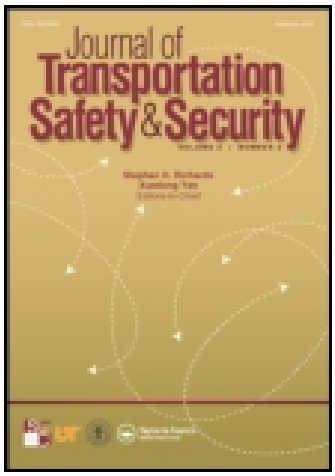

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Synthesis of State-of-the-Art in Visibility Detection Systems' Applications and Research

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Visibility is a critical component to the task of driving on all types of roads. The visibility detection and warning systems provide real-time, automated detection as well as appropriate responses to counteract reduced visibility conditions due to fog, heavy rain, snow, smoke, dust, or haze by informing drivers of present conditions and lowering the speed limits to match the reduced visibility condition. The objective of this research is to provide a synthesis of visibility detection systems and traffic control techniques that are developed and/or implemented in the United States and around the world. This article provides an overview of the best practices of fixed visibility systems at areas of recurrent dense fog and mobile systems for seasonal visibility reduction for areas of predicted seasonal fog or smoke from wildfires. Ongoing research efforts of developing new camera-based visibility detection systems are also discussed.

Keywords visibility detection systems, visibility-related crashes, fog, dust, haze, smoke

1. Introduction

Fog, snow, dust, smoke, and rain can result in a sudden reduction in visibility on roadways leading to an increased risk of crash occurrence. Effect of adverse weather conditions on the operations and safety of transportation is considerably researched these days. According to the Federal Highway Administration (FHWA) (Pisano et al., 2008), weather contributed to more than 24% of the total crashes in the last 14 years from 1995 to 2008 based on the National Highway Traffic Safety Administration (NHTSA) data. This means that adverse weather can easily increase the likelihood of crash occurrence. Several studies, in fact, concluded that crashes increase due to vision obstruction during rainfall by 100% or more (Brodsky & Hakkert, 1988; National Traffic Safety Board [NTSB], 1980), whereas others found more moderate (but still statistically significant) increases (Andreescu & Frost, 1998;

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Andrey & Olley, 1990). Sudden reduction in visibility due to fog and smoke was found to increase severity level of crashes and tend to involve more vehicles. Statistics from the Fatality Analysis Reporting System (FARS) showed that fatal crashes during inclement weather events, that is, rain, snow, fog and smoke, are certainly a major problem that needs to be mitigated. Unsurprisingly, northern states of the United States were found to be more associated with snowy weather whereas southern states were found to be associated with rain, fog, and smoke-related crashes. Inclement weather of rain, snow, and fog/smoke resulted in 31,514 out of 306,135 total fatal crashes (about 10.29%) between 2000 and 2007 in all 50 states, the District of Columbia, and Puerto Rico (National Center for Statistics and Analysis, 2012).

Koetse and Rietveld (2009) addressed the effect of the climate change on transportation in general, whereas others discussed the effect of the particular weather condition on traffic operations, safety, traffic demand, flow and traffic intensity, and operating speeds (Cools et al., 2008; Edwards, 1999; Maze et al., 2006). Driver behavior based on actual and forecasted weather has been studied by Kilpelainen and Summala (2007) that indicated that drivers should be informed locally and more specifically of weather conditions rather than a forecast of the whole region. Ahmed et al. (2012) utilized real-time weather information in risk assessment on freeways and showed that the inclusion of weather information is essential in proactive traffic management systems; their system unlike any other systems has the capability of detecting hazardous traffic patterns on specific roadway segments in real-time using traffic data. They confirmed the conclusion that drivers need to have localized real-time information at the segment level rather than regional level especially during inclement weather, including pavement conditions, visibility level, snowfall, rain, and fog.

All aforementioned facts depict that the problem descends from the inadequacy of traffic control techniques to provide guidance for drivers and the unpredictability of locations and times of reduced visibility on highways. Therefore, the main goal of this review article is to provide an up-to-date synthesis of visibility systems implemented by different states and agencies in the area of traffic safety as well as other areas such as aviation. Also, this research sheds some lights on fixed and mobile visibility detection systems using sensors as well as in-vehicle and roadside systems using video cameras. Various issues of system components development, power sources, and communication are discussed in the following sections.

2. Visibility Detection Systems in the United States

There are two main mitigation strategies to account for reduction in visibility: active and passive systems. Active systems comprise visibility, weather, and traffic detection sensors in combination with driver warning systems, for example, flashing lights, dynamic message signs, and variable speed limit signs. Active systems may be as simple as flashing lights and advisory warning fixed signs to warn motorists that the roadway is susceptible to reduction in visibility due to various weather events or advanced Intelligent Transportation System (ITS) systems providing dynamic advisory messages based on visibility level and traffic flow parameters. Passive systems provide measures to help warn and delineate traffic such as delineators, reflectors, stripping, and so on.

With the help of the Florida Department of Transportation (FDOT) and the U.S. Department of Transportation, information regarding the state of the practice of visibility detection systems in the United States have been collected from the literature and confirmed through an e-mail survey. Eighteen states with visibility detection systems were identified

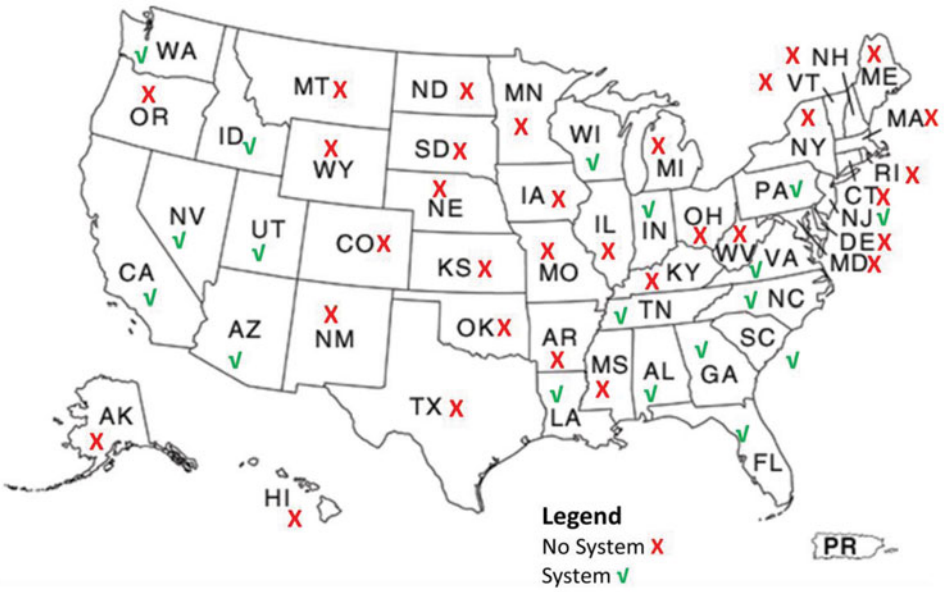

Figure 1. Visibility detection systems in the United States.

as indicated in Figure 1: Alabama, Arizona, California, Florida, Georgia, Idaho, Indiana, Louisiana, Nevada, New Jersey, North Carolina, Pennsylvania, South Carolina, Tennessee, Utah, Virginia, Washington, and Wisconsin. Other states that were identified with no visibility systems are shown as well. Table 1 provides detailed information about systems' components, length, locations, communication, power source, type of system, system cost, and current operating status.

