non-wind-influenced crashes. In California, 22.2 percent of wind-influenced crashes involved at least one truck, compared to 12.7 percent of non-wind-influenced crashes.

The observation that trucks are more commonly involved in wind-influenced crashes is especially evident when looking at one-vehicle crashes. In Minnesota, only 3.5 percent of non-wind-influenced one-vehicle crashes involved a truck, compared to 25.4 percent of wind-influenced one-vehicle crashes. In California, only 6.0 percent of non-wind-influenced one-vehicle crashes involved a truck, compared to 17.6 percent of wind-influenced one-vehicle crashes.

4.2.2. Type of Collision

Each state has different methods of describing collisions. In Minnesota, collision type is described in two data fields: one which diagrammatically describes the crash (for example, sideswipe), and another which characterizes the participating actors in the crash (for example, crash with vehicle). In California, these characteristics are essentially combined.

Minnesota data showed that the predominant type of wind-influenced crash was run-off-the-road crashes, with these comprising 45.9 percent of all wind-influenced crashes. In contrast, only 14.8 of non-wind-influenced crashes were described as run-off-the-road. Hit object crashes are also relatively more common in wind-influenced crashes than in non-wind-influenced crashes. In addition, 38.5 percent of wind-influenced crashes were described as vehicle overturn crashes, compared to only 6.1 percent of non-wind-influenced crashes. As shown in Table 4-2, the observation that hit object and overturn crashes are more frequent in wind-influenced crashes compared to non-influenced crashes holds true in California as well.

Table 4-2: Percentage of Crash by Type in California

Collision Type	Wind	Non-Wind
Auto/Pedestrian	0.6%	0.8%
Broadside	9.9%	9.6%
Head-on	1.6%	1.5%
Hit Object	30.2%	22.6%
Not Stated	0.0%	0.0%
Other	9.1%	4.1%
Overturn	12.0%	3.0%
Rear End	24.4%	42.9%
Sideswipe	12.1%	15.5%
Total	**100.0%**	**100.0%**

4.2.3. Crash Severity

Table 4-3 shows how the severity of wind-influenced crashes compares with non-wind-influenced crashes. In both states, wind-influenced crashes are more likely to result in fatalities or injuries than non-wind-influenced crashes. This would appear to be a relationship that is causative, not correlative, in nature. Crash types that tend to have more harmful outcomes (for example, overturned vehicles) are more likely to be caused by wind than crashes with less harmful outcomes (e.g. rear end collisions). A chi-square analysis showed that the relative severity of wind-influenced versus non-wind crashes of the same crash type was different for each crash type, although ambiguous in the direction of difference.

Table 4-3: Severity of Wind-Influenced and Non-Wind Crashes

Incident Severity	California		Minnesota	
	Wind	Non-Wind	Wind	Non-Wind
Fatal	1.4%	0.8%	1.2%	0.7%
Incapacitating Injury	3.5%	2.0%	3.3%	3.3%
Non-incapacitating Injury	15.1%	12.7%	17.6%	13.5%
Possible Injury	15.7%	19.3%	17.2%	19.3%
Property Damage Only	64.3%	65.1%	60.7%	63.2%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**

4.2.4. Road Surface

In both states, a higher percentage of wind-influenced crashes occurred on icy or snowy road surfaces than did non-wind-influenced crashes. In Minnesota, 46 percent of wind-influenced crashes occurred on icy or packed snow road surfaces compared to 12 percent of the same in non-wind conditions. In California, only 3.8 percent of wind-influenced crashes occurred on icy, snowy or slippery road surfaces, but this compared to 1.2 percent of non-wind-influenced crashes. This suggests wind may act as a compounding factor in lowering visibility or decreasing drivers' ability to control their vehicles.

Additional investigation into the interrelationship between road surface, crash severity and the presence of winds showed that wind-influenced crashes were generally more severe than non-wind-influenced crashes, controlling for the road surface present at the time of the crash. In other words, a wind-influenced crash appears to be more severe than a non-wind-influenced crash, whether the pavement is dry or not.

4.3. Summary

In the preceding analysis, there was a statistically significant difference between the typical characteristics of wind influenced crashes and the non-wind crashes. Chi-square tests were used to test the statistical significance of the difference in the distribution of accident type and vehicle type between wind-influenced and non-wind crashes. Z-tests were used for testing whether the average number of vehicles involved and the average number of trucks involved are statistically different between wind influenced and non wind crashes. Table 4-4 highlights the results of these tests of significance between wind influenced and non-wind crashes. Table 4-5 summarizes the analysis of the characteristics of wind-influenced crashes. Estimating the probability of a given accident having been influenced by high wind conditions is beyond the scope of this document and needs further research. Table 4-6 depicts the "typical" characteristics of a wind influenced crash based on the number and type of vehicles involved, the type and severity of collision and road surface conditions during the crash.

