DRIVING BLIND

Weather-Related Vision Hazards and Fatal Motor Vehicle Crashes

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The death toll from motor vehicle crashes due to weather-related vision hazards exceeds the number of fatalities caused by well-known hazards such as tornadoes, floods, tropical cyclones, and lightning.

Widespread or locally dense fog, smoke, and dust events are not typically thought of as dramatic geophysical hazards, but their impairment of motor vehicle driver visibility can lead to reduced roadway speeds, higher speed variability, and increased crash risk (Pisano and Goodwin 2002; Goodwin 2003a; Maze et al. 2006; USDOT 2013). These atmospheric conditions, and affiliated driver visibility reductions, may play a role in singular, multiple, and chain reaction vehicular crashes that can produce casualties. For example, during the early morning hours of 29 January 2012, a plume of smoke engulfed Interstate 75 in north-central Florida causing a series of multiple vehicle collisions; this incident resulted in 25 damaged vehicles, 11 deaths, and over 20 major injuries (FDLE 2012). A fog-induced series of chain reaction crashes on Thanksgiving morning 2012 along Interstate 10 near Beaumont, Texas, involved 140–150 vehicles and resulted in 80+ injuries and two fatalities (NBC News 2012). Blowing dust provoked a series of crashes involving 21 vehicles along Interstate 10 near Picacho Peak on 29 October 2013 that resulted in three fatalities and a dozen injured (AZDPS 2013). In another recent instance, excessive driver speed in dense fog caused a set of chain reaction (17 distinct) crashes on 31 March 2013 that involved over 95 vehicles near Fancy Gap, Virginia, killing three people and injuring dozens (Fig. 1). Unfortunately, these are not isolated cases with numerous multivehicle "pileups" and singular crashes induced by weather-related visibility hazards reported by media each year in the United States. Despite the substantial threat to the safety of drivers on the nation's roadways, no focused effort has been made within the research community to catalog these particular vision hazard events and quantify their effects at the national scale.

This research presents a nationwide analysis of fog-, smoke-, and dust storm–related vehicular fatalities in the United States from 1994 to 2011. The overarching goal of the research is to generate an

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Fig. 1. The aftermath of a chain reaction crash on 31 Mar 2013 because of hazardous conditions caused by dense fog along Interstate 77 near Fancy Gap, Virginia. This event involved 95 vehicles in 17 separate crashes, which left dozens injured and three dead (images courtesy of WXII Channel 12, Winston–Salem, North Carolina, and *The Roanoke Times*/www.roanoke.com).

essential understanding of the characteristics of these fatal hazard events that can be used to inform future mitigation activities focused on reducing visibility-related hazard impacts on the nation's roads.

BACKGROUND. Over 5.5 million motor vehicle crashes occur in the United States annually, resulting in nearly 33,000 deaths and an estimated 2.24 million injuries in 2010 alone (USDOT 2012). Despite long-term declines in both motor vehicle crash fatalities and fatality rates, vehicular crashes remain a leading cause of death in the United States (Subramanian 2012; CDCP 2013). Though many factors can lead to vehicle crashes, historically, adverse weather conditions are a primary cause or underlying circumstance, with roughly one-quarter of all weather-related vehicular crashes comprising 480,000–800,000 injuries, 7,000 deaths, and $22–$55 billion (U.S. dollars) in costs each year (NRC 2004; Atmospheric Policy Program 2004; Pisano et al. 2008; USDOT 2013). Adverse weather conditions—ranging from visibility impairments, to precipitation, to high winds, to temperature extremes—can affect driver capabilities and behavior, vehicle performance, pavement friction, traffic flow, and, ultimately, crash risk (Andrey and Knapper 1993; USDOT 2013). Prior research on weather-influenced vehicular accidents has primarily focused on more frequent and sensible hazardous weather conditions, namely, those produced by rain and/or snow [Andrey and Olley 1990; Andrey and Yagar 1993; Doherty et al. 1993; Brodsky and Hakkert 1988; Knapp et al. 2000; Khattak and Knapp 2007; Andrey et al. 2003; Eisenberg 2004 (cf. in particular his Table 1); Eisenberg and Warner 2005; Qui and Nixon 2008]. While some past research has examined visibility impairment of vehicular drivers, most have focused on visibility impairments related to rainfall (Ivey et al. 1975; OECD 1976; Morris et al. 1977; Bhise et al. 1981; Eisenberg 2004). While these precipitating weather conditions are responsible for most adverse, weather-affected crashes, there are still a large number of crashes and resulting casualties instigated by visibility-related hazards such as fog, smoke, and dust (Goodwin 2002; Pisano et al. 2008).

Motor vehicle crash research examining specifically visibility impairment effects on crash rates and casualties is limited. Investigations have generally focused on a broad evaluation of weather-related crashes, with fog as the lone visibility-related hazard in most U.S. (Goodwin 2002, 2003a; Pisano et al. 2008) or state-scale (Khan et al. 2008; Abdel-Aty et al. 2011) assessments. For instance, Pisano et al. (2008) discovered that, from 1995 to 2005, fog and/or fog with rain/sleet were implicated as the underlying weather condition in nearly 39,000 crashes, 16,000 casualties, and 630 deaths. These tallies suggest that weather visibility impairments are a substantial hazard to the driving public, on par with more dramatic weather hazards that garner far more media and research attention.

DATABASE CONSTRUCTION. A database of fatal, weather-related motor vehicle crashes from 1994 to 2011 was constructed from the National Highway Traffic Safety Administration (NHTSA)'s Fatality Analysis Reporting System (FARS), which is a census of fatal traffic crashes for the entire United States (NHTSA 2005). Though FARS records extend to the 1970s, we chose 1994 as our initial year of analysis since this is when query tools and various output options were accessible via the online data portal at NHTSA (see www-fars.nhtsa.dot.gov). FARS is assembled by state-specific, trained personnel (i.e., FARS analysts) who gather, translate, and transmit fatal crash information from official documents such as police accident reports (PARs), state vehicle registration files, death certificates, and so on. Various quality control procedures are performed to maintain overall FARS data quality, completeness, and accuracy (NHTSA 2005). The database contains a number of different characteristics that can be associated with each specific crash; most important for this study are the environmental conditions (e.g., weather and/or visibility conditions) for each incident. Naturally, we focus our investigation on fatal events where visibility hazards—fog, dust, or smoke—were occurring in order to quantify the effects these hazards have on traffic safety.

Throughout the investigation period, the method of data coding for many of the FARS fields changed, which led to inconsistency in attribute delineation and categorization. Because of these coding changes, a method was implemented to standardize the data by grouping similar fields in the database and recode them to permit consistent analysis. Nevertheless, standardization was inhibited in some instances since some fields in FARS were discontinued while new ones were created. For example, until 2006, fog was considered a single weather condition category, but there were also categories for rain and fog, and sleet and fog, simultaneously. In 2007, the fog category was discontinued and another field—fog, smog, and smoke—was created. A very similar change occurred from 2006 to 2007 with blowing sand, soil, and dirt. Before 2006, smoke and smog were considered a part of the same category as the previously listed conditions and have since been listed in their own separate category. Another change in the atmospheric conditions occurred in 2007 with the addition of a second atmospheric condition category. While the majority of the fatal events only have one atmospheric condition listed, at times this double-attribute field created a conflict between the most important conditions. Overall, the rearrangement of classes created a notable discontinuity in counts of each atmospheric condition. To resolve this conflict, we manually selected events for each case where fog, smoke, and/or blowing dirt/sand/soil were present in either attribute field.

Even if a visibility-related weather hazard was reported in the atmospheric condition field, it is possible that the atmospheric condition had little or nothing to do with the fatal crash. As an example, it is plausible that a driver distracted by a cell phone crashed and was fatally injured with conditions of fog present. To attempt to filter these possible occurrences and focus on fatal crashes that were caused a weather visibility obstruction, we employed the "driver's vision obscured by" field in FARS. One of the codes that can be present in this field is "rain, snow, fog, smoke, sand, dust," and this provided the basis to restrict the analysis to incidents where the weather visibility hazard was likely a major contributing factor. Once this was complete, it permitted an analysis of all incidents where weather was a factor in obscuring the driver's vision and thereafter we could distill the data further by only selecting those cases where fog, smoke, or blowing dirt/sand/soil were reported.

To summarize, our analyses focus on two weather classifications: visibility-related (VR) crashes, which are fatal crashes where a visibility-related weather hazard (fog, smoke, and/or blowing dirt/sand/soil) was recorded as an environmental condition in FARS, and vision-obscured (VO) crashes, which are FARS cases where driver vision was reported obscured by weather coincident with the report of an adverse visibility-related hazard. The latter classification provides a conservative estimate of those fatal motor vehicle events where a visibility-related hazard was likely a major contributing factor or trigger in the crashes.