2.1. Components of Active Visibility Detection Systems

Although some of the active visibility detection systems in the United States vary in their management strategies, they share similar basic configurations. The main concept of a successful visibility detection system is the ability of accurately detecting reduction in visibility and sending real-time information to the traffic management center. The acquired real-time data can then be used to enact a response, displaying a warning message via Dynamic Message Signs (DMSs), disseminating advice using Highway Advisory Radio Service (HARS), text messages to road users' cell phones and/or adjust the speed limits via Variable Speed Limit (VSL) signs. Information can also be sent to roadway officials using e-mail, phones, or cell phones.

Visibility detection systems comprise Road Weather Information System (RWIS), Visibility Sensors, Traffic Surveillance, Remote Processing Unit, Communication Devices, Power Source, Dynamic Message Signs, Variable Speed Limits, and Static Message with Flashing Lights signs.

RWIS station utilizes a combination of technologies that use historic and current climatological data. RWIS's main elements are (1) environmental sensors to collect air temperature, amount and type of precipitation, visibility, dew point, relative humidity, and wind speed and direction, surface pavement temperature, surface condition (dry, wet, frozen), amount of deicing chemical; (2) models and advanced processing systems to develop

Table 1
U.S. visibility detection systems

State/ Location	Type/ Length	Visibility Reduction Due to	Visibility Sensors/ Sensors/Weather Stations	Traffic/ Speed Detectors	Warning System	Communications	Power	Management Strategy	Cost
Alabama/I-10 (Mobile)	Fixed/6.2 miles	Fog	6 forward scatter visibility sensors, 25 CCTV	Loop detectors/radars	24 VMSs/5 DMSs	Fiber optics	Power lines	Automatic	$18,000 excluding VMSs and loops/active
Arizona/I-10 (Bowie, Texas Canyon)	Fixed/30 miles	Dual snow and dust (DUST)	ESS, forward scatter visibility sensors, anemometers, CCTV	None	DMSs/ HARS	Wireless ethernet	Solar photovoltaic cells	Manual/partial automatic	Unknown/active
California/Rt. 99/I-5 (San Joaquin Valley)	Fixed/13 miles	Fog	9 Full ESS (Vaisala forward scatter visibility sensors, rain gauges, wind speed and direction, humidity, thermometer, barometer and remote processing unit, CCTV, thermal cameras	Wavetronix SmartSensor HD radars	80 VMSs/9 DMSs/ HARs, Morning Broadcast on Local Radio and TV	Proxim Wireless/Verizon Wireless EVDO modems	40% Solar	Automatic	$3,600,000/Active

Colorado/20 interstates and arterials including (I-25, I-70, I-76, etc.)	Fixed/unknown	Fog and snow	Weather stations, cameras, streaming cameras	RTMS and AVI	6 LED Roadside VMSs, overhead VMSs	Dial-up phone	Power lines	Manual	$275,000/active
Florida/Central Florida I-4	Prototype mobile system/variable	Fog and smog	4 Vaisala forward scatter visibility sensor, cameras	Based on the location	Variable LED DMSs/VSL	XTend Radios/cellular wireless modems	100% solar/car batteries	Fully Automated/Manual Override	$25,000/2 miles/inactive
Georgia/I-75 (Florida border)	Fixed/14 miles	Fog	19 Vaisala Forward Scatter visibility sensors, 5 CCTVs	5 loop detectors	2 LED DMSs	Fiber optics	Unknown	Fully automated	$4,000,000/Active
Idaho/I-84	Fixed/45 miles	Fog	3 visibility forward scatter sensors, weather station, video camera	Automatic traffic counters	VMSs	Unknown	Unknown	Unknown	Unknown/unknown
Indiana/I-69 (Fort Wayne)	Fixed/$\frac{3}{4}$ mile	Snow and white-out conditions	1JayCor 1200 Visibility Sensor	None	LED VMSs	Wireless	Unknown	Automatic	$100,000/inactive

(Continued on next page)

Table 1
U.S. visibility detection systems *(Continued)*

State/ Location	Type/ Length	Visibility Reduction Due to	Visibility Sensors/ Sensors/Weather Stations	Traffic/ Speed Detectors	Warning System	Communications	Power	Management Strategy	Cost
Kentucky/Bridge over Kentucky River	Dismantled fixed/unknown	Fog	7 RWISs, Backscatter Visibility Sensor	None	Static Signs	Unknown	Power Lines	Automatic	Unknown/Inactive
Louisiana	Fixed/unknown	Fog	3 RWISs	Loop detectors	12 VMSs (7 fog, 2 detours, and 3 for ice), 38 VSLs	Fiber optics/dial-up phone	Power lines	Automatic	$2,400,000/Inactive
Maryland/I-68	Fixed/unknown	Fog	2 RWIS, forward scatter visibility sensor, cameras	Unknown	4 ground mounted signs with solar powered Flasher	Unknown	Power lines/solar	Unknown	$375,000/Inactive
Michigan	Dismantled fixed/unknown	Fog	11 RWIS, 1 fog visibility sensor	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown/inactive
Missouri/City of St. Peters	Fixed/unknown	Fog	26 RWIS	None	Static flashing light sign	Unknown	Unknown	Unknown	Unknown/active
Nevada/I-80	Fixed/one location	Fog	1 visibility sensor	None	4 VSLs (2 in each direction)	Unknown	Unknown	Unknown	Unknown/unknown

New Jersey/Route 287	Fixed/Unknown	Fog	RWIS, visibility sensors, rain gauges, wind speed and direction, humidity, thermometer, barometer and remote processing unit, still frame video cameras	Loop detectors	VMSs	Cellular Digital Packaged Data (CDPD) modem	Power lines	Inactive/data collection only	Unknown/active
North Carolina/I-40 (Haywood County)	Fixed/5 miles	Fog	3 Belfort forward scatter visibility sensors	None	2 VMSs	Fiber optics and dial-up connections	Power lines	Automatic	$1,100,000/active
Ohio	Fixed/multiple highway corridors	Fog	172 visibility sensors	Unknown	Unknown	Unknown	Power lines	Inactive	Unknown/inactive
Pennsylvania/Rt. 22 (Crescent Mountain)	Fixed/2 miles	Fog	1 RWIS, CCTV	None	VMSs, Highway Advisory Radio	Fiber optics	Power lines	Manual/upgraded to automatic	$411,010 plus $1,200,000 in up-grades/unknown

