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Environmental Sensor Systems for Safe Traffic Operations

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report will be of interest to traffic engineers and administrators responsible for development and operation of systems to warn motorists of adverse environmental conditions such as icy roads, strong crosswinds, and fog ahead. The report presents the functional requirements for each of the various types of sensors and then compares the requirements with known commercial environmental sensors.

Because of the lack of information on visibility sensors, laboratory and field tests were conducted on sensors that were supplied by the manufacturers on I-35 near Duluth, Minnesota. A video camera was also installed at the field test site as a possible visibility sensor. A visibility sensor was also mounted on a highway vehicle to see if it could be used as a probe for measuring visibility as it traveled down the roadway.

Two copies of this report are being sent to each Region, and six copies are being sent to each Division office. At least four of the copies sent to the Division should be sent to the State highway agency by the Division office.

Acting Director, Office of
Safety and Traffic Operations
Research and Development

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16. Abstract

This report provides the results of a detailed investigation of environmental sensors and their applicability in highway operations. It describes the functional requirements for a weather condition detection device to be applied to the roadway infrastructure based upon current guidelines of various State and Federal agencies.

The report also analyzes the results of a year-long series of field tests of visibility sensors. A group of five stationary and one mobile sensor were examined to determine the applicability of the data reported by these devices. Among the areas of focus was the accuracy of the reported visibility to the actual conditions, time to respond to visibility changes, and the robustment of the systems.

The results of the test appear to indicate that these devices have definite possibilities for future deployment, particularly in conjunction with ITS technologies.

This report is intended for use by those organizations with interest in transportation and safety-related issues.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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CHAPTER 1. INTRODUCTION

This document forms the final report for the Federal Highway Administration (FHWA) study, "Environmental Sensor Systems for Safe Traffic Operations." It provides a detailed assessment of the functional requirements for environmental sensors in highway applications, as well as examining the state-of-the-art in sensing systems. It goes on to discuss the results of a year-long series of field tests of visibility sensors currently in use or prototypes ready for deployment.

Adverse weather and other harsh environmental features are common throughout the United States, due to the country's vast size and diverse range of geographic characteristics. Severe winter weather, involving ice, snow, and hail, occurs throughout the northern and central States and in mountainous areas of the southern regions. Dust storms are experienced in arid zones, while rain, fog, and strong winds are common across much of the country. The impact of these conditions on highway users is considerable, with loss of mobility and reduced safety. Statistical analyses have shown that a disproportionate number of accidents and fatalities occur under adverse environmental conditions. It has been estimated that between 25 and 35 percent of all interurban accidents occur during adverse weather conditions, with the risk of accidents increasing during bad weather by a factor of between 2 and 5.(1)

The most important meteorological parameters which affect drivers and their safety are rainfall, snow, ice, fog, and wind. The effects of these conditions are worsened when they occur in combination or during darkness. Whatever the environmental cause or combination of causes, the effects on traffic can generally be categorized in three areas. These are reduced:

- Surface friction, causing steering and braking difficulties.
- Visibility, often leading to drivers traveling at unsafe speeds with insufficient visible emergency braking distance.
- Stability, creating potential vehicle rollover problems or hazards associated with specific roadway structures.

There is a significant need for real-time, accurate data on environmental conditions that may adversely affect traffic. This demand has led to the development of sensors and systems to collect data on characteristics such as pavement temperature and chemical composition; air temperature and humidity; wind velocity and direction; visibility; and precipitation. A detailed examination of typical systems is presented in this report.

Roadside or in-pavement environmental sensors can be used to provide transportation agencies with data on current environmental conditions or provide information for dissemination to travelers in the affected areas. Advance warnings of hazardous conditions permit drivers to reroute, delay their trip, or travel by an alternative mode. Transportation agencies can utilize the information to initiate winter maintenance measures such as sanding or plowing activities. Rapid response of appropriate measures can potentially save lives, as well as retain mobility.

Current users of environmental data identify a very real need for reliable, accurate, and affordable sensor systems. However, perhaps the greatest potential for such sensors lies within their integration into intelligent vehicle-highway systems (IVHS) scenarios. IVHS represents the application of computer processors, communications, and other advanced technologies to improve highway transportation. A key requirement for almost all IVHS concepts is accurate, real-time data on which to base control decisions and information dissemination. Applications of environmental systems in IVHS can already be envisioned through examining current technology research and development efforts in the United States and Europe.

Following this introduction, chapter 2 provides a review of environmental monitoring activities based on literature reviews, an analysis of State activities, and site visits. Chapter 3 investigates the adverse environmental characteristics themselves through consideration of basic meteorological principles, the frequency and severity of adverse weather, and detailed examination of a case study area.

Chapter 4 presents an analysis of the impact of adverse weather on the driving function, including a safety assessment. It also defines the needs of users from a driver perspective and examines the requirements of State agencies for environmental monitoring. This information is used in chapter 5 to prepare a list of functional requirements for sensor systems, in terms of performance criteria, parameters to be measured, location of sensors, data output, and operation and control.

A review of commercial systems is described in chapter 6. This addresses the basic operating principles of the major systems, as well as describing a broad range of currently-available systems. Chapter 7 follows by reviewing research and development initiatives into systems to detect adverse weather conditions, including the use of vehicles as probes for monitoring. The review is split into United States, European, and worldwide developments.

Chapter 8 considers the functional requirements against the current technologies to identify the present limitations or omissions.

Chapter 9 presents a brief profile of each sensor examined as part of the study and the method of visibility detection each sensor employs. Chapter 10 discusses the methodology utilized for testing the sensors. The approach methods utilized for both the functional tests and the real-world tests are presented along with a description of the data collection procedures for the course of the test period. The results of the functional tests are noted and summarized in chapter 11.

The approaches used in the analysis of the real-world data are described in chapter 12. These descriptions include all aspects of the evaluation process. Building on chapter 12, chapter 13 presents the results gained from analysis of the real-world test data. The descriptions include the significance of the results and highlights other factors of interest.