An example of the data impediments uncovered is revealed by an assessment of FARS data for the states of Mississippi and Montana, which depict no VO fatal motor vehicle crashes from 1994 to 2011, and Virginia, which only reported two VO fatal crashes, both occurring in 2010. Regrettably, there is no standard PAR form for all states; thus, state PAR forms are subject to temporal variations and inconsistencies from state to state. Mississippi and Montana simply do not employ a PAR form that includes a field that indicates that possible weather-related vision impairments could have been an environmental aspect of a fatal crash; whereas, Virginia's PAR form from 1994 to 2009 did not contain any coded information on atmospheric conditions present during a fatal crash [D. Flemons, NHTSA–National Center for Statistics and Analysis (NCSA), FARS Program Analyst, 2013, personal communication]. Further, there are several factors that could have influenced whether or not a police officer or highway patrol person designated that a weather-related visibility condition and/or weather-related vision impairment was present during a fatal motor vehicle crash. These factors include what value(s) is (are) available to code in each PAR in a given state, how many choices may be selected in the design of the PAR for a given state, what other choices are competing for "mention" in any particular crash on a state's PAR, and what the officers are instructed to do (or not to do) in a particular state [i.e., what guidance, if any, is provided in the state's PAR coding manual (D. Flemons, NHTSA–NCSA, FARS Program Analyst, 2013, personal communication)].

As further illustration of issues uncovered during data processing, a notable smoke- and fog-related event[1] on 9 January 2008 that involved 72 vehicles along Interstate 4 in Florida (resulting in 28 injuries and 5 deaths) was not technically a FARS VO-related crash. Though the incident is in the FARS database, it only met the VR criteria and not the more stringent VO threshold since driver vision was not recorded as obscured by a visibility-related hazard on a PAR and thus in FARS. This is despite undeniable evidence that drivers' vision was obscured and was a major factor in the incident (Collins et al. 2009). A similar "non-VO" case occurred on 11 December 1997 along Interstate 5 in the Central Valley of California where blinding fog was an instigating factor in a chain reaction incident that killed five (Gunnison 1997; NOAA 1997).

Despite the detailed assessment of FARS and event-by-event evaluation of environmental conditions therein, it is probable our visibility hazard subclassifications fail to include all cases where a vision-obscuring weather hazard induced, to some extent, a fatal motor vehicle crash. To create a truly complete dataset would require 1) the assumption that all environmental conditions were reported at the crash scene correctly and thereafter coded properly in a comprehensive PAR form that includes weather and environmental fields and 2) the laborious and likely unfeasible task of examining crash incident reports for all municipalities, counties, and states in the United States that maintain and provide those records to the public.

RESULTS. *Fatal visibility-related and vision-obscured motor vehicle crashes.* From 1994 to 2011, there were 653,733 fatal motor vehicle crashes and 726,784 crash-related fatalities that occurred in the United States (Table 1) or roughly 36,300 fatal crashes and 40,400 deaths per year (Table 2). While 83% of those crashes and fatalities are related to nonadverse conditions (i.e., no weather reported and on dry pavement), the remaining 17% of fatal crashes occurred in adverse conditions where a nonfair weather element and/or slick pavement was reported. On average for the study period, there were 6,171 fatal crashes and 6,911 deaths annually associated with adverse road and/or weather conditions. As an illustration of the relative enormity of these numbers, the 12-yr fatality average (2002–13) for all weather hazards (i.e., lightning, tornado, flood, tropical cyclone, heat, cold, winter, rip current, and nontornadic winds) is over an order of magnitude smaller or 571 fatalities per year (NWS 2014).

Of the fatal crashes and fatalities that occurred in adverse road or weather conditions (Table 2), 46% occurred in rain, 12% occurred in frozen precipitation, and 10% occurred in fog, smoke, or blowing dirt, soil, or sand (hereafter, dust). While the latter group of atmospheric conditions are pres-

[1] Achtemeier (2003, 2008, 2009) coined the term "superfog" for these unique cases where a mixture of smoke and fog produce localized areas of exceptionally low (1–3 m) visibility.

Table 1. Total, annual mean, and percentage contribution by classification and adverse weather subclassification for all weather-related fatal motor vehicle crashes and fatalities in the United States from 1994 to 2011. Crashes with nonadverse conditions occur in the presence of no weather (clear, cloudy, other, not reported, or unknown atmospheric conditions) and on dry pavement. Crashes in adverse conditions occur in weather (rain, sleet, snow, fog, rain and fog, sleet and fog, and severe crosswinds) and/or on slick pavement (wet, snow, slush, ice, frost, or standing/moving water) (after Pisano et al. 2008).

	Fatal crashes			Persons killed		
	Total	Annual mean	Percentage	Total	Annual mean	Percentage
All conditions	653,733	36,319	100.0%	726,784	40,377	100.0%
Nonadverse conditions	542,649	30,147	83.0%	602,387	33,466	82.9%
Adverse conditions	111,084	6,171	17.0%	124,397	6,911	17.1%
Slick pavement and no weather	36,367	2,020	32.7%	40,452	2,247	32.5%
Slick pavement and weather	66,961	3,720	60.3%	75,243	4,180	60.5%
Dry pavement and weather	7,756	431	7.0%	8,702	483	7.0%

ent for only a tenth of the total crashes in adverse road and weather conditions, this still amounts to approximately 600 fatal crashes and 680 fatalities each year; as exemplified prior, this annual mortality rate is equivalent to *all* weather hazards combined. The majority of the VR crashes arose when fog, as opposed to dust or smoke, was present during the time of the crash (Table 3). Although the data coding for some of the FARS fields changed during the study period as illustrated in Table 3, concatenating fog across the fields for the record suggests that this hazard was present during 8,975 (83%) and 10,108 (83%) of all VR fatal crashes and crash fatalities, respectively; smoke and dust represent the remaining 17% from 1994 to 2011. Consequently, approximately 500 fatal crashes each year occurred when fog was recorded. The breakdown of gender of the VR crash victims was analogous to that found for all fatal crash victims: 70% of victims were male, or, as discussed by West and Naumann (2013), the death rate for males was 2.5 times that for females.

Throughout the 18-yr study period, there were a total of 1,331 fatal motor vehicle crashes and 1,582 crash fatalities where a visibility-related weather hazard and a weather-related vision obstruction (i.e., the driver's vision obscured by rain, snow, fog, smoke, or dust) were both present during the time of crash or, what we termed, a VO fatal crash (Table 4). Again, we contend that this crash classification affords an approximation of those fatal motor vehicle events where a visibility-related weather hazard was likely a major contributing crash cause. Fog appears as the most frequent VO weather hazard, composing 1,204, or 90%, of this classification of fatal crashes. Smoke or dust was reported as obscuring the driver's visibility in the remaining 10% of VO fatal crashes and fatalities. Weather-related VO motor vehicle crashes account for approximately 88 fatalities a year based on our conservative methodology. Comparatively, more notable and captivating hazards such as tornadoes, floods, tropical cyclones, and lightning are responsible for an equivalent, if not smaller, number of annual deaths in the United States (Fig. 2). Thus, the mean annual death toll from motor vehicle crashes thought to have been caused in part by a weather-related VO hazard exceeds the mean annual number of fatalities associated with atmospheric phenomena that garner far more media, research, and mitigation attention.

Table 2. Approximate annual total, percentage of all, and percentage of weather-related fatal motor vehicle crashes and fatalities for 1994–2011.

	Fatal weather-related crash statistics		
Road or weather conditions	Approximate annual rates	Percentage fatal crashes	Percentage weather-related fatal crashes
Rain	2,820 fatal crashes 3,150 persons killed	7.8%	45.7%
Snow/sleet	750 fatal crashes 850 persons killed	2.1%	12.2%
Fog/smog/smoke/blowing sand, soil, or dirt/rain and fog/sleet and fog	600 fatal crashes 680 persons killed	1.7%	9.7%
Wet pavement	4,600 fatal crashes 5,140 persons killed	12.7%	74.6%
Snow/slushy pavement	550 fatal crashes 610 persons killed	1.5%	8.9%
Icy pavement	590 fatal crashes 670 persons killed	1.6%	9.6%
Total weather-related	6,170 fatal crashes 6,910 persons killed	17.0%	—
Total	6,213,880 total 1994–2011 crashes	—	—
	36,320 fatal crashes 40,380 persons killed	5.8%	—

Table 3. VR fatal motor vehicle crashes and fatalities by year. VR crashes include those crashes where fog, smog, smoke, or blowing sand/soil/dust/dirt was reported at the time of crash. Dash indicates that a FARS field did not exist for that year.

	Fog, smog, and smoke		Fog		Rain and fog		Sleet and fog		Blowing sand, soil, and dirt		Smog, smoke, blowing sand, or dust		Total	
	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities
1994	—	—	570	655	34	36	9	11	—	—	99	107	712	809
1995	—	—	488	560	36	40	7	8	—	—	113	135	644	743
1996	—	—	594	684	55	66	17	19	—	—	116	126	782	895
1997	—	—	503	586	42	45	3	3	—	—	62	73	610	707
1998	—	—	556	646	59	66	8	8	—	—	70	78	693	798
1999	—	—	461	514	45	52	3	3	—	—	67	78	576	647
2000	—	—	493	561	32	35	13	14	—	—	235	266	733	876
2001	—	—	548	626	36	39	5	7	—	—	89	106	678	778
2002	—	—	421	506	43	50	6	8	—	—	133	157	603	721
2003	—	—	474	528	44	57	7	7	—	—	272	316	797	908
2004	—	—	493	544	38	45	3	3	—	—	281	313	815	905
2005	—	—	445	490	31	32	10	11	—	—	189	215	675	748
2006	—	—	441	491	28	32	5	5	—	—	67	78	541	606
2007	438	478	—	—	—	—	—	—	18	24	—	—	456	502
2008	439	495	—	—	—	—	—	—	13	16	—	—	452	511
2009	327	376	—	—	—	—	—	—	16	23	—	—	343	399
2010	319	361	—	—	—	—	—	—	13	13	—	—	332	374
2011	346	377	—	—	—	—	—	—	11	13	—	—	357	390
Total	1,869	2,087	6,487	7,391	523	595	96	107	71	89	1,793	2,048	10,839	12,317

Table 4. As in Table 3, but for VO crashes. VO includes crashes where the "vision obscured by" field was checked in FARS and the associated FARS hazard code was a visibility-related weather hazard. Only the crashes where a weather visibility obstruction was present are included in the table.