(Continued on next page)

Table 1
U.S. visibility detection systems *(Continued)*

State/ Location	Type/ Length	Visibility Reduction Due to	Visibility Sensors/ Sensors/Weather Stations	Traffic/ Speed Detectors	Warning System	Communications	Power	Management Strategy	Cost
South Carolina/I-526	Fixed/7 miles	Fog	5 forward scatter visibility sensors, 8 CCTVs, remote processing unit	Loop detectors	8 DMSs, pavement lights, adjustable street lights	Fiber optics	Power lines	Automatic	$5,000,000/active
Tennessee/I-75 (Calhoun)	Fixed/19 miles	Fog	8 forward scatter visibility sensors, 2 ESS RWIS stations	44 traffic detectors	10 DMSs, 10 VSLs, 2 HAR	Fiber optics/microwave communication	Power lines	Automatic	$4,460,580/active
Utah/I-215 (Salt Lake City)	Fixed/2 miles	Fog	4 forward scatter visibility sensors	6 loop detectors	2 DMSs	Ultra-high frequency radio modems			$461,000/active
Vermont	Fixed/2 miles	Fog	Highway patrol	None	Fixed signs with flashing lights	None	Power lines	Remote dispatch	Unknown/active
Wisconsin/I-43 and US 41 (Green Bay area)	Fixed/2 locations	Fog	Manual	None	Static signs with flashing lights	Dial-up phone	Power lines	Manual	Unknown/active
Wyoming	Fixed/Unknown	Fog and adverse weather	Highway Patrol	Unknown	VSL	None		Manual	Unknown/Active

VMSs = Variable Message Signs; DMSs = Dynamic Message Signs; CCTV = Closed-Circuit Television Camera; HARS = Highway Advisory Radio System; ESS = Environmental Sensor Stations; HD = High Definition; EVDO = Evolution Data Optimized; RTMS = Remote Traffic Microwave Sensor; AVI = Automatic Vehicle Identification, LED = Light-emitting Diode; VSL = Variable Speed Limit; RWISs = Road Weather Information Systems.

forecast and interpret the information into an easily understood format; (3) transmission platforms to send information to DMSs/VMSs and to Traffic Management Centers (TMCs) for decision making. Of these elements, the visibility sensor is the most important component to visibility detection systems. There are two main types of visibility sensors, forward and backward scatter sensors, both sensors can detect the type of precipitation (none, rain, snow, or drizzle); precipitation intensity (light, moderate, or heavy); precipitation rate, liquid equivalent (in actual length per time unit, e.g., ft/h), and measurement of visibility.

Remote traffic surveillance is also an important component that has been used in many states for operational strategies. Close Circuit Television (CCTV), Inductive Loop Detectors (ILD), Infrared Cameras, and Remote Traffic Microwave Sensors (RTMS) are among the most common deployed surveillance systems in the United States. CCTV and still video cameras have been used by many agencies as a visual evidence to confirm current visibility and traffic conditions. Effective measures for traffic management including hazard warnings and speed limit reduction can be developed based on the visibility level that is determined by RWIS or visibility sensors and traffic condition.

All weather and visibility sensors and traffic detection devices connect to a Remote Processing Unit (RPU) that transmits all sensed information to a server located at the TMC. The collected data by the server can be viewed by TMC personnel or can be used directly in an automated management strategy.

These systems' components are either powered by power lines if available on the roadway section such in the states of Alabama, Colorado, New Jersey, Ohio, Pennsylvania, South Carolina, Tennessee, Vermont, and Wisconsin, or fully/partially powered by solar photovoltaic cells such in Arizona, California, and Maryland.

Different types of communication devices are used depending on the location and the availability of phone services. For example, Alabama, Georgia, Pennsylvania, South Carolina, and Tennessee are using fiber optics lines to connect their systems to the TMCs. Dial-up phone owned or leased lines are also used in other states such in Colorado, North Carolina, and Wisconsin. Locations where there is neither fiber optics nor dial-up phone lines, the cellular wireless network is utilized such as in California.

2.2. Management Strategies and Operation

Many agencies in the United States have already deployed automated visibility detection systems, other states are using visibility detection systems, however, they are not fully automated and manual control is still needed. Systems in Alabama, California, Georgia, and Indiana are among the fully automated ones, the type of management strategy is listed for each state in Table 1. It is worth mentioning that other states with no visibility detection systems are still relying on actual observation of reduction in visibility by Highway Patrol.

The basic concept of any management strategy is to assess visibility and traffic conditions over a sample period, after enough samples are read, the threshold set inside the RPU determines if action should be taken. If reduction in visibility was determined, the RPU will transmit all information about the affected roadway location (mile marker), visibility reading in feet, direction, traffic parameters by lane if available, and other information to the TMC for further control/advisory actions. It should be noted that different visibility thresholds are used by different agencies to determine the necessary countermeasure. California has also implemented two fog countermeasures, the highway patrol pacing traffic through the fog section (PACE) program and the Trucks At Rest In Fog (TARIF) program. Louisiana used the single-lane concept on the Lake Ponchartrain Bridge. Table 2 shows the management strategies, control and advisory messages for visibility detection systems for

Table 2
Management strategies

Alabama DOT Low Visibility Warning System Strategies (Goodwin, 2003)

Visibility Distance	Advisories on DMS	Other Strategies
Fewer than 900 feet (274.3 meters)	"FOG WARNING"	Speed limit at 65 mph (104.5 kph)
Less than 660 feet (201.2 meters)	"FOG" alternating with "SLOW, USE LOW BEAMS"	• "55 MPH" (88.4 kph) on VSL signs • "TRUCKS KEEP RIGHT" on DMS
Fewer than 450 feet (137.2 meters)	"FOG" alternating with "SLOW, USE LOW BEAMS"	• "45 MPH" (72.4 kph) on VSL signs • "TRUCKS KEEP RIGHT" on DMS
Fewer than 280 feet (85.3 meters)	"DENSE FOG" alternating with "SLOW, USE LOW BEAMS"	• "35 MPH" (56.3 kph) on VSL signs • "TRUCKS KEEP RIGHT" on DMS • Street lighting extinguished
Fewer than 175 feet (53.3 meters)	I-10 CLOSED, KEEP RIGHT, EXIT 1/2 MILE	Road Closure by Highway Patrol

California DOT Motorist Warning System Messages (Goodwin, 2003)

Conditions	Displayed Message
Average speed between 11 and 35 mph (56.3 kph)	"SLOW TRAFFIC AHEAD"
Average speed less than 11 mph (17.7 kph)	"STOPPED TRAFFIC AHEAD"
Visibility distance between 200 and 500 feet (152.4 meters)	"FOGGY CONDITIONS AHEAD"
Visibility distance less than 200 feet (61.0 meters)	"DENSE FOG AHEAD"
Wind speed greater than 35 mph	"HIGH WIND WARNING"