Chapter 14 involves a review of a mobile visibility sensor and results gathered from a field test of the device. Included in this examination is a discussion of the applicability of mobile sensors for use as a possible permanent vehicle-mounted unit. Chapter 15 presents the findings of the investigation of the potential for computer algorithms to discern low-visibility from video images collected during the test period.

Conclusions drawn from the detailed sensor investigation as well as the functional and real-world tests are presented in chapter 16. Results drawn from the mobile sensor examination and the prototype sensor are also discussed.

CHAPTER 2. ENVIRONMENTAL MONITORING ACTIVITIES

LITERATURE REVIEW

The use of environmental monitoring sensors to provide real-time weather information for highway applications has been the topic of numerous studies and demonstrations throughout the United States and Europe. In the early- and mid-1970's, several environmental monitoring systems became commercially available. State and Federal agencies initiated demonstration projects to assess the utility of these technologies for State and municipal transportation applications. These early demonstrations reported a limited degree of success. It was determined that, while the implementation of these technologies could be a valuable tool in improving highway safety and reducing highway maintenance costs, the available technology did not provide the accuracy and reliability to warrant mass deployment.(2)

Although these demonstrations did not lead to widespread use of environmental sensors, many important issues regarding performance criteria and motorist behavior were addressed. The obvious benefits to be gained by successful deployments of sensor technologies, and more clearly-defined criteria for environmental detection sensors, led to further research and development. The advances in sensor and communication technologies over the past few years have brought about a resurgence of interest by State and municipal agencies to deploy environmental sensors for early detection of adverse weather conditions for winter treatment and travel advisories. The renewed interest has led to a demand for an assessment of available technologies and user applications.(3)

In the 1970's, studies focused primarily on assessing the functionality of the sensor technology and defining the transportation needs for these technologies. FHWA sponsored several research initiatives to evaluate these characteristics. These studies included:

- An assessment of highway ice detection.
- An assessment of detection and preferential icing on bridges using traffic and meteorological data.
- An assessment of a microwave radiometer for highway ice detection.
- An assessment of snow/ice detection weather systems.
- A feasibility study of snow/ice detection and warning systems.
- An assessment of visibility restrictions in fog.

Each of these studies helped define the limitations and utility of remote highway surface monitoring technologies. In the study of highway ice detection, it was determined that the existing structure of the sensors was not suitable for highway applications because the sensors were easily damaged by snowplow blades, deicing chemicals, and heavy trucks. The study of

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traffic and meteorological data assessed the utility of these data in determining ice formations. Although the detection messages received were not very reliable, it was determined that this information could be used in conjunction with other detection techniques for improved reliability.(4)

The study of a prototype microwave radiometer for snow and ice detection found that the technique was promising and made specific recommendations for improved coverage and alarm protocol.(5) The study of snow and ice detection warning systems assessed the behavioral responses of motorists to these warnings. Results indicated that motorists responded well to these warnings.(6) The feasibility study of these warning systems examined the overall functional requirements of these technologies for travel information applications.

The study of visibility restrictions in fog indicates that the formation of fog is a relatively rare occurrence and is difficult to predict. However, in certain areas of industrial activity and geographic topography, the occurrence of fog is much more predictable. The study concluded that chemical methods of dissipating fog would be ineffective because the duration of fog is relatively short and the startup time and standby maintenance expense make it impractical for most instances of fog. The study also concluded that the most effective safety measure in fog conditions is variable message signs that warn drivers of fog ahead and of desirable operating speeds.(7)

In 1978, the Oregon Department of Transportation conducted a study to examine the effects of speed advisory information in reduced visibility conditions. The study examined the effects of various speed and message advisory information on traffic flow in fog conditions. The study concluded that signing was more important prior to fog than well into the fog. The study indicated that the use of speed differentials on signing prior to the fog and the use of flashing lights generally yielded lower speeds and smoother deceleration profiles into the fog. The study also noted that additional information such as "no stopping" or "maintain 15 mph in fog" also had a positive impact on speed profiles.(8)

Additional studies of environmental sensor systems by State agencies were aimed at utilizing environmental detection in specific locations that were subject to frequent, adverse weather formations. These studies addressed specific State needs and served to provide the agencies with an indication of possible applications in State services. In most instances, these sensor deployments did not provide the necessary accuracy or reliability to automate State services. Many States found the sensors of limited use. The sensors' indication of probable road hazards, however, helped State maintenance crews to prioritize verification procedures to better initiate winter treatment and hazard advisories. State agencies perceived the benefits of a more reliable system despite the limited utility of the sensor technology at the time.

Similarly, in Europe the potential benefits to be obtained from roadway applications of environmental sensor systems was investigated in the 1970's and 1980's. Several sensor deployments and cost/benefit analyses were conducted to determine the feasibility of utilizing sensor technologies for early hazard warnings and winter treatment planning. In the United Kingdom, the Institution of Highways and Transportation conducted a study to seek out new methods of cooperation between meteorological forecasters and county highway engineers. The objective of the study was to establish a more cost-effective and safer system of winter road maintenance. This initiative included a study of remote environmental highway sensors and a cost/benefit analysis of accurate and inaccurate weather information. The study concluded that environmental sensors could potentially have significant cost savings on winter maintenance costs.(9)

In the winter of 1983/84, the Meteorological Unit at Birmingham University developed an experimental road danger warning system to assess the accuracy of environmental ice sensor technology.(10) This study served to identify the inadequacies of available technology and set the specifications for future sensor developments.

Studies of environmental sensors for highway maintenance applications also proved promising in Finland, The Netherlands, and Sweden. Each of these countries independently pursued environmental sensor deployments and research initiatives. These early studies served as a foundation for a more extensive system demonstration. The European Community initiated a project in the mid-1980's called COST 30 (European Cooperation in the Field of Scientific and Technical Research), which focused on the development of a road weather detection system. It comprised a number of localized road weather monitoring stations which detected weather conditions on a particular section of the highway. The study involved 14 European countries contributing information concerning operational systems or active research in weather detection for road weather service. This study offered evidence that remote monitoring of weather equipment and warning systems continually saved money on winter maintenance costs by preventing overreacting.(11)

In recent years, interest in the deployment of environmental sensor technologies and warning systems has increased significantly. Current advances in sensing technologies and remote communications technology have created a greater impetus for more extensive deployments. In the United States, both State and Federal transportation agencies are actively developing programs to utilize advanced weather information to improve traffic safety and reduce winter maintenance costs. A review of current State activities is included in the subsequent sections. Research initiatives into environmental sensor technologies are covered in chapter 7.