	Fog, smog, and smoke		Fog		Rain and fog		Sleet and fog		Blowing sand, soil, and dirt		Smog, smoke, blowing sand, or dust		Total	
	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities	Fatal crashes	Fatalities
1994	—	—	56	63	0	0	0	0	—	—	7	8	63	71
1995	—	—	67	80	0	0	0	0	—	—	3	12	70	92
1996	—	—	75	86	3	3	0	0	—	—	9	9	87	98
1997	—	—	76	84	5	6	0	0	—	—	1	1	82	91
1998	—	—	84	98	10	12	0	0	—	—	5	7	99	117
1999	—	—	65	73	7	10	0	0	—	—	11	15	83	98
2000	—	—	65	72	4	5	1	1	—	—	10	13	80	91
2001	—	—	62	74	2	2	0	0	—	—	8	9	72	85
2002	—	—	52	77	2	2	0	0	—	—	17	24	71	103
2003	—	—	71	81	6	13	1	1	—	—	7	9	85	104
2004	—	—	65	82	2	2	0	0	—	—	11	14	78	98
2005	—	—	59	64	5	6	0	0	—	—	6	7	70	77
2006	—	—	67	71	2	4	0	0	—	—	8	13	77	88
2007	53	54	—	—	—	—	—	—	5	8	—	—	58	62
2008	54	66	—	—	—	—	—	—	4	7	—	—	58	73
2009	49	56	—	—	—	—	—	—	8	13	—	—	57	69
2010	73	87	—	—	—	—	—	—	3	3	—	—	76	90
2011	61	70	—	—	—	—	—	—	4	5	—	—	65	75
Total	290	333	864	1,005	48	65	2	2	24	36	103	141	1,331	1,582

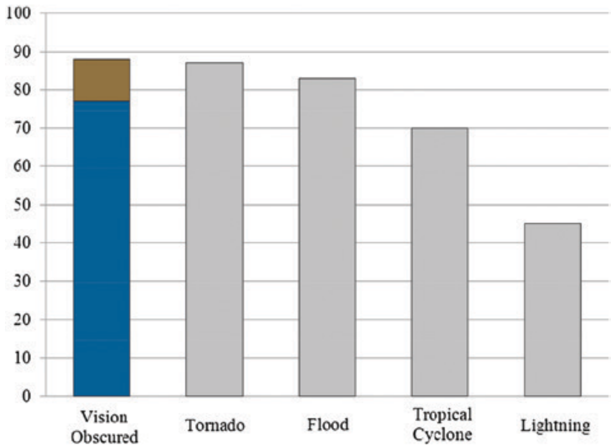

Fig. 2. Mean annual (1994–2011) weather-related vision-obscured motor vehicle fatalities in comparison to other notable weather hazards (NWS 2014). Dark blue bar indicates those vision-obscured fatalities associated with fog conditions, and dark brown exemplifies fatalities that occurred during smoke or dust.

Spatiotemporal analysis. Motor vehicle crash fatalities tend to be elevated during the warm season (Fig. 3a) when the monthly vehicle kilometers traveled swells to approximately 434 billion, compared to approximately 346 billion km during winter months (USDOT 2014). VO fatal crashes and fatalities are at a minimum during June and July and reach an extended high percentage of annual contribution from September to February. Nearly 28% (16%) of VO (all) crash fatalities occurred in the midwinter months of December and January, whereas 9% (18%) of VO (all) crash fatalities occurred in the midsummer months of June and July. These percentages reveal a dichotomy in risk between VO and other possible causes of fatal motor vehicle crashes.

As discovered previously, fog was the greatest contributor to VO fatal crashes during the period of study, and therefore a relationship between the seasonal frequency of fog and these fatal crashes should exist. Relatively little research attention has been given to the identification and spatiotemporal distribution of fog in the United States (Meyer and Lala 1990). Though a thorough contemporary climatology of fog does not appear in the literature, national annual subjective (Peace 1969) and monthly objective (Hardwick 1973) analyses of fog reveal that the weather element is most common in California and the Pacific Northwest, Gulf Coast, Appalachians, Great Lakes region, and New England. Low visibility and heavy fog (≤0.40-km visibility) climatologies assembled from the Climate Atlas of the United States (Fig. 4; NCDC 2002) corroborate the spatial distribution found in earlier annual climatologies by Peace and Hardwick. Hardwick (1973) illustrated that the mean number of days with heavy fog are most pronounced during the

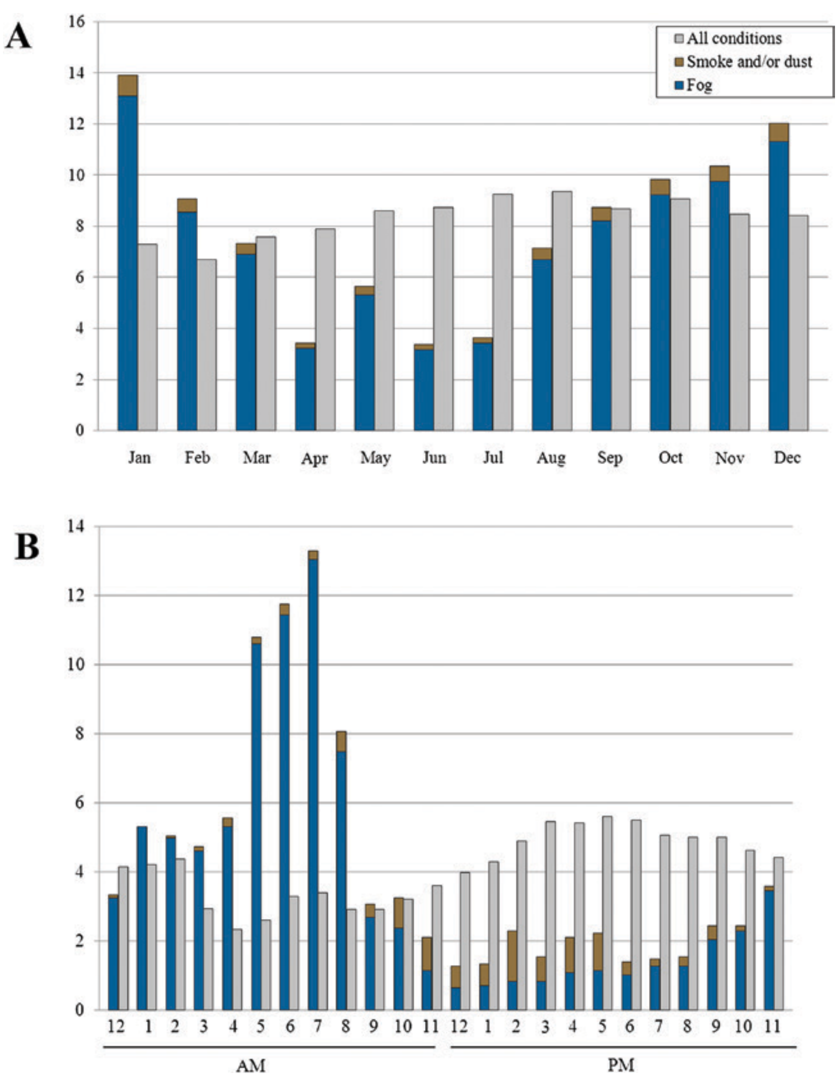

Fig. 3. The temporal percentage contribution of all U.S. motor vehicle crash fatalities and VO crash fatalities for 1994 to 2011 by (a) month and (b) local time.

cool and transitions seasons for the conterminous United States as a whole. In the Midwest, low stratus ceiling and fog days were far more common during the transition and cool seasons, reaching a peak during the November through March period (Roebber et al. 1998; Westcott 2007). In the interior Northeast, a distinct late summer/early autumn maximum in radiation fog occurs because of the overlapping of sufficient nocturnal radiational cooling scenarios with ample low-level moisture (Meyer and Lala 1990). The monthly frequency of fog events in the coastal areas of the Northeast does not reveal a strong seasonal signal, likely because of the prevalence of advection fog enhanced by the direct influence of the coastal marine environment (Tardif and Rasmussen 2007). Though the instances of fog are microscale dependent due to changes in surface water and orography, these climatologies reveal that the monthly character of fog-related VO crash fatalities found complements the climatology of this hazard at the national and regional scale (Fig. 3a).