Florida DOT Prototype Portable System (Abdel-Aty et al., 2010)

Highway Visibility Range	E-mail Title
<20 ft	EMERGENCY: No visibility
<200 ft	URGENT: Extremely low visibility
If visibility is between 200–500 ft	WARNING: Moderate visibility
If visibility is between 500–800 ft	WARNING: Fog or Smoke Conditions affecting visibility
Visibility greater than 800 ft	NORMAL CONDITIONS

South Carolina DOT Low Visibility Warning System Strategies (Goodwin, 2003)

Conditions	Advisory Strategies	Control Strategies
700 to 900 feet (213.4 to 274.3 meters)	"POTENTIAL FOR FOG" and "LIGHT FOG CAUTION" on DMS	"LIGHT FOG TRUCKS 45 MPH" and "TRUCKS KEEP RIGHT" on DMS
450 to 700 feet (137.2 to 213.4 meters)	"FOG CAUTION" and "FOG REDUCE SPEED" on DMS	Pavement lights illuminated "FOG REDUCE SPEED 45 MPH" and "TRUCKS KEEP RIGHT" on DMS
300 to 450 feet (91.4 to 137.2 meters)	"FOG CAUTION" on DMS	Pavement lights illuminated and overhead street lighting extinguished "FOG REDUCE SPEED 35 MPH" and "TRUCKS KEEP RIGHT" on DMS

(Continued on next page)

Table 2
Management strategies *(Continued)*

Alabama DOT Low Visibility Warning System Strategies (Goodwin, 2003)		
Visibility Distance	Advisories on DMS	Other Strategies
Less than 300 feet	N/A	Pavement lights illuminated and overhead street lighting extinguished "DENSE FOG REDUCE SPEED 25 MPH" and "TRUCKS KEEP RIGHT" on DMS If warranted, "PREPARE TO STOP," "I-526 BRIDGE CLOSED AHEAD USE I 26/US 17," and "ALL TRAFFIC MUST EXIT" on DMS

Tennessee Low Visibility Warning (Dahlinger, 2001)	
Visibility Distance	Control Strategies
From 480 feet (146.3 kph) to 1,320 feet	The speed limit is reduced from 65 to 50 mph
From 240 to 480 feet.	The speed limit is lowered to 35 mph (56.3 kph)
Less than 240 feet or 73.2 meters	Road close due to fog

Conditions	Advisories on DMS	Other Strategies
Speed reduced	"CAUTION" alternating with "SLOW TRAFFIC AHEAD"	N/A
Fog detected	"CAUTION" alternating with "FOG AHEAD TURN ON LOW BEAMS"	• "FOG" displayed on VSL signs

Speed limit reduced	"FOG AHEAD" alternating with "ADVISORY RADIO TUNE TO XXXX AM" "FOG AHEAD" alternating with "REDUCE SPEED TURN ON LOW BEAMS" "FOG" alternating with "SPEED LIMIT XX MPH"	• "FOG" & Reduced Speed Limits displayed on VSL signs • HAR messages broadcasted
Roadway closed	"DETOUR AHEAD" alternating with "REDUCE SPEED MERGE RIGHT" "I-75 CLOSED" alternating with "DETOUR" "FOG AHEAD" alternating with "ADVISORY RADIO TUNE TO XXXX AM"	• "FOG" displayed on VSL signs • HAR messages broadcasted • Ramp gates closed

Utah DOT Low Visibility Warning System Messages (Perrin, 2000)

Visibility Conditions	Displayed Messages
656 to 820 feet (200 to 250 meters)	"FOG AHEAD"
492 to 656 feet (150 to 200 meters)	"DENSE FOG" alternating with "ADVISE 50 MPH"
328 to 492 feet (100 to 150 meters)	"DENSE FOG" alternating with "ADVISE 40 MPH"
197 to 328 feet (60 to 100 meters)	"DENSE FOG" alternating with "ADVISE 30 MPH"
Less than 197 feet (60 meters)	"DENSE FOG" alternating with "ADVISE 25 MPH"

DOT = Department of Transportation; DMS = Dynamic Message Sign; VSL = Variable Speed Limit; HAR = Highway Advisory Radio.

different states. Table 3 summarize issues and lessons learned from the implementation of visibility systems at various states.

2.3. Effect on Traffic Safety and Operation

Many states have reported the effectiveness of the deployed visibility detection systems in terms of safety and operation. Alabama's low visibility system was found to be effective in improving safety, reducing average speed, and minimizing crash risk in low visibility condition (Goodwin, 2003). Although the number of days with fog increased after implementing the California low visibility warning system (41 days compared to an average of 26 days), the number of crashes significantly decreased (nine crashes compared to an average of 34) (Berman et al., 2009; Schreiner, 2000). Liang et al. (1998) conducted a study to determine the efficacy of using Idaho Visibility Warning System to warn motorists of inclement weather conditions and to quantify the nature of the speed–visibility relationship. The results indicated that drivers respond to adverse environmental conditions by reducing their speeds by about 5.0 mph during the fog events and approximately 12 mph during the snow events. Also, it was found that the primary factors affecting driver speed were reduced visibility and winds exceeding 25 mph. Goodwin (2003) reported that the South Carolina low visibility warning system improved mobility and safety on I-526. No fog-related crashes have occurred since the system was deployed in 1992. In Tennessee, after deployment of the warning system in 1994, safety improved significantly as only one visibility related crash has occurred due to fog (Dahlinger, 2001; Dahlinger & McCombs, 1995; Tennessee Intelligent Transportation System, 2000). Although a study by Perrin et al. (2002) showed that Utah's visibility warning system failed to reduce mean speed, it succeeded in reducing the variation between vehicle speeds by 22% during reduced visibility conditions.

2.4. Development and Implementation Issues, and Lessons Learned from Different States

Various lessons can be learned from the deployed and or developed visibility systems in the United States. For example, the backscatter fog detectors were proven to provide poor performance especially near water bodies because the reflection from the water's surface can distort visibility readings. Also, manufacturers recommend that backscatter fog detectors should face North to avoid the exposure to direct sun, and hence this will decrease the detection accuracy. In 2000, Alabama Department of Transportation (ADOT) was the first to find out that forward scatter fog detectors might be more suitable for such application on highways. ADOT replaced all backscatter detectors with forward scatter ones; however, concerns about fog detectors' accuracy remained as all fog detectors have a 25% margin of error when it comes to determining visibility distance. This margin of error is considered too great, especially when it comes to lower visibilities.

Although it is better to place the fog detectors as close as possible to the roadway, Tennessee had to move all sensors back off the road by 50 to 60 feet because the rain splash from passing trucks were registering false reduced visibility conditions.

Source of power for the Fog Detection System on I-68 in Maryland was a huge challenge because of the infeasible AC power to operate the radio and warning signs, therefore solar power was used to operate the flashing beacons, radio spectrum, and solar control panel.