STATE ACTIVITIES

As part of Task A, the project team performed an assessment of the environmental monitoring activities currently being undertaken in a range of States by transportation agencies. To obtain this information, the team visited several site installations in Colorado and Minnesota, as well as contacting the transportation agencies in New York, Virginia, Tennessee, Florida, North Carolina, Washington, New Mexico and California. Detailed contributions to this section were also provided by Minnesota Department of Transportation (Mn/DOT) and Colorado Department of Transportation (CDOT).

Adverse environmental conditions affect road conditions across the whole of the U.S. Environmental hazards such as rain and fog affect almost all regions in the United States, while other hazards such as ice, snow, smoke, and high winds are more prevalent in specific regions. Several States have experimented with the use of remote environmental detection sensors to provide real-time or predictive environmental information for maintenance planning or highway advisories. Extensive implementation of these, however, is limited to only a few regions. In most States, remote environmental sensor systems are utilized only in isolated locations which experience extreme hazard situations.

Colorado and Minnesota have deployed a significant number of environmental sensors because of the severity and consistency of environmental hazards. Other States which experience more varying weather patterns employ a few sensors in key locations to offset the most dangerous driving scenarios. Most States utilizing sensor technology for road hazard warnings place the sensors on key bridges or roadways which have a high tendency for ice, snow, or fog formation. These sensor detections are then utilized to alert maintenance crews or to initiate travel advisories and road closings.

Colorado

CDOT currently has a network of 14 environmental sensor sites installed in the Denver metro area. There are plans to expand the network in the near future to approximately 40 more sites in other parts of the State. The distribution of the sites is shown in figures 1 and 2.

All the equipment installed has been provided by a single supplier, SSI. The parameters measured by this proprietary system include: presence of precipitation; wind speed and direction; ambient air temperature; pavement temperature; relative humidity; and calculation of chemical factor present on the roadway surface.

The present system of sensors has been in operation in Denver for 5 years. The sensors are calibrated annually, which usually takes 30 to 45 minutes per station. Periodic checks of the stations are also made when the data received from a particular station are suspected of being in error, based upon information received by surrounding stations and comparisons to known data. The reliability of the existing system to date is considered good.(12)

The predominant use of the environmental sensor system in Colorado is for scheduling winter maintenance activities. Colorado spends around $20 million a year on winter maintenance, so increased efficiency can pay big dividends. The use of the system has already led to savings through a reduction of standby time for plowing and sanding crews, and reductions in the quantity of deicing chemicals from the more timely application of the chemicals.

In 1991, CDOT participated in a Strategic Highway Research Program (SHRP) research study. Infrared radiometers were calibrated and then used to check the surface temperature of the roadway, and were compared to data received by the pavement sensors. The results showed good correlation between roadway temperatures measured by the radiometer and the SSI system when skies were overcast. A discrepancy of 2-4 °C (4-8 °F) was seen when measurements were made in full sunlight. This was not seen as a serious problem as the system is most useful during inclement weather and/or at night.

Problems with the system in use in Colorado relate not to the performance of the equipment but to the fact that the equipment is a proprietary product. This prevents a competitive bid process for replacement parts and additional weather sensing stations.