Dust storms can be caused by many different environmental scenarios: thunderstorm outflow and, sometimes, inflow (Brazel and Nickling 1986; Steenburgh et al. 2012); dryline passage (Jones and Christopher 2010); lower-tropospheric mixing of high velocity air (Schultz and Meisner 2009); channeling of air and downslope windstorms due to orography (Whiteman 2000); intense pressure gradients induced by extratropical cyclones; fronts or baroclinic troughs (Brazel and Nickling 1986; Bach et al. 1996; Steenburgh et al. 2012); tropical disturbances (Brazel and Nickling 1986; Lei and Wang 2013); and low-level mass adjustments due to jet streak dynamics (Kaplan et al. 2013). Climatologies of dust storms (smoke) and their types in the literature are scarce (nonexistent). Analyses by Bach et al. (1996) and Tong et al. (2012) found that dust events in the western United States were most common in the desert Southwest (namely, the Chihuahuan, Mojave, and Sonoran Deserts) and in the high wind power region of Colorado with a peak in events from March to June and a secondary peak

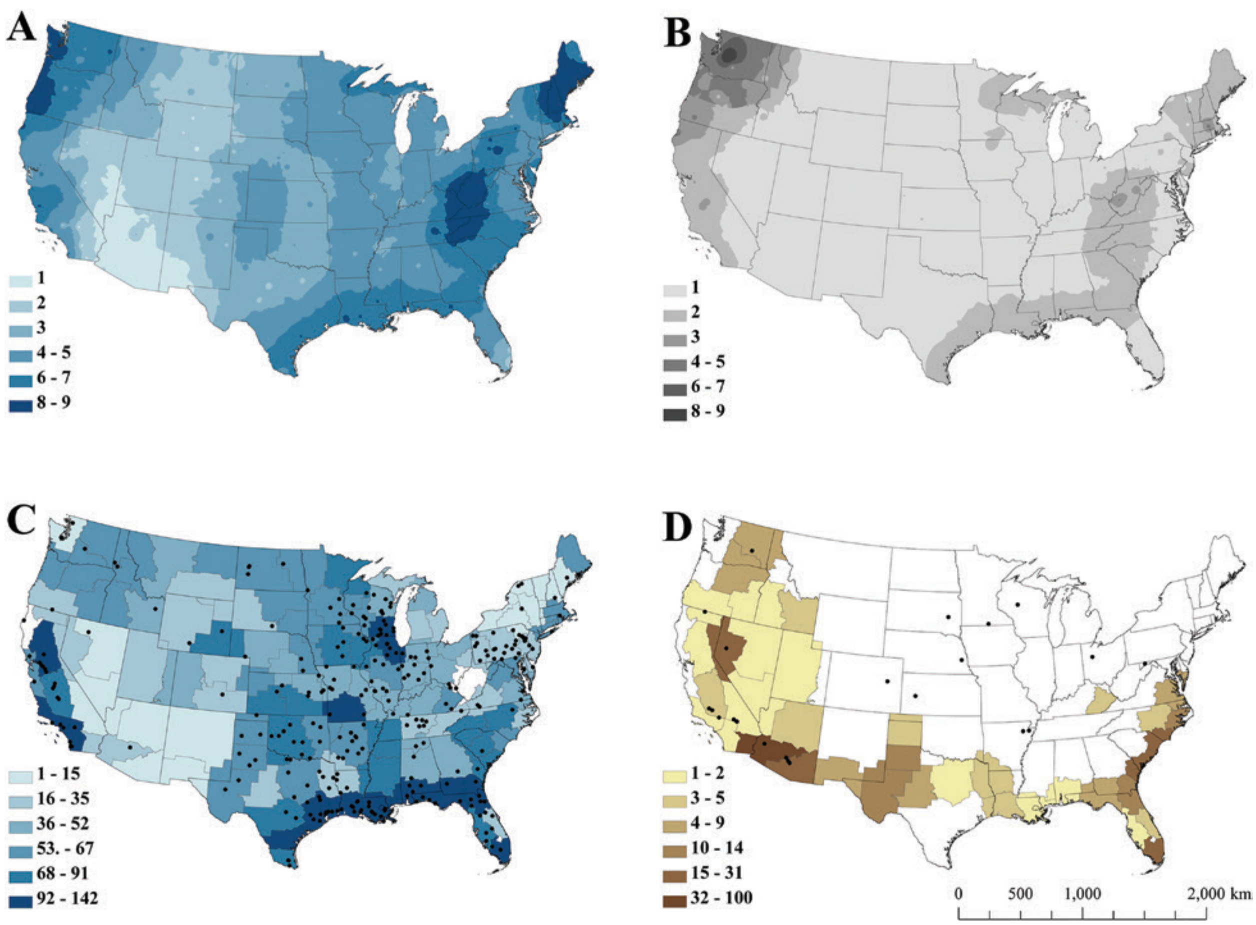

Fig. 4. The mean annual (a) number of days with at least one occurrence of heavy fog visibility (≤0.40 km) and (b) percentage of hours with visibility ≤ 0.40 km (after NOAA 2002). The number of (c) fog and (d) dust and/or smoke advisory issuances by NWS county warning area, as well as fatal VO crashes (black dots) for 2007–11.

from September to November. Both of these periods correspond to seasonal maxima in extratropical cyclones and affiliated fronts and intense wind fields that can traverse the region, while the later summer/early fall phase overlaps the period of greatest enhancement of convection in the desert Southwest because of the North American monsoon (Adams and Comrie 1997). A more geographically expansive study by Changery (1983) found dust storm maxima in the desert Southwest, in addition to the central and southern high plains, central Great Basin, and in the San Joaquin Valley. The central and southern high plains region, which stretches from approximately Odessa, Texas, to North Platte, Nebraska, had the greatest concentration of high-impact, long-lived events, with most of those events concentrated in the spring transition season of March through May when the dryline is most active (Hoch and Markowski 2005). In general, the nonfog VO crash fatalities were most common in April, when extratropical cyclones and drylines are most frequent, and again in August through October, when high-based thunderstorms and their downbursts can promote blinding dust events. These climatological analyses partly explain the distributions uncovered in the west (Fig. 5e); conversely, it is difficult to ascertain relationships between the climatologies of these variables and the relatively infrequent nonfog-related VO crash fatality east of the Interstate 35 corridor due to the lack of spatiotemporal analyses of these hazards in the literature. Anecdotal evidence suggests that at least some of the fatal crashes in agriculturally rich regions of the United States may be due to intense surface winds across fallow or recently plowed fields inducing localized dust storms (Pankratz 2009; Biasco et al. 2012; Associated Press 2012).

Diurnally, VO crash fatalities are most common in the dawn and early morning hours; specifically, from 0500 to 0800 local time (LT). (Fig. 3b). This contradicts the daily cycle of total vehicular fatalities, which illustrate a broad maximum during midafternoon through early evening. Fog is the largest contributor (90%; Table 4) of VO crash fatalities and most often develops and persists during the overnight and early morning hours (Croft et al. 1997; Tardif and Rasmussen 2007; Westcott 2007; O'Hara 2011; Aguado and Burt 2013). The enhanced diurnal maximum in fog overlaps the morning traffic volume maximum (0600–0900 LT; UTCM 2011), leading to the elevated frequency of fatal crash events and deaths during this period. Nonfog VO crash fatalities were more frequent in the late morning and afternoon (1000–1700 LT), revealing a relationship with the prevalence of high wind producing environments (e.g., high-based thunderstorms, dryline slosh, and strong mixing) affiliated with the peak in the diurnal solar cycle.

The majority of fatal motor vehicle crashes occurred in proximity to large metropolitan areas (Chicago, Illinois; the Interstate 95 corridor between Washington, D.C., and Boston, Massachusetts; Los Angeles and San Francisco, California; Atlanta, Georgia, etc.; Fig. 5a) primarily because of high-traffic volume (Fig. 6) and greater road density (Cervero and Murakami 2010). VR fatal crashes occur throughout the United States (Fig. 5b) but are elevated in specific regions, including the Interstate 5 corridor of California, Oregon, and Washington; the north-central Gulf Coast region; central Florida; southern Great Lakes and northern Ohio Valley regions; and coastal and interior mid-Atlantic and Northeast. The more restrictive classification of VO fatal crashes reveals several distinct hotspots (Figs. 5c,f). In particular, the San Joaquin Valley of California exemplifies the greatest frequency of VO fatal crashes. Most of the fatal crashes in this particular region were due to fog occurring along high-volume roadway corridors (Fig. 5d). California's Central Valley historically experiences long-lived, spatially extensive radiation fog during the late fall through early spring seasons; this fog is locally referred to as "tule fog" (Suckling and Mitchell 1988; Underwood et al. 2004). Instances of the fog hazard in this region leading to chain reaction crashes and injurious consequences are relatively common. For example, on 5 February 2002, radiation fog led to visibilities less than 15 m on State Highway 99, south of Fresno, California (Hatfield 2002; Aguado and Burt 2013). These poor visibility conditions forced the California Highway Patrol to intervene, implementing a traffic "pacing" plan to induce safe speeds for the conditions. Despite the mitigation effort, a chain reaction pileup with 87 motor vehicles occurred, leaving two dead and many more injured (Hatfield 2002; Aguado and Burt 2013). Five years later, in November 2007, similar weather conditions caused a pileup involving 125 motor vehicle and two fatalities. An earlier, and eerily similar, case from 1997 was discussed in an earlier section.