Table 3
Implementation issues and lessons learned

State	Issues/ Lessons Learned	System Advantages	Solutions/ Upgrades
Alabama/I-10 (Mobile)	Visibility sensor: Backscatter sensors performed poorly near water bodies or under direct sunlight.	The warning system improved the safety measurement in term of reduction of the average speed of the vehicles and potentially reduced crashes during the low visibility conditions.	Backscatter sensors replaced by forward scatter ones (2000); communication method to point to point system of Ethernets; Radar Vehicle Detection (2008).
California/Rt. 99/I-5 (San Joaquin Valley)	Communication devices: Dial-up lines experience malfunctioning.	Significant reduction in the number of fog related crashes was achieved after the system deployment.	Proxim Wireless/Verizon Wireless EVDO modems, and radar vehicle detectors (2008).
Florida/Central Florida I-4	Communication devices: Connection between the portable detection systems and DMSs has problem due to incompatibility of the radio systems between the two parts.	The system comprised inexpensive and available components and could be installed as either fix or portable system. The system uses car battery as power source.	
Idaho/I-84	System Level: The system has EXTENSIVE technical and reliability problems. Communication devices and power source: In extreme rural areas the communication and power problems were reported.	Special laser/radar visibility sensing system covers larger area.	

(Continued on next page)

Table 3
Implementation issues and lessons learned *(Continued)*

State	Issues/ Lessons Learned	System Advantages	Solutions/ Upgrades
Louisiana/I-10	Communication devices: Fiber optic communications were affected by high water table and the cost could be doubled.		Fiber optic trunk line was laid.
North Carolina/I-40 (Haywood County)	System level: False alerts were generated due to noise, static, or EMI coming down the communication lines to the central office. Communication devices: North Carolina DOT faces difficulties in interfacing software with the VMSs.	Travel speeds decreased by 5 to 10 mph when weather-related signal timing was utilized.	
South Carolina/I-526	System Level: SCDOT paid more than expected for maintenance cost. Electronic components: The electronic devices were affected by humid and hot weather; Microwave communication system was struck by lightning.	No major accidents and fatalities due to fog were reported after the system deployment.	Fiber optic relays were installed in replacement of the microwave communication system. Air conditioning unit was installed in the cabinet where electronics were stored.
Tennessee/I-75 (Calhoun)	Visibility sensor: Rain splash from passing trucks led to false reduced visibility conditions.	The system is able to decrease the speed limit from 55 mph to 35 mph as fog density starts to increase.	The visibility sensors were moved back off the road by 50 to 60 feet.
Utah/I-215 (Salt Lake City)	System level: The system failed to reduce mean speed.	Reduction in speed variability was achieved among vehicles driving in foggy conditions.	

EVDO = Evolution Data Optimized; DMSs = Dynamic Message Signs; EMI = Electromagnetic Interference; DOT = Department of Transportation; VMSs = Variable Message Signs.

The Laser Detection and Ranging (LIDAR) system consists of a special laser/radar visibility sensing system that covers a larger area was tested by Idaho Department of Transportation (IDT). The LIDAR system was not considered in their final system due to extensive technical and reliability problems (Schreiner, 2000).

Problems with the system's communications have been reported by Caltrans in California: the system used dial-up lines to notify the TMC of reduction in visibility that are maintained by a local phone company, the dial-up lines malfunctioned multiple times, the system was upgraded in 2008 and utilized Proxim wireless devices to communicate between different components along the 13-mile corridor, the main backhaul communication to the TMC was performed via Verizon Wireless Evolution Data Optimized (EVDO) modems. The main reason of using all wireless communication systems was due to the rural nature of the project area and the instability of dedicated wire-line communications.

Communication and power problems were reported by IDT because of poor power and phone lines in extreme rural areas. High water table could be a challenge and may double the cost of fiber optics communications as reported by Louisiana DOT. Alabama DOT had a major upgrade to their system in 2008 when they changed the communication system to a point to point of Ethernet. North Carolina DOT reported some difficulties in interfacing software with the VMSs.

Also, University of Central Florida and FDOT faced challenges connecting their portable detection systems with the DMSs due to incompatibility in the interface between the implemented XTEND 900 MHz radio they used and the radio system in the DMSs.

Hot weather and humid environment could be a problem for electronic components; South Carolina DOT SCDOT had to install an air conditioning unit in the cabinet where the electronics were stored because of the extreme heat inside. Also, the microwave communication system was replaced with fiber optics because it was struck by lightning. SCDOT paid more than expected for maintenance cost to clean the lighted markers and the fog detectors once a month (Goodwin, 2003).

It is worth mentioning that the DOTs and transportation agencies sometimes upgrade their systems because of the availability and affordability of newer technologies. During the last decade, new nonintrusive detection devices were deployed as alternatives to ILDs, such as video, microwave, and laser radar; passive infrared; and ultrasonic and acoustic sensors. Nowadays, nonintrusive detection devices have improved in terms of accuracy, cost, and ease of use. Installation and maintenance are relatively easy than the loop detectors because the nonintrusive detection devices can be mounted above or alongside the roadway and hence enhance and increase reliability. Although the inductive loops are expected to continue to function for several years, many transportation agencies seem to be shifting attention to nonintrusive alternatives, for example, Alabama DOT in 2008 upgraded their fog system by installing Radar Vehicle Detection every third mile of the roadway.

Caltrans is going to enhance the performance of their system through utilization of latest technology such as colored Matrix VMS, full RWIS, thermal cameras, pulsing in-pavement, and the integration of incident detection system (Berman et al., 2009).

2.5. Fixed vs. Mobile Systems

Site selection to install a visibility detection system depends on historical crash and meteorological records, however, when location can vary such as in cases of wild fires, mobile systems could be a substantial alternative. In 2010, the researchers at University of Central Florida (UCF) developed an Early Detection System for Reduced Visibility. This system can detect any reduction in visibility below certain acceptable levels and respond accordingly in

real time to convey specific warning messages to drivers in an effective way and report this information to the appropriate TMC. The innovation in this system is that it was developed from components that are inexpensive and available commercially. Also, this system can be employed as a portable or fixed system. A fixed system might be useful in areas that tend to have dense fog (e.g., rural sections of freeways). However, the portable system can be used every time a wildfire occurs close to a highway. Furthermore, the system uses radio and cellular communications and can be powered using regular car batteries so it does not depend on power lines that make it more suitable for rural areas. Although a preliminary testing was conducted to test the performance of the different system components, a field study is necessary to reach a final conclusion about the effectiveness of the system in real fog and/or smoke conditions.