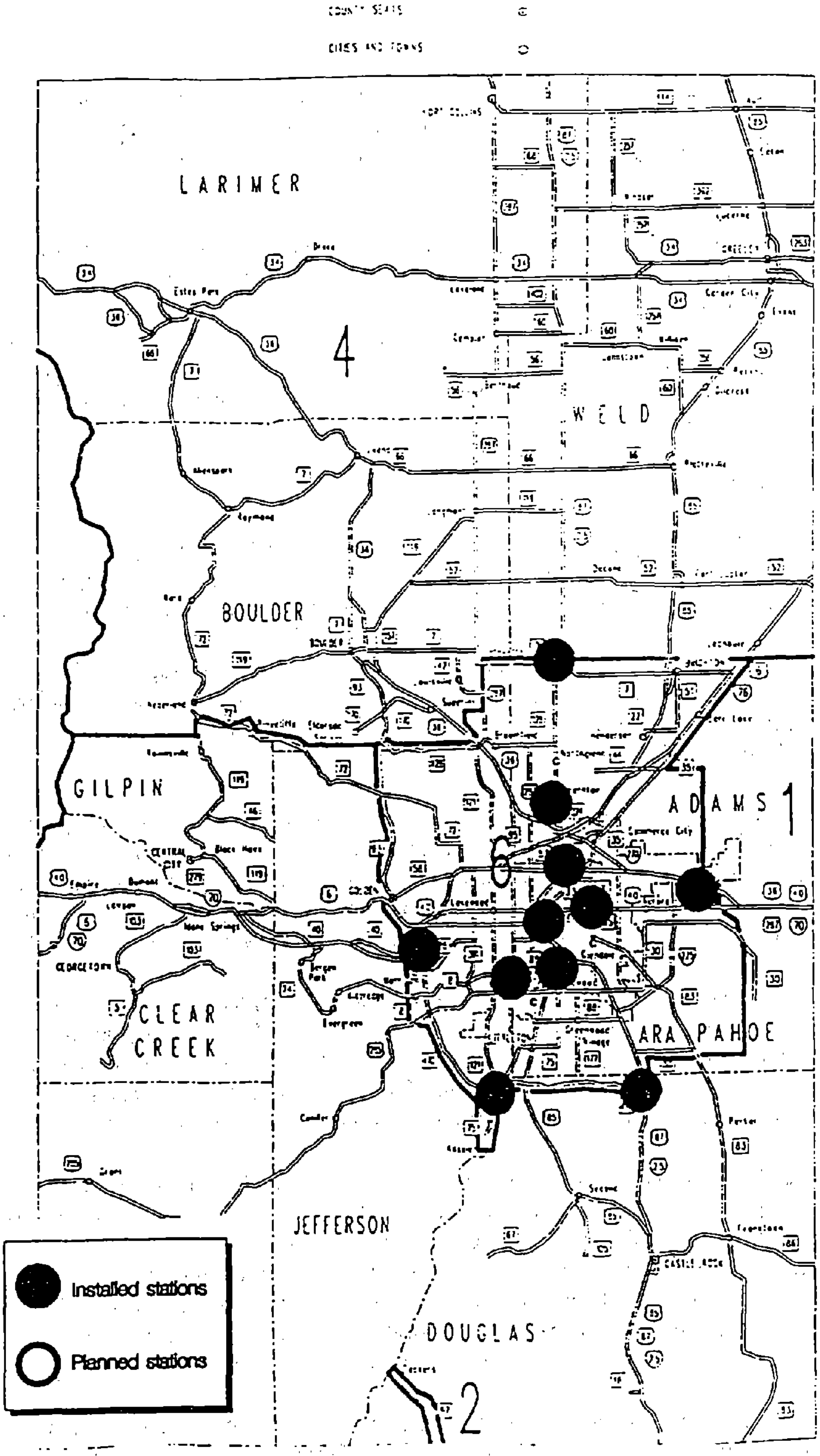

Figure 1. Weather stations in Denver

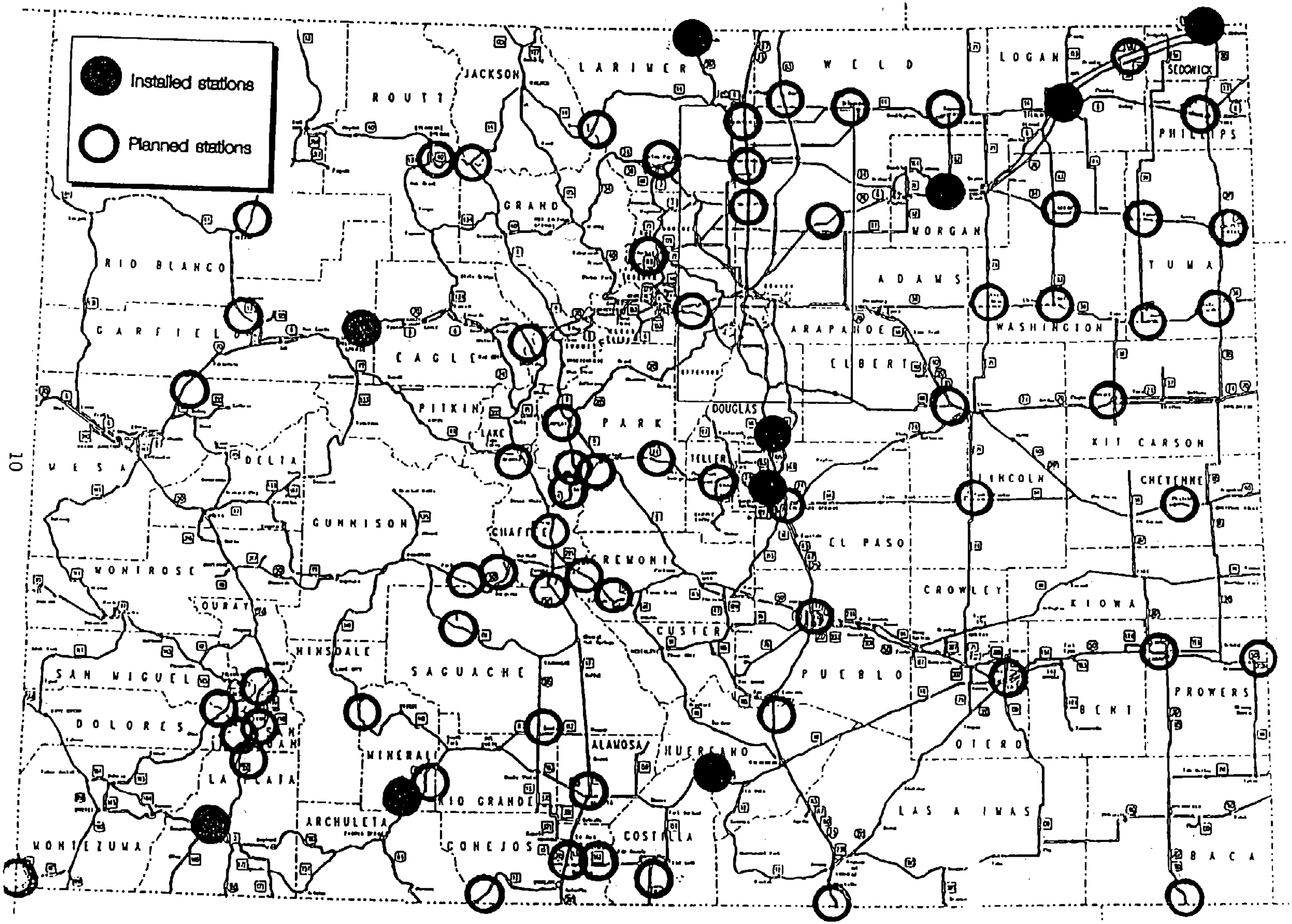

Figure 2. Weather stations in Colorado

There are two areas where CDOT would like to expand its current capabilities. These are in monitoring or sensing environmental conditions for the detection of avalanches and for the measurement of visibility conditions. The avalanche problem is particularly serious on southwestern Colorado's scenic Red Mountain Pass.

Minnesota

The road weather information system in Minnesota consists of a number of remote automatic weather stations and central processor units. These systems have been supplied by several manufacturers, including SSI and Climatronics. The remote automatic weather stations normally consist of atmospheric and pavement sensors, tower, and a remote processing unit (RPU). The station is generally located alongside the highway. The RPU is a solid-state microprocessor for logging and handling data from the sensors, and contains a communications module which disseminates data to the CPU and provides power to the sensors.

The pavement sensors measure pavement temperature and condition. Depending on the particular system, the sensor can also measure the relative amount of chemical on the roadway surface or provide the freezing point of the brine. Atmospheric sensors detect the presence of precipitation, and measure wind speed and direction, air temperature, and relative humidity.