Other locations that illustrate high frequencies of VO fatal crashes include the Gulf Coast (e.g., Houston region, southern Louisiana, and west-central Florida), areas in the Midwest (Wisconsin, Illinois, and Indiana), and interior mid-Atlantic and Northeast (Pennsylvania, in particular). Advection fog is commonplace during the cool and transition seasons near the Gulf of Mexico, when warm, moist air from the Gulf moves over, or advects, atop relatively cool land. In addition, radiation fog can form in many of the riverine, bay, and estuary valleys that are found in this area. These environmental situations promote the enhanced frequency of fog events across the Gulf Coast region (Fig. 4) and, when juxtaposed with traffic along many of the roadways in the region (including heavily traveled Interstate 10; Fig. 6), VR and VO fatal crashes can result.

The high number of VO fatal crashes in the interior locations of the mid-Atlantic and Northeast are triggered by two different types of fog: 1) radiation fog

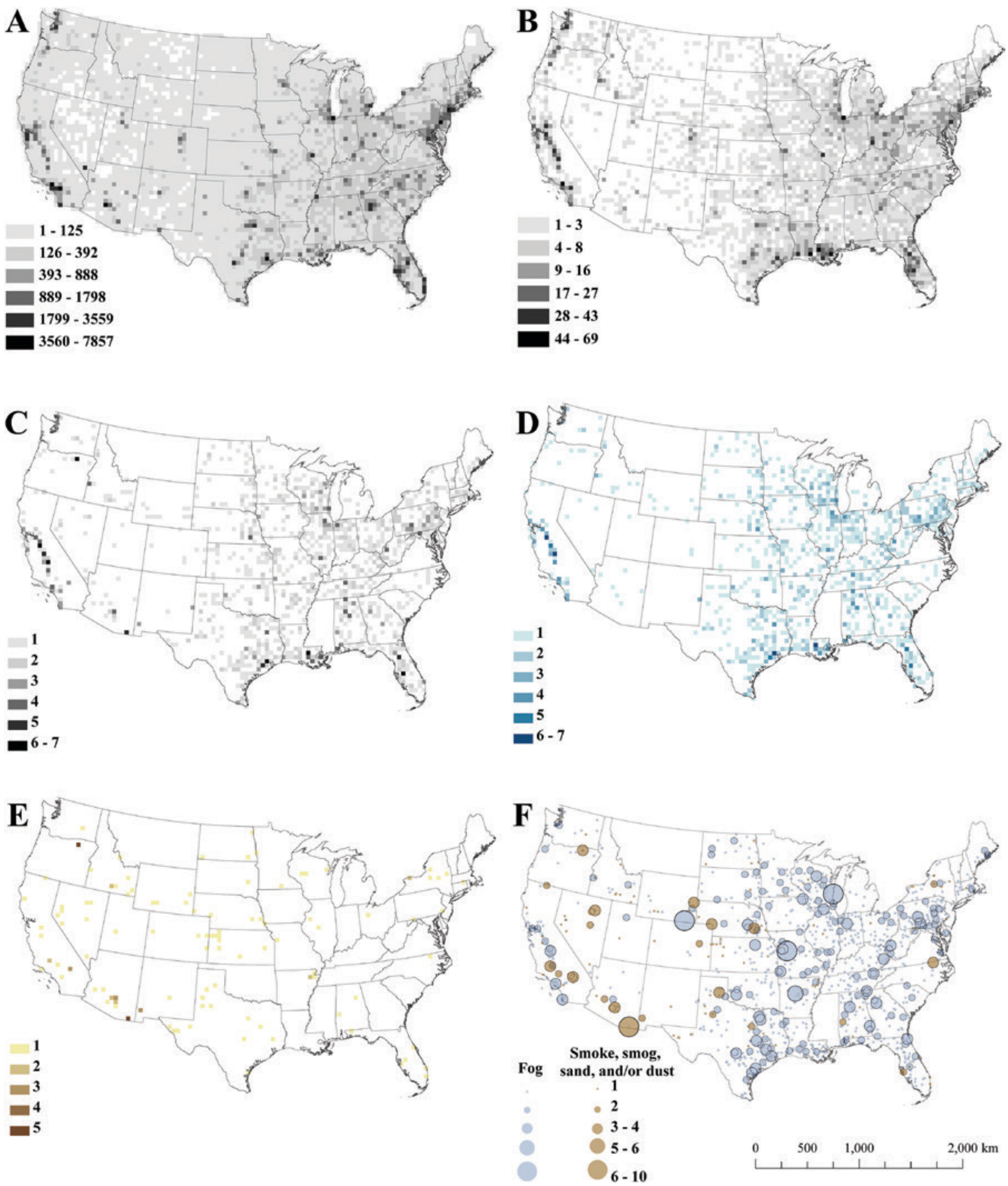

Fig. 5. Conterminous U.S. 40-km grid illustrating the frequency of (a) all fatal motor vehicle crashes, (b) VR weather hazard fatal crashes, (c) VO weather hazard fatal crashes, (d) VO crashes where driver vision was obscured in fog conditions, (e) VO crashes where driver vision was obscured in dust and/or smoke conditions, and (f) VO weather hazard crash locations with graduated circles representing the number of fatalities by event for 1994–2011. Though not represented graphically, Alaska (Hawaii) experienced 1296 fatal crashes, with 24 (5) VR-related, and 3 (0) VO-related during the 18-yr period.

that is caused when relatively moist, cool air pools in many of the river valleys that interlace the region and 2) fog caused by stratiform clouds that can intersect ridges of the Appalachians. The elevated frequency of reduced visibility conditions combined with the high-traffic volume rates (Fig. 6) and variable speed because of the roadways intersecting the orography commonplace in Pennsylvania leads to the high rates found in this region. Comparatively, other parts of the Appalachians that experience a large number of low visibility and/or fog events do not have similar fatal crash frequencies. In particular, areas near the spine of the Appalachians have relatively low VO fatal crashes despite a prominent maximum in visibility hazards (Fig. 4). This lack of correspondence between VO fatal crashes and low visibility climatology is due to the reduced number of thoroughfares and traffic volume found in this region (Fig. 6). Albeit, some areas that have relatively low volume have a heighted tendency to produce devastating chain reaction crashes because of the unique roadway conditions (e.g., steep grade and river valley) and commonality of a visibility-related hazard mixing with "too fast for conditions" driving. For example, a particular stretch of Interstate 77 along the North Carolina–Virginia border (the Blue Ridge escarpment near Fancy Gap, Virginia) has experienced multiple fatality-inducing pileups during the past 15 years (fog-related pileups including ≥46 vehicles in 1997, 1998, 2001, 2010, and 2013; Fig. 1) despite mitigation efforts (Lynn et al. 2002). Additional interstate fog-induced crash "hotspots," as well as weather-responsive traffic management and crash mitigation plans implemented by states in these areas, are discussed in Lynn et al. (2002) and Goodwin (2003b).

We further evaluated the fatal crash information by state, normalizing by state area, lane distance, and annual kilometers traveled (Table 5). Again, Mississippi, Montana, and Virginia had limited information regarding weather and environmental conditions—especially as it pertains to weather-related vision hazards and their obscuration—on their PAR forms, likely resulting in an undercount of VO fatal crashes in those states. Texas and California had far more VO fatal crashes than other states; though when normalizing by area, these states are not even in the top 10. Instead, Northeast and mid-Atlantic states, as well as Indiana and the Southeast states of Florida, Louisiana, and Alabama, are in the top 10 for fatal crashes normalized by area. States in the Sun Belt dominate the top 10 of fatal crashes when normalized by state lane distance. States in the central and northern plains, as well as northern Mountain West, are ranked highest when the number of fatal crashes is normalized by driving distance.

Fatal VO crashes by route type. Most VO fatal crashes (33%) and fatalities (32%) transpired on state highways (Table 6). U.S. numbered highways ranked second among all route types with 21% of VO crash fatalities, while county roads were third at 18%. Local streets and routes (township, municipality, and frontage roads, as well as other or unknown road types) make up 11% of total VO crash fatalities. Although local streets and routes compose a relatively small cumulative proportion of all fatal crashes, partially owing to low-speed limits, the opposite does not hold true with interstates (i.e., routes with the highest speed limits). Interstates only represent a collective 14% and 18% of all VO fatal crashes and fatalities,

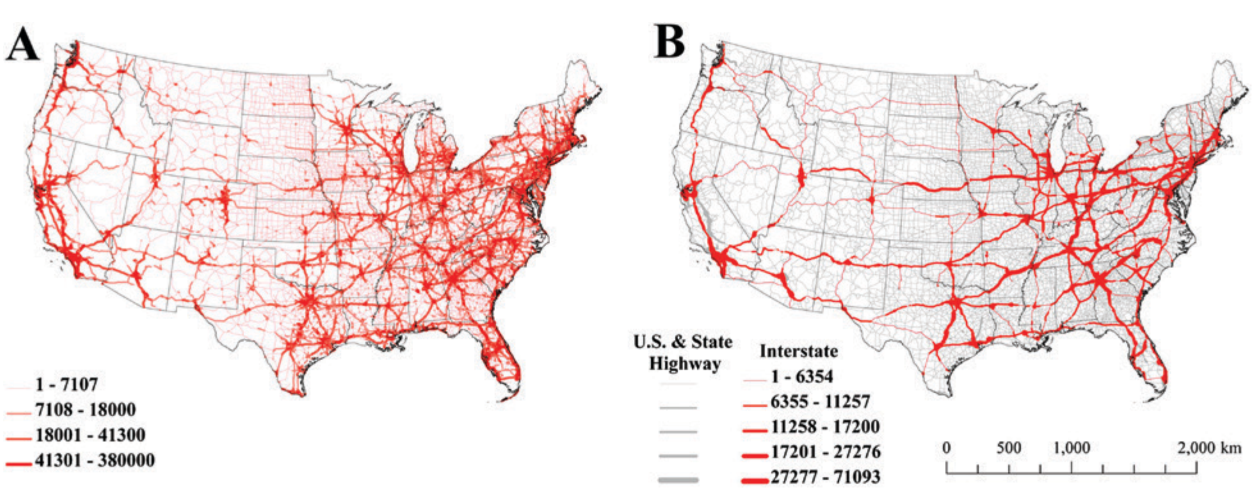

Fig. 6. Annual average daily traffic volume (vehicles per day) on interstates, state, and U.S. numbered highways for (a) all vehicle types (USDOT 2011b) and (b) long-haul freight vehicles (USDOT 2007).