3. Passive Visibility Detection Systems

As mentioned earlier that there are several passive systems that are implemented in the United States, Connecticut has static signs located on the approach to certain fog-prone bridges. Maine, Massachusetts, Mississippi, Montana, and Wisconsin also have static signs to warn motorists that they are entering a fog area. Missouri implemented a static flashing light sign warning drivers of fog, the sign flashes continuously. Vermont has a fixed sign with flashing lights warning drivers to reduce speed during fog or snow that is activated by remote dispatch. West Virginia DOT has installed fog delineators on US 19.

4. Active Visibility Detection Systems in Europe

In 1990, an automatic fog warning system was designed by the Traffic Control and Communications Division of the Department of Transport, London. This system was installed on the M25 London orbital motorway to warn drivers about formation of fog by displaying a "Fog" legend on roadside matrix signals. The Transport Research Laboratory (TRL), United Kingdom, evaluated the effectiveness of the system in reducing the variation in vehicles' speeds during inclement visibility conditions due to fog. The results indicated that there is about a 1.8 mph reduction in mean vehicle speeds when the signals are switched on based on data measured from six test sites. The speed reductions indicated that drivers are alerted to the presence of fog ahead together with a credible automatic system means that drivers are more likely to respond more quickly to the hazard itself. Control office staff are notified of the presence of fog but are relieved of the difficult task of operating motorway signals in response to fog whose density and location is likely to be continuously changing (Cooper & Sawyer, 1993; MacCarley, 1999).

The Austrian Motorway Administration (ASFINAG) is considered one of the leading agencies to equip a large portion of their motorway network with an advanced traffic management system (Intelligent Line Control System) that combines variable speed limits for congestion, incident detection and warning system, and weather information (i.e., black ice, fog, etc.). Moreover, to prevent mass pile-ups as a result of quickly developed thick fog, a pilot fog warning system was installed on the A1 West motorway in the area around the Upper Austrian lakes. Five visibility sensors were installed in each direction on a 6.2-mile section (one sensor every 0.62 mile). In addition to the variable speed limits based on visibility levels, a further measure to reduce fog-related crashes was the introduction of fog reflectors. The fog-prone roadway sections were equipped with fog reflectors to delineate the roadway edges for better visibility. These sections were selected by motorway

organizations, meteorologists and operating personnel. The system was proven to reduce 19% of injuries and up to 25% of fatal crashes based on 3-year crash data.

The Dutch Ministry of Transport implemented an automatic fog warning system to elicit safer driving behavior during adverse visibility conditions along 12-km (7.4 mile) section of the A16 Motorway in the Netherlands. The system consists of 20 visibility sensors to continuously measure the visibility range. This system warns drivers of reduced visibility due to fog by displaying an explicit fog warning on overhead matrix signs together with a maximum speed limit that depends on the actual measured visibility distance. Hogema and Horst (1997) evaluated the Dutch fog warning system in terms of driving behavior for a period of more than 2 years after implementing the system. Using inductive loop detectors at six locations (four experimental and two control locations), continuous traffic measurements for individual vehicles were obtained. Data on the local visibility conditions and on the messages displayed on the matrix signs were available on a 1-minute basis. The results showed that the system has a positive effect on speed choice in fog as it resulted in an additional decrease of speed of about (4.9–6.2 mph) on top of a lower mean speed caused by the reduced visibility (Hogema & Horst). For A16 in the Netherlands, the displayed speed limits are based on the visibility conditions captured by 20 visibility sensors along the road. If the visibility drops below 140 m (456 ft), then the speed limit would drop to 80 km/h (49 mph). If visibility drops below 70 m (228 ft), the speed limit drops to 60 km/h (37 mph). Besides, if an incident is detected, 50 km/h (31 mph) on the first sign upstream and 70 km/h (43 mph) on second sign upstream will be displayed.

The effects of weather-controlled speed limits and signs for slippery road conditions on driver behavior on the Finish E18 were examined (Rama & Luoma, 1999). Weather and roadway conditions were automatically monitored by two RWIS stations. Variable speed limits were utilized during adverse weather and road conditions, and in some cases signs for slippery road conditions were displayed as well. Speed and headway data were obtained from loop detectors. The results showed that the weather-controlled system decreased the mean speed and the standard deviation of speeds and increased the homogeneity of driver behavior especially during adverse weather conditions.

5. Visibility Detection Systems in Aviation, Maritime, and Railway

It is worth to mention that visibility is a vital component not only in road transportation but also in other transportation modes, such as aviation, maritime, and rail. In modern aviation, visibility detection is core to the management and operation of airports. Automated airport weather stations are designed to serve weatherforecasting. Three major automated weather detection systems are in application, namely are the Automated Weather Observing System (AWOS), Automated Surface Observing System (ASOS), and Automated Weather Sensor System (AWSS) (Federal Aviation Administration, 2013). All of these systems are equipped with similar forward scatter visibility sensors to provide visibility information. The principle for visibility measurement behind the sensors is determining the amount of light scattered by particles in the air that passes through the optical sample volume. The airport visibility sensors are not made to distinguish between finer gradations of fog, and hence the margin of error might be quite large in highway applications.

Visibility is also a major concern for maritime traffic. National Oceanic and Atmospheric Administration (NOAA) and State Port Authorities are working together to identify locations susceptible to heavy fog. Recently, multiple visibility stations were installed at the U.S. ports, for example, Mobile Bay in Alabama. Maritime uses forward scatter visibility sensors similar to those used in aviation (NOAA, n.d.).

Inclement and foggy weather conditions exert a major impact on railroads; precipitation and fog lead to decreased visibility of signals. Railway systems utilize different measures that are not applicable to highways to overcome the reduction in visibility such as laser signaling systems, radio frequency (RF) signaling systems, positive train control (PTC) technology, electronically controlled brakes, intelligent grade crossings, automatic equipment identification, and automated scheduling systems (Rossetti, 2007).

6. Roadwayside and In-Vehicle Camera-Based Visibility Detection Systems

Optical transmission and scattering techniques are prevalent visibility detection methods nowadays. Scattering sensors are widely employed at airports and weather stations. These instruments are expensive for installation; however they are relatively accurate in adverse weather and can handle the night visibility. Recent years have also seen a trend in researches exploring the feasibility of utilizing cameras as road visibility detecting tools. Roadside cameras have long been a vital component in the ITS, and their number is still growing. In-vehicle cameras, though not currently common, appeal to researchers due to the superior mobility. The commonly used roadside cameras and the promising in-vehicle cameras, if utilized for visibility detection, can have a major impact on traffic safety at a marginal cost.

The basic issue with camera-based visibility detection is that images compress the road and environmental information from a 3-D space to a two dimensional space. As a result, the depth information is lost. To obtain visibility distance from images, researchers made tremendous effort in restoring the depth information through image processing and developing visibility distance algorithms. For roadside cameras, edge detection is normally conducted to keep the necessary information for visibility calculation. Wavelet algorithm (Busch & Debes, 1998), Sobel edge detection (Babari et al., 2011, 2012; Bäumer et al., 2008; Chen et al., 2009; Hallowell et al., 2007; Kwon, 1998), and Canny edge detection (An et al., 2010; Hautière, Labayrade, et al., 2006) are most commonly applied.