A central computer located at the maintenance headquarters is responsible for polling each of the RPU's for data, processing the data into display format and archiving the data. Information received is used to help make the best operational decisions for snow and ice control. The predictive capabilities of the systems allow the onset of black ice and frost to be forecast. It is also used as a tool to determine when and how much deicing chemicals should be spread, thus providing the opportunity to improve control of spreading chemicals.

There are weather monitoring sites at 12 locations in Minnesota, including 7 in the Twin Cities metro area. Mn/DOT is currently expanding the State's road/weather monitoring network by installing six additional automated road/weather stations on the Minneapolis-St. Paul metropolitan freeway system.

Other State Activities

New York State has recently completed a weather sensor system experiment in the Genesee Valley Region, to measure atmospheric and pavement conditions to provide early detection of travel hazards. The weather sensor systems were connected to an RPU which transferred the information to a regional office computer via local telephone lines. The pavement system monitored surface temperature, moisture, frost, snow, and ice. The atmospheric sensors monitored the air temperature, relative humidity precipitation, dew point, and wind conditions. These characteristics were matched with the recorded levels of chemical treatment and critical temperature change levels to indicate hazardous road conditions and initiate appropriate warnings.(13)

The Kansas and Missouri DOT's and the City of Kansas have cooperated in a venture to implement ice and snow detection sensor systems in strategic locations in the region. The sensors are linked to an RPU, together with atmospheric sensors which measure air temperature and relative humidity. The processing unit relays the sensor information to the central processing unit in Kansas City. The information is formatted and matched with hazard indication criteria, and warnings of hazardous situations are issued in the form of a forecast narrative. The consortium has reported that this system has allowed the agencies to develop a much more efficient winter maintenance service for the region.(14)

The South Carolina Department of Highways and Public Transportation has implemented a fog mitigation system for use on the I-526 Cooper River Bridge. The system utilizes visibility sensors and closed circuit television (CCTV) cameras to monitor the incidence of low visibility on the bridge. When the sensors detect low visibility, operators monitor the CCTV screen to establish the severity of the fog and initiate appropriate fog mitigation procedures based on the severity of the condition. The bridge is equipped with variable message signs and lighted pavement markers to assist motorists in traveling during these hazardous periods.(15)

The Washington State Department of Transportation (WSDOT) is currently conducting a demonstration of in-vehicle signing and variable speed limit systems along a rural section of I-90 across Snoqualmie Pass. The purpose of the demonstration is to determine the effects of these technologies on safety in a rural environment. The 64-km (40-mi) section of highway receives an average of 13 m (527 in) of snow and 1.5 (60 in) of rain a year.

In the demonstration, the maximum speed limit was set at 105 km/h (65 mi/h) for cars and 97 km/h (60 mi/h) for trucks. Variable message signs and in-vehicle message signs were centrally controlled to change the speed limit based on information from traffic detectors and environmental monitoring sensors along the corridor. Information relating traffic flow, temperature, humidity, precipitation, wind, visibility and road surface conditions will be communicated to a central computer, which will determine a safe traveling speed and initiate speed limit changes and warnings to the variable message signs and in-vehicle signing transmitters along the corridor.(16)

The States of Virginia, Florida, and North Carolina have also experimented with visibility sensors for fog detection. The Virginia Department of Transportation operates a visibility sensor for detecting fog on Afton Mountain along I-64. The detection system is utilized in conjunction with variable message signs. The North Carolina Department of Transportation is implementing visibility sensing systems on I-40 linked to variable message signs as a means of warning drivers of upcoming hazards.(17)

I-75 Fog Detection/Warning System

The Tennessee Department of Transportation has implemented a fog detection and automated driver warning system in a fog-prone area at the I-75 crossing of the Hiwassee River near Chattanooga. The system uses fog detection sensors to monitor climatological conditions at the site and variable message signs to initiate changing speed limits and hazard advisories. Predetermined visibility levels or control access from the Highway Patrol initiates the advisories. The system will soon be modified to include 44 radar vehicle flow detectors to monitor the number and speed of vehicles.

Extensive environmental warning systems are currently deployed in California, Wisconsin and Michigan. The California Department of Transportation has incorporated several surface monitoring and fog detection sensors into its highway information network. The Departments of Transportation in Wisconsin and Michigan have an extensive network of surface and atmospheric remote monitoring systems to assist in winter road maintenance activities.(18)

Wyoming Transportation Department has remote weather information systems in operation on I-80 near Laramie.(19) These are used to detect strong and gusty winds. On detection of a critical condition, a changeable message sign is automatically activated to display a high wind warning message.

Environmental detection sensors have proved to be beneficial to a number of State and municipal agencies. Studies have indicated that further implementation of these technologies would be beneficial to many State agencies.

OVERSEAS ACTIVITIES

United Kingdom Fog Warning System

In the United Kingdom a number of automatic fog warning systems have been implemented to cope with this frequent adverse weather condition. One such system was recently installed on the M25 London Orbital Motorway.(20) Following several fatal accidents in fog, the UK Department of Transport commissioned studies to investigate the suitability of commercially-available fog detectors, and to examine the most appropriate locations for siting the detectors.

The fog sensors have been incorporated into the second-generation National Motorway Communications Systems (NMCS2) which are used on the M25. NMCS2 is an industry standard motorway control system in the UK, providing support for functions such as freeway signalling, emergency phones and automatic incident detection. When the sensors detect a reduction in visibility a warning is sent to the local control center. Further deterioration in visibility to less than 305 m (less than 1,000 ft) causes the detectors to automatically switch on fog warning signs in the locality. If the visibility falls to less than 91 m (300 ft), fog warnings are displayed to drivers over a wider area.

Dutch Fog Detection and Warning System

In response to severe accidents during fog conditions, the Dutch Ministry of Transport recently initiated a trial of a fog detection and warning system on the freeway between Rotterdam and Belgium.(21) Twenty visibility sensors, of the forward scatter type, were installed along a 13-km (8-mi) stretch of highway. Visibility data are transmitted to a control center computer, which then determines the appropriate speed to display to drivers on overhead warning signs. The system is fully automatic, comparing visibility data with preset thresholds and then switching all signs and lamps accordingly.