Table 5. VO fatal motor vehicle crashes and fatalities for 1994–2011, normalized by state area, lane distance, and annual distance driven. Mississippi, Montana, and Hawaii are not included in the table as they contained no reported VO cases during the period of examination.

			Normalized by state area (km^2)			Normalized by state lane distance (km)			Normalized by annual distance driven (km)		
State	Fatal crashes	Fatalities	Area (km^{-2})	Fatal crashes/area $[(km^2)^{-1}$ (× 10,000)]	Rank	State lane distance (km)	Fatal crashes/lane distance $[km^{-1}$ (× 10,000)]	Rank	Annual distance driven (km)	Fatal crashes/distance driven $[km^{-1}$ (× 10,000)]	Rank
Alabama	54	64	135,765	3.98	10	193,772	2.79	3	98,830	5.46	12
Alaska	3	4	1,717,854	0.02	47	121,233	0.25	41	8,293	3.62	17
Arizona	22	37	295,254	0.75	36	239,982	0.92	20	101,329	2.17	27
Arkansas	33	39	137,732	2.40	17	468,387	0.70	26	53,383	6.18	10
California	91	111	423,970	2.15	20	447,390	2.03	7	528,366	1.72	33
Colorado	6	7	269,601	0.22	44	182,899	0.33	37	78,396	0.77	41
Connecticut	3	3	14,357	2.09	21	46,486	0.65	30	51,584	0.58	42
Delaware	3	4	6,447	4.65	4	13,255	2.26	6	15,261	1.97	30
Florida	72	79	170,304	4.23	6	404,375	1.78	8	331,719	2.17	28
Georgia	35	45	153,909	2.27	18	217,581	1.61	9	181,117	1.93	31
Idaho	21	23	216,446	0.97	33	310,768	0.68	28	25,399	8.27	4
Illinois	58	66	149,998	3.87	12	389,399	1.49	10	172,977	3.35	21
Indiana	47	51	94,321	4.98	3	348,522	1.35	13	115,032	4.09	15
Iowa	28	31	145,743	1.92	23	406,789	0.69	27	50,297	5.57	11
Kansas	35	38	213,096	1.64	25	352,095	0.99	18	48,357	7.24	8
Kentucky	28	28	104,659	2.68	14	234,252	1.20	15	77,350	3.62	16
Louisiana	56	61	134,264	4.17	7	142,120	3.94	1	73,025	7.67	7
Maine	8	10	91,646	0.87	34	89,797	0.89	21	24,196	3.31	22
Maryland and Washington D.C.	13	16	32,250	4.03	9	264,025	0.49	34	90,933	1.43	34
Massachusetts	12	12	27,336	4.39	5	260,615	0.46	35	88,628	1.35	37
Michigan	7	7	250,494	0.28	43	421,310	0.17	45	168,359	0.42	45
Minnesota	29	34	225,171	1.29	29	350,143	0.83	22	92,107	3.15	24
Missouri	39	58	180,533	2.16	19	333,448	1.17	16	111,287	3.50	19

Table 5. Continued.

				Normalized by state area (km^2)		Normalized by state lane distance (km)			Normalized by annual distance driven (km)		
State	Fatal crashes	Fatalities	Area (km^{-2})	Fatal crashes/area $[(km^2)^{-1}$ (× 10,000)]	Rank	State lane distance (km)	Fatal crashes/lane distance $[km^{-1}$ (× 10,000)]	Rank	Annual distance driven (km)	Fatal crashes/distance driven $[km^{-1}$ (× 10,000)]	Rank
Nebraska	31	41	200,345	1.55	26	229,547	1.35	12	31,284	9.91	3
Nevada	12	16	286,351	0.42	41	88,229	1.36	11	35,640	3.37	20
New Hampshire	3	3	24,216	1.24	30	88,206	0.34	36	21,660	1.39	36
New Jersey	4	4	22,588	1.77	24	170,863	0.23	42	122,554	0.33	46
New Mexico	5	6	314,915	0.16	45	305,860	0.16	46	43,211	1.16	39
New York	29	31	141,299	2.05	22	357,486	0.81	24	220,056	1.32	38
North Carolina	8	11	139,389	0.57	39	321,688	0.25	40	166,724	0.48	43
North Dakota	18	21	183,112	0.98	32	336,030	0.54	32	12,624	14.26	2
Ohio	31	34	116,096	2.67	15	397,558	0.78	25	178,043	1.74	32
Oklahoma	27	30	181,035	1.49	27	326,621	0.83	23	76,560	3.53	18
Oregon	15	19	254,805	0.59	38	297,082	0.50	33	55,925	2.68	25
Pennsylvania	76	91	119,283	6.37	2	211,337	3.60	2	174,934	4.34	13
Rhode Island	3	4	4,002	7.50	1	119,123	0.25	39	13,898	2.16	29
South Carolina	7	9	82,932	0.84	35	248,093	0.28	38	82,252	0.85	40
South Dakota	26	31	199,731	1.30	28	278,827	0.93	19	14,492	17.94	1
Tennessee	37	40	109,151	3.39	13	663,950	0.56	31	114,551	3.23	23
Texas	169	200	695,621	2.43	16	611,124	2.77	4	391,783	4.31	14
Utah	2	2	219,887	0.09	46	100,621	0.20	44	43,182	0.46	44
Vermont	3	3	24,901	1.20	31	143,547	0.21	43	12,382	2.42	26
Virginia	4	4	110,785	0.36	42	262,170	0.15	47	132,090	0.30	47
Washington	13	16	184,665	0.70	37	197,218	0.66	29	91,634	1.42	35
West Virginia	26	31	62,755	4.14	8	247,377	1.05	17	33,094	7.86	6
Wisconsin	67	86	169,639	3.95	11	251,698	2.66	5	95,744	7.00	9
Wyoming	12	21	253,336	0.47	40	94,821	1.27	14	15,073	7.96	5
United States	1331	1582	9,309,971	1.43	—	13,274,982	1.00	—	3,029,822	4.39	—

Table 6. VO fatal motor vehicle crashes and fatalities by route signing for 1994–2011.

Route signing	Fatal crashes		Fatalities	
Interstate	186	14%	283	17.9%
U.S. highway	294	22.1%	339	21.4%
State highway	441	33.1%	506	32%
County road	263	19.8%	291	18.4%
Local street, township	38	2.9%	41	2.6%
Local street, municipality	52	3.9%	58	3.7%
Local street, frontage road	1	0.1%	1	0.1%
Other	51	3.8%	58	3.7%
Unknown	5	0.4%	5	0.3%
Total	1331	100%	1582	100%

respectively. This is counter to our initial hypothesis, which suggested that U.S. interstates and numbered highways would have the greatest number of fatal crashes because of elevated speeds and relative volumes (Fig. 6). The interstate (U.S. numbered highway) system is 75,439 km (253,832 km) long, with 24.4% of all vehicle kilometers traveled in the United States along interstates (USDOT 2008, 2010a,b). Other expressways and principal arterial roads compose an additional 30.4% of vehicle kilometers traveled, revealing that collector, minor arterial, and local roadway traffic constitute a majority of all motor vehicle travel in the United States. Despite these roadways' lower speeds, the sheer number of roadway kilometers and collective traffic volume enhances the exposure of travelers to weather, environmental, and other hazards on these roads.

Relationship between VO crashes and NWS advisories. We assessed whether VO fatal crashes occurred under a visibility-related weather hazard advisory issued by the National Weather Service (NWS). Archived nonprecipitation warning, watch, and advisory (NPW) data from 2007 to 2011 were acquired from the NWS's online verification and performance management (VPM) tool. This period of analysis was selected because information for visibility-related weather advisories prior to 2007 was unavailable (B. MacAloney 2013, personal communication). VPM NPW data were further cross checked with georeferenced NWS advisory data hosted by the Iowa State University at their "Iowa Environmental Mesonet (IEM) valid extent time browser" (http://mesonet.agron.iastate.edu/vtec/). Advisory/warning types examined included dense fog, freezing fog, blowing dust, dust storm, and dense smoke. We manually joined the fatal crash data with visibility-related weather advisories provided by the NWS to confirm if an overlap of the spatiotemporal attributes of the advisory and fatal crash occurred, which revealed the percentage of "warned" (i.e., advisory was in place at time of crash) weather-related VO fatal crashes for the period.