For onboard cameras, because of the always-changing background, researchers used numerous approaches to reconstruct a 3-D road surface in their studies (Hautière, Labayrade, et al., 2006; Pomerleau, 1997). Kidono and Ninomiya (2007) instead of doing the image processing used a multiband camera and took advantage of the difference between wavelength bands. Visibility distance algorithms do not vary due to the camera location. Two general approaches are often seen: the first is to detect a selected object at the maximum distance based on the definition of visibility, the second method correlates the contrast in the scene with the visual range estimated by additional reference sensors, and a learning phase is necessary (Babari et al., 2011). Several studies were conducted around the world following the two approaches. The first approach was researched in China (An et al., 2010; Chen et al., 2009), France (Boussard et al., 2008; Hautière et al., 2008; Hautièr, Labayrade, et al., 2006; Hautière, Tarel, et al., 2006;), Germany (Bäumer et al., 2008; Busch and Debes, 1998), Japan (Kidono & Ninomiya, 2007), and the United States (Hallowell et al., 2007, Xie et al., 2008), whereas the second one was researched in France (Busch et al., 1998, Babari et al., 2012), Japan (Hagiwara et al., 2006), and the US (Hallowell et al., 2007; Xie et al., 2008).

Koschmieder's and Duntley's equations (Middleton, 1952) are normally adopted by the first approach. With the development of machine learning techniques, some detection methods involving a reference and a learning phase are raised.

Encouraging as it may be, camera-based visibility still have to cope with some challenging difficulties. As mentioned above, visibility detection during adverse weather is

crucial. The existing studies have successfully dealt with daytime fog visibility; however, visibility at night and in glare are not sufficiently addressed and are much more difficult for evaluation. Night visibility detection requires constant light source but easily interfered by the headlight of passing vehicles. Kwon (1998) developed a diffusion model that fitted into the image well. Kidono and Ninomiya's (2007) multiband camera also offered a solution for night-time visibility determination. The source of glare is often the sun or the vehicles' headlights. When the camera looks toward the sun, aperture is automatically decreased (Bäumer et al., 2008). Visibility detected in glare by camera will then be low (Pomerleau, 1997). A camera with back light compensation feature can minimize the impact by glare (Kwon, 1998).

7. Conclusion

The information relevant to driving is predominantly visual (Sivak, 1996). Reduction of visibility poses serious safety hazard for drivers. Adverse weather conditions like fog, smoke, haze, or rain and snow can all deteriorate the visibility. This synthesis study is intended to provide a review of current transportation agencies practices of visibility detection systems and ongoing research efforts of developing new visibility detection systems. Information used in this study was acquired through a review of the literature and email communications with the states' DOTs with the help of USDOT and FDOT.

To prevent pile-up crashes during limited visibility, countermeasures are needed that ensure drivers proceed through adverse weather conditions at uniform reduced speed. A comprehensive limited-visibility countermeasure system should include visibility sensors and traffic flow detectors that automatically activate traffic control and provide advisory and warning messages. The credibility of visibility detection and warning systems is essential to ensure the drivers' compliance with the system. Although visibility detection systems in the United States share similar basic configurations, that is, components, power sources, communications, and so on, they vary in their management strategies. The disparity among states could cause driver confusion and result in nonhomogeneous driver response.

Measures to reduce fog-related crashes in different states have demonstrated that morning broadcast on radio and TV were successful in increasing public awareness (Goodwin, 2003). Other means of informing the drivers about reduction in visibility in real-time are the use of bulb matrix displays of the portable CMSs and LED DMSs that are visible even during dense fog, the use of the portable HARs, which can provide additional information to motorists, the use of highway patrol PACE units such as in California, and the single-lane concept on the Lake Pontchartrain Bridge in Louisiana.

There is a major focus on the development of new visibility detection systems from existing affordable technologies such as roadway side cameras. Camera-based visibility detection is still in its infancy stage. Image processing and algorithm construction are the focus points. Different types of weather can result in different requirements for the visibility detection system. Nevertheless, the idea of a low-cost and mobile real-time camera-based visibility detection system is so appealing that we will surely see more novel and advanced techniques and models in the future.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research in the area of utilizing new technologies for visibility detection systems continues, new knowledge should be added.

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References

Abdel-Aty, M., Oloufa, A., Hassan, H., Ahmed, M., Siddiqui, C., & Morrow R. (2010). *Portable visibility warning system for the safety of highways*. Paper presented at the 17th ITS World Congress, Busan, Korea.

Ahmed, M., Abdel-Aty, M., & Yu, R. (2012). Assessment of the interaction between crash occurrence, mountainous freeway geometry, real-time weather and AVI traffic data. *Journal of the Transportation Research Board*, *2280*, 51–59.

An, M., Guo, Z., Li, J., & Zhou, T. (2010). Visibility detection based on traffic camera imagery. In *3rd International Conference on Proceedings of the Information Sciences and Interaction Sciences (ICIS)*, Chengdu, China (pp. 411–414).

Andreescu, P., & Frost, D. (1998). Weather and traffic accidents in Montreal, Canada. *Climate Research*, *9*(3), 225–230.

Andrey, J., & Olley, R. (1990). Relationships between weather and road safety, past and future directions. *Climatology Bulletin*, *24*(3), 123–137.

Babari, R., Hautière, N., Dumont, É., Brémond, R., & Paparoditis, N. (2011). A model-driven approach to estimate atmospheric visibility with ordinary cameras. *Atmospheric Environment*,*45*(30), 5316–5324.

Babari, R., Hautière, N., Dumont, É., Paparoditis, N., & Misener, J. (2012). Visibility monitoring using conventional roadside cameras–emerging applications. *Transportation Research Part C: Emerging Technologies*, *22*, 17–28.

Berman, M., Liu, J., & Justison, L. (2009). Caltrans fog detection and warning systems. ICX Technology. Retrieved from http://gs.flir.com/uploads/file/white-papers/caltrans%20fog%20detection%20and%20warning%20system.pdf.

Bäumer, D., Versick, S., & Vogel, B. (2008). Determination of the visibility using a digital panorama camera. *Atmospheric Environment*, *42*(11), 2593–2602.

Boussard, C., Hautiere, N., & D'andrea-Novel, B. (2008). Vehicle dynamics estimation for camera-based visibility distance estimation. In *IEEE/RSJ International Conference on Proceedings of Intelligent Robots and Systems*, Nice, France (pp. 600–605).

Brodsky, H., & Hakkert, S. (1988). Risk of a road accident in rainy weather. *Accident Analysis and Prevention*, *20*(2), 161–176.

Busch, C., & Debes, E., (1998). Wavelet transform for analyzing fog visibility. *Intelligent Systems and their Applications*, *13*(6), 66–71.