United Kingdom Ice Prediction System

In the United Kingdom, over 60 counties or districts have installed an ice prediction system. As part of the system they also receive a forecasting service tailored to their local climate. The main motivations for system installation are to make savings on deicing chemicals, provide a better service to the general public, and reduce environmental damage caused by deicing chemicals.

In conjunction with the ice prediction systems, there has been widespread use of thermal mapping techniques in the United Kingdom. More than 37 000 km (23,000 mi) of highway have been mapped, yielding information about the thermal behavior of the roads under different weather conditions. Data from the mapping activities enable deicing strategies to be developed, together with assisting in the identification of sites for sensor placement.

CHAPTER 3. METEOROLOGICAL CONDITIONS

In the assessment of environmental sensor systems, it is important to examine the adverse environmental conditions themselves. This chapter contains a description of the main meteorological conditions which seriously impact transportation users. It provides background to the occurrence of certain weather conditions, as well as delineating the frequency and characteristics of those conditions. The parameters that should be measured in the development of a comprehensive prototype meteorological sampling system are also addressed.

WEATHER HAZARDS

There are several different types of climatic conditions which represent a hazard to drivers in the United States. These can be divided into five categories: fog, rain, snow, wind, and ice. In addition to these naturally-occurring phenomena, smoke from industrial sources or forest fires presents a further hazard. Each of the hazards is described in detail below.

Fog

Fog is one of the least predictable hazards, varying over time and from location to location, and with no known means for its prevention. Fog is a visible concentration of small water droplets that forms at or near ground level. Fog occurs when visual range is reduced to less than 1 000 m (3,300 ft). The median duration of fog is about 1.5 h. Most fog in the United States occurs at temperatures above 0 °C (32 °F), and the denser forms usually involve industrial pollution.(7) There are five main types of fog:

- Radiation.
- Precipitation.
- Steam.
- Upslope.
- Advection.

Radiation Fog

Radiation fog occurs when ambient air is cooled to saturation, forming a surface-based cloud. It is usually shallow, forming in low areas where cold air drainage adds to radiational cooling. Air movement is slight. Radiation fog is a nighttime phenomenon, although in some cases it can persist into daylight hours. In notable exceptions, which will be covered later, it can persist for long periods, changing characteristics.

Radiation fog can be dense, sometimes reducing visibility to zero. It is a significant hazard, since there is usually no warning to an approaching motorist. Fortunately, the time of occurrence reduces the obvious accident hazard. The most hazardous period for radiation fog is just after sunrise. At that time air movement begins, deepening the layer. The condition is further exacerbated by the synergistic effect of sunlight on atmospheric turbidity.

Shallow radiation fog will usually burn off rapidly, due to surface warming. Thicker layers, however, can be a significant hazard as noted above, particularly since morning traffic will be affected. In this case, cloud layers above the fog will delay burn-off. In this instance, the fog may in fact become thicker and develop into an area of general fog. Visibility is usually more than 0.8 km (1/2 mi) during daylight hours when this takes place.

Precipitation Fog

Persistent periods of rain, mostly during the cool seasons, will saturate the ambient atmosphere, causing extensive areas of fog. In this situation, visibility is usually not restricted below 0.8 km (1/2 mi). The fog, however, will persist for several hours after precipitation has ended.

Steam Fog

Steam fog forms when very cold air moves across a warmer body of water. The vapor pressure of the water exceeds the vapor pressure of atmospheric water vapor, forcing moisture into the layer at the water surface. In addition, the atmospheric layer at the water surface is warmed by conduction, causing a shallow unstable layer. Steam fog occurs along rivers, around lakes, and over oceans. Drifting over roadways, it can cause surface frost in addition to the hazard of visibility, which is frequently less than 0.2 km (1/8 mi). It usually does not cover wide areas, but can be a significant hazard.

Upslope Fog

Upslope fog occurs when low-level wind patterns force relatively moist air up rising terrain. The rising air is cooled adiabatically to 0.4 km (1/4 mi) or less. In addition, drizzle, light rain, or very light snow can develop from a layer of upslope fog. Icing from freezing precipitation can then result. The eastern slopes of the Rockies and Appalachians are the most frequent and widespread areas of development, but this condition can occur wherever rising orographic conditions exist. In Minnesota, the north shore of Lake Superior, and especially at Duluth, upslope fog is a frequent phenomenon, often combined with other types of fog conditions.

Advection Fog

This type of fog occurs in two ways: (1) fog that forms in one area is advected into another; or (2) fog that forms when the movement of moisture-laden air over a cool surface lowers the temperature of the airmass to saturation.

1. The most favored areas for this type of fog are coastal regions. The cold waters off Newfoundland are notorious sources of fog that advects into coastal areas as far south as the New England coast. Inland bodies of water of significant size are also sources of fog that are advected over wide areas. The Great Lakes region is one such source. Duluth, Minnesota is frequently affected. It is a significant hazard that can persist for 24 hours or more.

2. The second type of advection fog is a wintertime phenomenon over the snowfields across the Great Plains and the Midwest. It not only reduces visibility to near zero for extended periods, but may be accompanied by freezing drizzle or sublimation frost deposits on roadways. A significant feature of this phenomenon is persistence; it can last for several days.

Although the foregoing identify and describe individual types of fog, two or more types may coexist. Also, developments may change from one type to another. Detection and prediction of its occurrence will form a major thrust of this study.

Rain

As with fog, there are several different types of rain. These comprise:

- Showers and thunderstorms.
- Steady rain.
- Freezing rain.

Showers and Thunderstorms

These phenomena are caused by atmospheric instability. In the process, low-level, moisture-laden air is lifted into conditionally unstable layers above the surface. The rising air cools adiabatically to saturation, clouds form, and vertical motion and condensation continue until a level sufficient to support precipitation is reached.