From 2007 to 2011, a total of 6,824 visibility-related weather hazard advisories were issued by the NWS across the contiguous United States. Of those thousands of advisories, most were related to dense fog (88.2%) and freezing fog (6%). Dense smoke (2.4%), dust storm (2.1%), and blowing dust (1.1%) made up the remaining percentage of products. Fog-related advisories were most common in California and, broadly, in the eastern two-thirds of the United States (Fig. 4c), which is supported by the climatologies in Peace (1969), Hardwick (1973), and Fig. 4a. However, the relatively small number of advisories issued in the Appalachians, Northeast, and Pacific Northwest during this 5-yr period is counter to these long-term climatologies. A comparison between the fog advisories and fog-related VO fatal crash distributions (Fig. 5d) reveals that some regions that have relatively elevated numbers of fatal crashes do not have correspondingly high fog advisory issuances. These areas include the interior Northeast and mid-Atlantic and western Washington. Dust- and smoke-related advisories were most common in the southern high plains through the desert Southwest and central basin and range ecoregion (Fig. 4d), which is similar to the areas of focus and dust climatologies produced by Changery (1983), Bach et al. (1996), and Tong et al. (2012). Nearly all advisories along the Gulf and Atlantic coasts in Fig. 4d were due to smoke, related to both wild land and prescribed fires that are common to the region

(Achtemeier et al. 1998; Wade et al. 2000; Zhang and Kondragunta 2008).

There were a total of 310 VO fatal motor vehicle crashes resulting in 363 fatalities during this 5-yr period of analysis (Table 7). Approximately 72% (74%) of all VO fatal crashes (fatalities) occurred during times when no visibility-related weather advisory had been issued by the NWS (Table 8). Yearly variation in unwarned VO fatal crashes (fatalities) ranged from 63.8% (66.1%) in 2007 to 81.1% (80.7%) in 2010. These percentages of unwarned VO crashes are far greater than the percentage of unwarned fatalities affiliated with more notable hazards such as severe nontornadic thunderstorm winds (53.2% unwarned) and tornadoes (23.7%) (Black and Ashley 2010). The percentage of unwarned VO fatal crashes is elevated during the warm season, with over 80% of all VO fatal crashes during the May–October period unwarned (Fig. 7a). The total percentage of unwarned fatal crashes and fatalities varied from 48.6% in February to nearly 96.6% in September. The relatively high percentage of unwarned VO fatal crashes during the warm season could be attributed to the less frequent occurrences of fog (Hardwick 1973), which could lead to reduced forecaster awareness during this period. Additionally, many weather-related vision-obscuring conditions are more isolated during the summer months as compared to the fall and winter when there is greater likelihood for widespread visibility-related hazard conditions to develop. Ultimately, the isolated nature of warm season, weather-related, vision-obscuring hazards makes it more difficult for forecasters to recognize, report, and advise for these threats.

Trends in the percentage of unwarned, weather-related, vision-obscured fatal motor vehicle crashes and fatalities by hour from 2007 to 2011 illustrate multiple maxima throughout the day (Figs. 7b,c). These maxima in the percentage of unwarned fatal crashes and fatalities tend to coincide when the fog (overnight–early morning) and dust (afternoon) hazards are more common and/or during periods of elevated traffic volume [i.e., early morning (0400–0600 LT), midday (1000–1200 LT), and late afternoon (1700–1900 LT); USDOT 2013; IDOT 2013]. However, discretion should be taken when examining these numbers as they suffer from small sample size.

Though not a part of our period of record, three of the four events discussed in the introduction did have NWS visibility-related advisories in effect; the Fancy Gap, Virginia, case had no visibility-related advisory posted because of the localized nature of the dense fog (www.erh.noaa.gov/rnk/Newsletter/Spring_2013/Spring_2013.pdf).

Top-ranked weather-related vision hazard fatal crashes. Nearly 86% of all VO fatal crashes from 1994 to 2011 involved one or two vehicles, revealing that most VO fatal cases are not affiliated with chain reaction or pileup incidents. Of those higher-end crash events assessed during the period of study, 14 VO and 10 VR crashes or series of crashes yielded fatality totals of four persons or greater (Table 8). Of these top 24 fatal events, three produced 10 fatalities or more while three others resulted in 7 fatalities. Three of every four of these "worst" VO and VR fatal crashes transpired during fog or superfog conditions, whereas the remaining were associated with dust or smoke conditions. Of these 24 top-ranked crash events, 17 occurred from the months of September through March, 18 occurred between 0400 and 1000 LT, 11 took place on the weekend (15 if Friday is counted), and 15 transpired on interstate routes. Overall, California (4) and Florida (3) had the greatest number of top-ranked fatal crashes; Missouri, Texas, and Wisconsin each experienced two of these high-end events during the period. While it is difficult to assess the total number of cars involved because of the complexity of many pileup and chain reaction

Table 7. VO fatal motor vehicle crashes that were warned and unwarned, as well as percentage unwarned, by year from 2007 to 2011.

	Weather-related vision-obscured fatal crashes			
Year	Total	Warned	Unwarned	Percent unwarned
2007	58	21	37	63.8%
2008	57	21	36	63.2%
2009	56	14	42	75.0%
2010	74	14	60	81.1%
2011	65	18	47	72.3%
Total	310	88	222	71.6%

TABLE 8. The most fatal weather-related visibility impairment crashes during the 1994–2011 period of record. List includes VO and VR crashes producing four or more fatalities that could be verified as occurring in a vision-related hazardous situation using media (LexisNexis and Google News) and/or governmental [National Transportation Safety Board (NTSB) highway accident briefs and NOAA Storm Data summaries] resources.

State	Vision hazard	Date	Local time	Day of week	Total fatalities	Route type	No. of vehicles	VO/VR
Arkansas	Fog	9 Jan 1995	0100	Monday	5	Interstate	9	VO
Arizona	Dust	9 Apr 1995	1600	Sunday	10	State highway	16	VO
Wisconsin	Fog	23 Sep 1996	0700	Monday	5	State highway	3	VR
California	Fog	11 Dec 1997	0700	Thursday	5	Interstate	37	VR
California	Fog	16 Nov 1997	0900	Sunday	11	State highway	2	VR
California	Fog	27 Mar 1999	0700	Saturday	4	County road	1	VO
Illinois	Fog	9 Oct 1999	0800	Saturday	4	State highway	2	VO
Oregon	Dust	25 Sep 1999	1000	Saturday	6	Interstate	27	VO
Mississippi	Fog and smoke	7 May 2000	0500	Sunday	5	Interstate	20	VR
Florida	Fog	28 Feb 2001	0600	Wednesday	6	State highway	4	VR
Georgia	Fog	14 Mar 2002	0700	Thursday	5	Interstate	62	VO
Missouri	Fog	18 May 2002	0500	Saturday	4	Interstate	12	VO
North Carolina	Fog and smoke	9 Jun 2002	0400	Sunday	4	Interstate	3	VO
New Mexico	Smoke	8 Mar 2002	1400	Friday	7	Interstate	12	VR
Wisconsin	Fog	11 Oct 2002	0700	Friday	10	Interstate	50	VO
Missouri	Fog	14 Feb 2003	1700	Friday	7	State highway	2	VO
Pennsylvania	Fog	5 Apr 2003	1000	Saturday	4	Interstate	19	VR
Texas	Fog	14 Jan 2004	0700	Wednesday	4	Rural intersection	2	VO
Wyoming	Fog	19 Aug 2004	1000	Thursday	7	Interstate	16	VO
Nevada	Dust	29 Jul 2005	1500	Friday	4	Interstate	7	VR
Texas	Smoke	12 Mar 2006	1100	Sunday	4	Interstate	9	VO
Florida	Fog	13 Mar 2007	0800	Tuesday	6	State highway	5	VR
California	Blowing sand/dust	9 Nov 2008	0800	Sunday	4	Interstate	10	VO
Florida	Fog and smoke	9 Jan 2008	0400	Wednesday	4	Interstate	24	VR