Table 4-4: Summary of Test of Significance Results

Variables	California		Minnesota	
	Z / χ^2 Value	Pass / Fail at 5 % Sig.	Z / χ^2 Value	Pass or Fail at 5 % Sig.
Average Number of Vehicles Involved	-32.94	Fail	-20.13	Fail
Accident Type	1426.2	Fail	942.82	Fail
Vehicle Type Involved	1409.32	Fail	316.76	Fail
Average Number of Trucks Involved	14.05	Fail	-56.44	Fail

Table 4-5: Comparison of Typical Wind-Influenced and Non-Wind Crashes

Description	California		Minnesota	
	Wind	Non-Wind	Wind	Non-Wind
Number and Type of Vehicles				
Average number of vehicles involved	1.69	1.99	1.36	1.86
Percent of single vehicle crashes	42.7%	23.6%	69.3%	24.7%
Percent of crashes with at least one truck	22.2%	12.7%	28.3%	6.3%
Percent of truck involvement in single vehicle crashes	17.6%	6.0%	25.4%	3.5%
Type of Collision				
Percent of run-off-the-road (ROR) crashes	-	-	45.9%	14.8%
Percent of vehicle overturn crashes	12.0%	3.0%	38.5%	6.1%
Percent of hit-object crashes	20.2%	22.6%	-	-
Road Surface				
Percent of crashes on icy/snowy/slippery roads	3.8%	1.2%	46.3%	12.2%

Table 4-6: List of "Typical" Wind Crash Characteristics

Descriptive Variable	**Predominant Value**	**2^{nd} Predominant Value**
Number of Vehicles Involved	Two Vehicles	Single Vehicle
Type of Vehicle Involved	Passenger Car / Pick Up / SUV	Trucks
Type of Collision	Run-off-the-road (ROR) Crashes / Hit Object	Other / Unknown / Rear End
Severity of Collision	Property Damage Only (PDO) Crashes	Complaint of Pain / Non-Incapacitating Injury
Road Surface Condition	Inconclusive	Inconclusive

5. CONCLUSIONS

An analysis of HSIS data on crashes in California and Minnesota revealed that wind-influenced crashes are significantly different from non-wind crashes. The predominant crash type for wind-influenced accidents is run-off-the-road (ROR) crashes or hit object crashes, while the predominant type for non-wind crashes was found to be rear-end crashes. It was also determined that the number of vehicles involved in wind influenced crashes is significantly lower than that of non-wind crashes. Wind-influenced crashes were found to be more severe than non-wind crashes. While all of these findings were statistically significant, it should be noted that reporting limitations in both states may tend to mask the true frequency of wind-influenced crashes. Improved reporting procedures would make future analyses of wind-influenced crashes more fruitful.

The research indicates several things. First, wind-influenced crashes appear to have some signature characteristics that could help to identify them when information on the presence of wind is not immediately available in a crash data set. This is an important consideration for data sets where wind is underreported – as is likely true in both the California and Minnesota data sets – as well as in data sets where wind is not included as a factor at all, such as Oregon. However, the exact frequencies of these characteristics, based on this two-state analysis, are not consistent enough to be directly transferable to other states. For example, while it is clear that wind-influenced crashes tend to involve fewer vehicles than non-wind crashes, it is difficult to assess the likelihood that a one-vehicle run-off-the-road crash involving an overturned truck was due to wind. Examination of crash data from other states could help to improve the precision of our understanding of these phenomena.

This difficulty of understanding when wind is or is not a factor in crashes would be improved with better data. Additional crash reporting requirements, especially when a factor like "severe winds" allows for significant investigator interpretation, may not be the answer. Another approach would be to seek better integration of weather data sources with crash reporting processes. The Federal Clarus initiative, sponsored by the ITS Joint Program Office, and the WeatherShare project, sponsored by the California Department of Transportation, are two projects which seek to pool current and forecast weather information from a variety of sources to improve transportation information.

Finally, this research provides clear implications regarding potential countermeasures for wind-influenced crashes. Transportation agencies have used a variety of treatments to deal with these crashes over the years. It appears that dynamic information systems and spot design improvements to address run-off-the-road and hit object crashes both have good potential to improve safety at locations where wind-influenced crashes are more frequent.

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