In the case of showers, the effect is manifested by some slipperiness on road surfaces but usually no significant restriction to visibility. However, studies have indicated a 20-percent drop in traffic volume along heavily traveled roadways from even light showers, due in part to motorist reaction to precipitation.

Thundershowers are a considerable hazard, since the accompanying showers are usually heavy. Brief, but severe, visibility restriction frequently occurs unexpectedly, causing numerous and often severe traffic problems. At the same time, gusty winds from varying directions add to the volatility of the situation. The random nature of these occurrences makes warning to motorists difficult. The results can be catastrophic. Fortunately, they are usually not widespread and usually last for only a short time.

Distribution of showers and thunderstorms is random across the country, with the most severe and numerous occurring in the thunderstorm belt across Oklahoma, Kansas, Illinois, Missouri, and eastward up the Ohio Valley. Less frequent but still significant occurrences extend on either side of this belt, as far south as the Gulf Coast and to the northern border, from Montana to the Great Lakes. The greatest frequency begins in the Gulf Coast area in February and gradually shifts northward to Minnesota by June.

Steady Rain

Steady rain generally results from two types of meteorological conditions. The first is "overrunning," where warm moist air is driven over a colder area of high pressure. Lifting and condensation occur due to the adiabatic process, and precipitation results. In this case, however, the cloudiness extends over wide areas. The precipitation is gentler and the condition will persist for relatively long periods. Thunderstorms can occur with the persistent steady rain, especially during fall and spring occurrences. In addition, a steady rain situation is the cause of the most significant freezing rain situations discussed below.

The second meteorological condition is a slow-moving cyclonic system that occludes and leaves a vortex far behind the advancing surface system. In this instance, steady rain can occur for several days, interspersed with periods of showers and thunderstorms.

A steady period of rain saturates the underlying strata and will eventually develop extensive areas of fog. The most frequent time of occurrence is in the cooler seasons. Distribution is from coast to coast and border to border, although the most persistent areas are from the eastern slopes of the Rockies to the East Coast.

Freezing Rain

Freezing rain occurs most frequently in one of the steady rain situations described above. In this instance rain, which forms in the warm strata riding over cold surface conditions, falls through the cold air and becomes super-cooled. The temperature of roads and other surfaces is below freezing. When the super-cooled raindrops impact cold surfaces, they congeal instantly, depositing layers of ice that can accumulate rapidly into one of the most hazardous driving conditions to be encountered.

The upslope fog condition previously described also develops freezing rain in mountainous areas, especially the eastern slopes of the Rockies, creating widespread and persistent hazardous conditions. Geographic distribution, aside from the mountains, shows a greater frequency in those States north of a line from Oklahoma to Tennessee and southern Pennsylvania.

Snow

The main types of snow are:

- Major snows of 0.1 m (4 in) or more, including blizzard conditions.

- Snows of less than 0.1 m (4 in), but nevertheless significant in their effect on highway traffic.
- Lake snows and East and West Coastal snows.
- Snows from poorly-defined systems.
- Blowing snow.

Major Snows (not including lake snows)

With the exception of the Gulf of Mexico coastal area, every section of the U.S. has experienced incidents of paralyzing snowfall. The greatest rate of occurrence is several times each winter from the Great Plains eastward along the Ohio Valley, across upper New York and through New England. Minnesota and mountain locations rank near the top in rates of occurrence.

In a high percentage of cases, major snows result from the most severe synoptic meteorological conditions. They are usually identifiable by experienced meteorologists and are quite well handled by computer models of the atmosphere. Therefore, especially in modern times, accuracy of forecasts of major storms is quite high.

Significant Snows (not including lake snows)

Snows of this type (less than 0.1 m (4 in) in depth) show a much more random frequency and distribution pattern. They are also less predictable, although there has been some improvement in that area in recent years due to technological improvements.

Lake Snows

Lake snows occur along the leeward shores of larger lakes or groups of lakes, most notably the Great Lakes, from the North Shore of Lake Superior, over the upper peninsula of Michigan, northern and eastern Wisconsin, the Chicago area, northern Indiana, all of lower Michigan, northern Ohio, northwestern Pennsylvania, and upper New York.

Arctic airmasses move out of northern Canada at a rate of about one per week from early December into early March. The Great Lakes are a heat sink of such size and volume that most of their surface area will not freeze over during the winter. For this reason, lake moisture is percolated into the lower layers of very cold air as it passes over the water, in an aggravated manifestation of the steam fog phenomenon discussed earlier.

The unstable layers produced by the long fetch across the lakes are deep enough to produce heavy snow showers (visibility 0.8 km (1/2 mi) or less) that persist for long periods of time. Snowfall totals of over 2.54 m (100 in) are common on the leeward shores of the Great Lakes.

East Coastal Snows

During the winter, the polar jetstream is frequently shunted southward by a strong ridge of high pressure in the Pacific Ocean. Surface lows follow the curvature of the jetstream along the Gulf Coast area through Georgia and curve towards the Carolinas. At that time, they meet warm and humid conditions along the Gulf Stream, resulting in rapid deepening of the system.

The track of such storms follows the curvature of the Atlantic coast. The storm centers stay just off the coast, feeding on warm Gulf Stream conditions and setting up an ideal collision of warm and cold air feeds to produce heavy snow from the western Carolinas northward to New England. The frequency of this development is about six per year, although only two or three follow a path that deposits the belt of heavy snow. These are the storms that cause the fabled "Nor'easters" along the New England coast.

West Coastal Storms

These are low-pressure systems that kick-out of strong low-pressure troughs that form north to south just off the West Coast of the United States. They come ashore from Vancouver to southern California, with strong and sometimes damaging winds. Heavy rain can occur in the lower coastal terrain, but the coastal mountain ranges lift and cool the incoming airmass, causing heavy snow in the coastal ranges.

Systems that pass over the coastal mountains frequently lose their identity in the plateaus and Rocky Mountains and may meander for 2 to 3 days, producing intermittent snows of varying intensity and windy conditions. In about 40 percent of these occurrences, a well-defined low-pressure system will develop somewhere on the eastern slopes of the Rockies, and an average of 40 percent of these will move east with the potential for heavy snow production somewhere in the high plains. Depending upon path curvature, there is a potential for heavy snow from southern Missouri to northern Minnesota and from the eastern slopes of the Rockies to the Great Lakes and Ohio Valley.