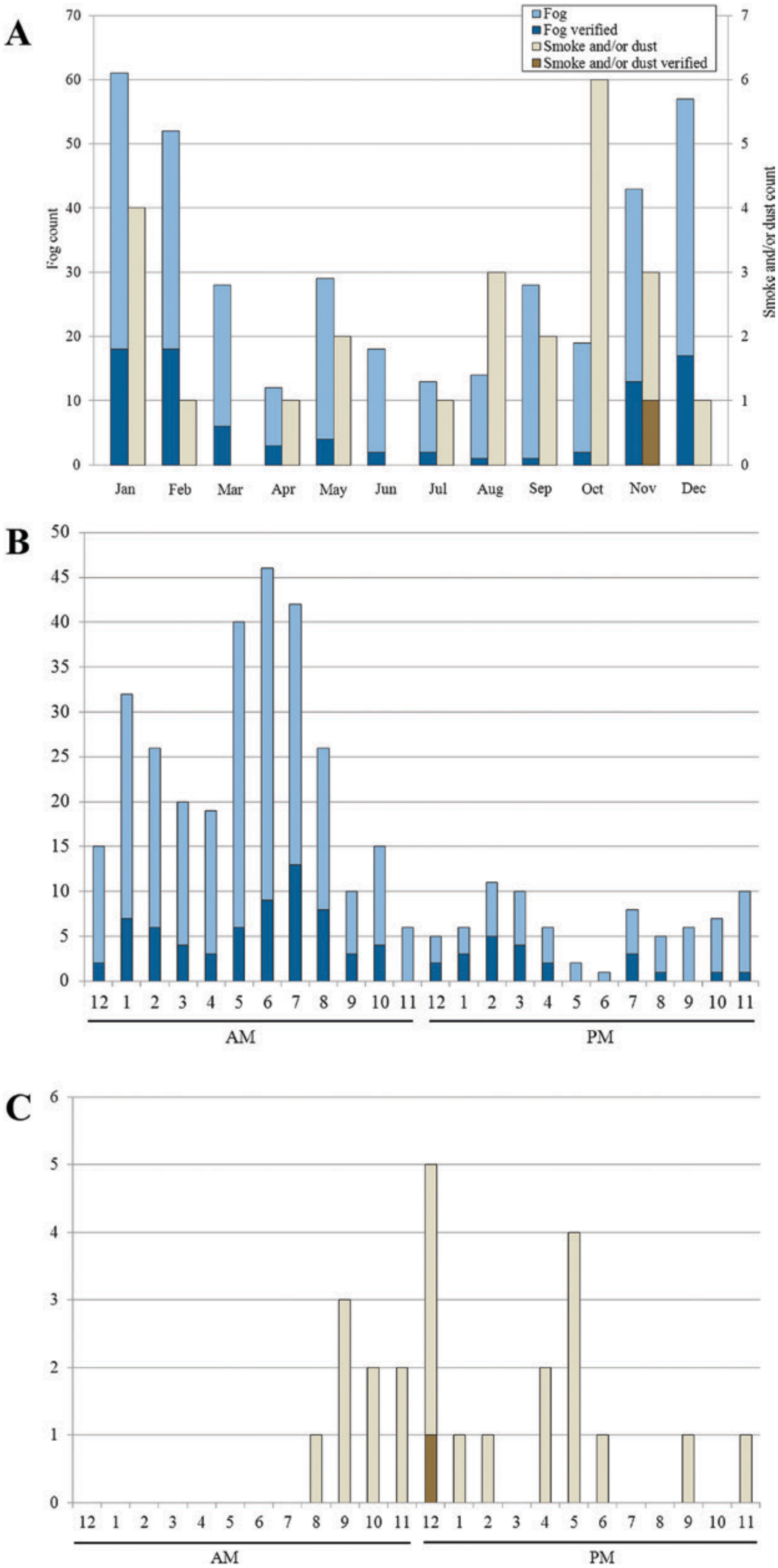

Fig. 7. Total counts of VO crashes where vision was obscured by fog, smoke, and/or dust conditions and total number fatal VO crashes that occurred during times a visibility-related weather advisory had been issued by (a) month, (b) local time for fog cases, and (c) local time for smoke and/or dust cases from 2007 to 2011.

situations, half of the top-ranked event involved 10 or more vehicles based on FARS counts.

Commercial motor vehicles (CMVs) were involved in 19 of the 24 high-end events; 18 of those 19 involved semitrailer trucks, while the remaining case involved a dump truck. These large gross weight vehicles are particularly vulnerable during low visibility situations because of the increased stopping distances required to avoid a crash, as well as the greater release of kinetic energy that produces a more severe impact (Pisano et al. 2008, USDOT 2011a). Overall, fatal weather-related crashes in commercial vehicles are nearly twice the rate (fatal weather crashes per vehicles' kilometers traveled) of all vehicle fatal weather-related crashes (Pisano et al. 2008). About 12% of fatal weather-related CMV crashes involved fog, which is 2%–4% greater than all motor vehicle fatal crashes that occur in fog (Pisano et al. 2008; USDOT 2011a). Pisano et al. (2008) postulate that since CMV operators characteristically have longer trip lengths than passenger car drivers, and because CMV operator travel is typically less discretionary, CMVs possess enhanced exposure rates to a variety of adverse mesoscale and misoscale weather hazards. Kostyniuk et al. (2002) compared unsafe driving acts in car–truck crashes with those in car–car crashes, concluding that most driving behaviors are equally likely to be recorded for both classifications. Uniquely, "driving with vision obscured by rain, snow, fog, or dust" was one of the four factors, out of 94, that were more likely to occur in fatal car–truck crashes than fatal car–car crashes (Kostyniuk et al. 2002; USDOT 2004).

CONCLUSIONS. Adverse roadway conditions due to the weather are evident in over 23% (17%) of all (fatal) crashes resulting in approximately 7,000 killed, 600,000 injuries, and an estimated $22–$55 billion in costs per year in the United States (NRC 2004; Atmospheric Policy Program 2004; Pisano et al. 2008; USDOT 2013; Tables 1 and 2). While a large majority of these events are due to precipitation and wet, snowy, or icy pavement, a nontrivial amount of these crashes occur in weather conditions that may be considered, at least initially, less significant. We focused on the lesser-acknowledged motor vehicle hazards of fog, smoke, and dust, illustrating the spatiotemporal characteristics of fatal crashes where these hazards may have acted to obscure the drivers' vision and potentially resulting in reduced driver capabilities and increased crash risk. Analyses revealed that weather-related VO crash fatalities were more common than fatalities due to other more notable weather hazards, including tornadoes and hurricanes. Fatal VO crashes most frequently occurred in fog, during the early morning hours when traffic volume is elevated and weather vision hazards are most common, during the cool season, and on state and U.S. numbered highways as opposed to the interstate system. Geographically, VO fatal crashes could occur anywhere in the United States, but were most widespread in the eastern half of the country. The Central Valley of California, Appalachian Mountain and mid-Atlantic region, the Midwest, and the Gulf Coast are specific areas that experienced multiple fatal crashes during the 18-yr study period.

Our spatial analysis lens was admittedly large, focusing on the overall trends in fatal crashes for the United States. Subsequent study should concentrate on the highly nuanced aspects of individual fatal and nonfatal events, whether media-focused chain reaction crashes and pileups along an interstate or, on the opposite end of the spectrum, a single vehicle crash on a rural road. There are many variables that lead to these crashes, and we presupposed that weather-related vision hazards were an important environmental factor in their cause. Crash complexities and database constraints (diversity in PARs, lack of detailed environmental and weather descriptions, and so on) precluded more conclusive evidence implicating hazards as crash triggers. As with all hazards, a synoptic perspective, such as the one we have presented, provides a single piece of a very complex puzzle. Despite mitigation efforts—from advance detection systems, to NWS advisories, to signage, to traffic pacing—these fatal crashes continue to occur and do not reveal a notable decrease during the period (Table 4).

As advocated by Pisano et al. (2008), additional research on the relationship between weather and motor vehicles should focus on the assessment of exposure (e.g., trip characteristics during weather events), human factors [e.g., driver decision making; influences on driver behavior; best modes of information receipt and action; see, e.g., Brooks et al. (2011) and Hassan and Abdel-Aty (2011)], education and training (e.g., increasing driver and transportation decision maker knowledge and appreciation of hazards), and mitigation endeavors (e.g., traffic weather management practices; in-vehicle weather and road condition information systems; detection, monitoring, and prediction technologies; information dissemination; and decision support). Efforts promoted by Lynn et al. (2002) and Goodwin (2003b), which focus on information broadcasting and traffic mitigation techniques in visibility hazard crash hotspots, should be updated and encouraged.

We provided evidence that many of these fatal crash events occurred in areas with no NWS advisory for the hazard. As is often performed for significant weather events, NOAA may want to support a service assessment for future high-impact, weather-related, vision hazard crash(es) to evaluate NWS warning performance, dissemination of products and services, decision making, and complementary physical *and* social science questions. Such appraisals could reveal best practices in warning and dissemination operations, identify deficiencies and potential solutions, evaluate efforts to compel driver behavioral change and response during advisories such that safety is improved, and strengthen relationships between public and private road weather stakeholders and the NWS. In the meteorological community, continual improvements of remote-sensing platforms and techniques (Ellrod and Lindstrom 2006), observational methods (Ward and Croft 2008), and modeling efforts (Pagowski et al. 2004; van der Velde 2010; Zhou and Du 2010) have uncovered analysis and forecasting techniques that can improve the detection of weather-related vision hazards, as well as understanding of their formation. Nevertheless, these hazards are still a major forecasting challenge, in large part because of their microscale nature.

Using vehicles as mobile weather and information-gathering platforms and instantaneously transmitting those data to the operational weather and transportation communities could improve safety and mobility across the nation's roadway system (Drobot et al. 2010; Mahoney et al. 2010; Mahoney and O'Sullivan 2013; Drobot et al. 2014). For instance, the recent NHTSA (2014) decision to facilitate "connected" vehicles (www.safercar.gov/v2v/) will provide the opportunity to integrate weather information acquired from vehicles into the Meteorological Assimilation Data Ingest System (MADIS; Mahoney et al. 2010). Such real-time, finescale data from vehicles embedded in potentially hazardous thoroughfares will assist forecasters and other decision makers, promoting improved information dissemination and warning performance, as well as mitigation activities.

In summary, this investigation generated a better understanding of weather-related vision hazards and their effects on fatal motor vehicle crashes in the United States. Evidence suggests that these subtle hazards have substantial impacts on the safety and efficiency of the nation's roadways. These results, as well positions offered in prior efforts (NRC 2004; Atmospheric Policy Program 2004; Pisano et al. 2008), advise that a concerted effort focused on improving meteorology and traffic safety operations is required to mitigate future mortality, morbidity, and costs of the approximately 1.5 million motor vehicle crashes due to visibility-related hazards and other adverse weather in the United States each year.

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