Chen, Z., Li, J., & Chen, Q. (2009). Real-time video detection of road visibility conditions. In *WRI World Congress on Proceedings of the Computer Science and Information Engineering*, Los Angeles, CA, USA (pp. 472–476).

Cools, M., Moons, E., & Wets, G. (2008). Assessing the impact of weather on traffic intensity. In *Proceedings of the 87th annual meeting of the Transportation Research Board [CD-ROM]*. Washington, DC: Transportation Research Board of the National Academies.

Cooper, B., & Sawyer, H. (1993). *Assessment of M25 Automatic Fog-Warning System - Final report* (TRL Project Report, Issue Number: PR 16, IRRD Document Number: 858269). Old Wokingham Road, Crowthorne, UK: Transport Research Laboratory, 6.

Dahlinger, D. (2001, May). Tennessee fog detection and warning system: Public works. Paper presented at the *Southern Rural Transportation Workshop*, Orangeburg, SC, USA.

Dahlinger, D., & McCombs, B. (1995, December). Fog warning system provides a safety net for motorist. *Public Works*, Tennessee Department of Transportation, Nashville, Tennessee, *126*(13), 36–37.

Edwards, J. B. (1999). Speed adjustment of motorway commuter traffic to inclement weather. *Transportation Research Part F, 2*(1), 1–14.

Federal Aviation Administration. (2013). Air Traffic Organization Policy. Retrieved from http://www.faa.gov/air_traffic/

Goodwin, L. (2003, May). *Best practices for road weather management, Version 2.0* (Report no. FHWA-OP-03-081). Washington, DC: US Department of Transportation.

Hagiwara, T., Ota, Y., Kaneda, Y., Nagata, Y., & Araki, K. (2006). Method of processing closed-circuit television digital images for poor visibility identification. *Transportation Research Record: Journal of the Transportation Research Board*, *1973*(1), 95–104.

Hallowell, R., Matthews, M., & Pisano, P. (2007). An automated visibility detection algorithm utilizing camera imagery. In 23rd Conference on IIPS, Washinton, DC. Retrieved from https://ams.confex.com/ams/87ANNUAL/techprogram/paper_120107.htm.

Hautière, N., Bigorgne, E., & Aubert, D. (2008). Daytime visibility range monitoring through use of a roadside camera. In *IEEE Intelligent Vehicles Symposium*. Eindhoven, The Netherlands: IEEE (pp. 470–475).

Hautière, N., Labayrade, R., & Aubert, D. (2006). Real-time disparity contrast combination for onboard estimation of the visibility distance. *IEEE Transactions on Intelligent Transportation Systems*, *7*(2), 201–212.

Hautière, N., Tarel, J. P., Lavenant, J., & Aubert, D. (2006). Automatic fog detection and estimation of visibility distance through use of an onboard camera. *Machine Vision and Applications*, *17*(1), 8–20.

Hogema, J., & Horst, R. (1997). Evaluation of A16 Motorway Fog-Signaling System with respect to driving behavior. *Journal of Transportation Research Board*, *1573*, 63–67.

Kidono, K., & Ninomiya, Y. (2007). Visibility estimation under night-time conditions using a multiband camera. In *IEEE Intelligent Vehicles Symposium*. Istanbul, Turkey: IEEE. (pp. 1013–1018).

Kilpelainen, M., & Summala, H. (2007). Effects of weather and weather forecasts on driver behavior. *Transportation Research Part F, 10*(4), 288–299.

Koetse, M. J., & Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D, 14*(3), 205–221.

Kwon, T. (1998). *An automatic visibility measurement system based on video cameras* (Publ. MN/RC-1998–25). St. Paul, MN: Minnesota Department of Transportation.

Liang, W., Kitchener, F., Kyte, M., & Shannon, P. (1998, January). The effect of environmental factors on driver speed: A case study. Paper presented at Transportation Research Board, 77th Annual Meeting, Washington, DC.

MacCarley, A. (1999, August). *Evaluation of Caltrans District 10 Automated Warning System, year two progress report, California PATH research report* (UCB-ITS-PRR-99–28). San Luis Obispo, CA: California Polytechnic State University.

Maze, H. T., Agarwal, M., & Burchett, G. (2006). Whether weather matters to traffic demand, traffic safety, and traffic operations and flow. *Transportation Research Record 1948*, 70–176.

Middleton, W. (1952). Vision Through the Atmosphere. Toronto, Canada: University of Toronto.

National Center for Statistics and Analysis (NCSA). (2012). *Data Resource Website, Fatality Analysis Reporting System, NHTSA*. Retrieved from http://www-fars.nhtsa.dot.gov/Main/index.aspx (accessed August 2012).

National Traffic Safety Board. (1980), *Fatal highway accidents on wet pavement—The magnitude location and characteristics* (NTIS. HTSB-HSS-80–1). Springfield, VA: National Technical Information Service.

National Oceanic and Atmospheric Administration. (n.d.). *NOAA adds wave, visibility data to PORTS® Navigational Data System*. Retrieved from http://oceanservice.noaa.gov/news/weeklynews/nov10/ports-news.html

Perrin, J. (2000, August). Effects of variable speed limit signs on driver behavior during inclement weather. Paper presented at Institute of Transportation Engineers (ITE) Annual Meeting, Salt Lake City, Utah.

Perrin, J., Martin, P., & Coleman B. (2002). *Testing the Adverse Visibility Information System Evaluation (ADVISE) – Safer driving in fog* (Paper no. 02-3140, 2002). Paper presented at Annual meeting of the Transportation Research Board, Washington, DC.

Pisano, P. A., Goodwin, L., & Rossetti, M. A. (2008, January). *U.S. highway crashes in adverse road weather conditions*. Paper presented at the 24th Conference on International Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology, New Orleans, LA.

Pomerleau, D. (1997). *Visibility estimation from a moving vehicle using the Ralph Vision System*. In IEEE Conference on Intelligent Transportation System. Boston, MA: IEEE. (pp. 906–911).

Rama, P., & Luoma, J. (1999). Effects of weather-controlled variable speed limits and warning signs on driver behavior. *Transportation Research Record*, *1689*, 99–0146.

Rossetti, M. (2007). *Analysis of weather events on U.S railroads*. Cambridge, MA: Volpe National Transportation Systems Center.

Schreiner, C. (2000, October). State of the practice and review of the literature: Survey of fog countermeasures planned or in use by other states. Charlottesville, VA: Virginia Tech Research Council.

Sivak, M. (1996). The information that drivers use: Is it indeed 90% visual? *Perception*, *25*(9), 1081–1089.

Tennessee Intelligent Transportation System (2000, October). *Fog project on I-75 between Chattanooga and Knoxville*. Retrieved from www.its.dot.gov/staterpt/tn.htm

Xie, L., Chiu, A., & Newsam, S. (2008). Estimating atmospheric visibility using general-purpose cameras. *Advances in Visual Computing*, *5359*, 56–367.