Other Systems

Snow-producing systems that are well-defined have been discussed. Other types of snow producers have a much greater frequency. These are not as easily detected and therefore have a lower predictability rate than better-defined systems. The most frequent types are described below.

The "Alberta Clipper"

As the name suggests, these eject rapidly out of Alberta Province. They are usually the remnants of Pacific storms that have migrated across the Canadian Rockies. Caught in a strong northwesterly wind pattern, they move at speeds up to 50 knots. This type does not pick up additional moisture during migration, but frequently dumps up to 0.1 m (4 in) of fluffy snow across North Dakota and northern Minnesota, causing traffic and maintenance problems.

This type of system may not appear significant on synoptic analyses of surface reports. We must therefore rely on computer-derived solutions, with comparative analysis of satellite photography. Fortunately, these technologies have increased both the detection and predictability of Alberta Clippers.

Upper air disturbances from lower latitudes

This is a type of storm that shows up on mid- and upper-atmospheric analyses, usually the 700 and 500 millibar charts. They show moderate to strong absolute vorticity, and the positive advection pattern of vorticity may be quite pronounced. A skilled meteorologist is required to analyze this phenomenon, as well as good detection equipment.

Overrunning snows

East of an occluded frontal system and north or northeast of a warm frontal system, are areas of snow development due to the lifting of warmer air over the colder airmass in place. These are usually lighter snows, although they usually last for longer periods of time and may be accompanied by fog and freezing drizzle.

On some occasions snow bursts may occur during overrunning snow occurrences. These are associated with the following phenomenon. A detectable jetstream at higher elevations cuts across the weather system. Imbedded in the jetstream are small segments of jet maxima, often referred to simply as jets. Some studies have centered around the right-rear quadrant of these maxima, an area that seems to be associated with the bursts. These are significant since they are quick-hitting, with obvious results on traffic movement and highway maintenance.

Snows caused by rapid advection of cold air across a region

Rapid movement of cold arctic airmasses across the plains and through the Great Lakes creates atmospheric instability that results in snow and snowshowers. Strong winds create blowing and drifting snow with poor visibility and a potential for icing on highways. Temperatures and wind-chill readings fall into the dangerous category. Except for the areas prone to lake snows, the total snowfall from this phenomenon is usually not great. Nevertheless, it creates both travel and maintenance problems. This condition can persist for 24 to 48 hours. When this phenomenon is coupled with heavier snowfalls, the result can be a blizzard of major proportions.

Wind

In general, wind alone is not a major cause of serious highway accidents. It can pose problems for high vehicles at exposed sites, or for all vehicles in arid climates where it produces blowing dust. Severe wind conditions, such as those associated with hurricanes, clearly represent a major hazard to all vehicles.

Exposure to strong winds at a given site is a complex function of the surrounding topography and the prevailing wind field.(22) Experience suggests that it can be difficult to estimate maximum wind speeds based directly on observations. For vehicles, the greatest problems exist where there are sharp fluctuations in wind speed and changes in wind direction.

Blowing dust can create hazardous driving conditions. In meteorology, a dust event is registered if the prevailing visibility at the weather station falls below 11 km (7 mi). Essentially there are two types of dust, one associated with arid and semiarid areas, and the other occurring in the plains areas.

Arid and Semiarid Areas

Strong winds across the arid regions of the Southwest cause blowing dust that occasionally causes major driving problems. Severe occurrences are infrequent but should be cataloged. The area of occurrence is the desert southwest from California to New Mexico, and semiarid regions from the eastern slopes of the Rockies southward to west Texas.

Plains Area

From Montana to Oklahoma and east to the Dakotas, New Mexico, Nevada and Iowa, there is a relatively high incidence of blowing dust, mostly in late winter and spring. Extensive agriculture leaves exposed bare earth which is picked up by strong winds, resulting in poor visibility and other problems. The Dust Bowl years were caused by this condition.

Ice

Ice formation on highway surfaces is a frequent occurrence throughout most of the United States. On untreated roads it can create a major hazard to drivers. Highway agencies therefore spend considerable resources on treating roads to prevent ice formation.

The critical temperature is 0 °C (32 °F). At this threshold, ice is at its most slippery. Sections of highway where the temperature falls for a short period to 0 °C (32 °F) are of more concern than those well below this threshold.

Smoke

In addition to meteorological, adverse environmental conditions, smoke can provide a further hazard to drivers. Smoke can come from industrial emissions (process smoke), forest fires or controlled agricultural fires.

Process Smoke

Process smoke comes from various industrial processes that emit smoke into the atmosphere. By itself, it is not a significant traffic hazard, since it rarely reduces visibility to dangerous levels. However, the presence of smoke in the atmosphere acts in synergy with other lithometeors and hydrometeors to produce the photochemical effect that results in smog. The result is a significant traffic hazard. Occurrence is at or near urban areas. Process smoke can also reduce the visibility levels of fog.

Forest Fire Smoke

Forest fires of even modest size create significant hazards to the movement of traffic. Visibility can be severely restricted by windblown smoke. Occurrence is scattered in forested areas of the country, most frequent in the west, where semiarid conditions create a fire hazard.

Agricultural Fires

Agricultural fires are controlled fires used to burn crops or to clear land. Moderate- and high-wind conditions sometimes displace the smoke from these fires to the open roadway, causing traffic hazards.

PROBLEM OCCURRENCE

The previous section described the main types of adverse weather condition which can affect highway users to some degree. In assessing the requirements for environmental sensors we need to examine the time taken from the occurrence of the problem to it becoming a real problem for drivers. This aspect will influence the frequency with which meteorological measurements need to be taken and the response to information dissemination.

Table 1 summarizes the effects of different weather phenomena. The estimates provided in the table are subjective since many variables affect the meteorological conditions at a particular locality.

CASE STUDY - DULUTH, MINNESOTA

As part of the Task A activities, a case study of adverse weather conditions at Duluth was undertaken. The site, Duluth Airport, was chosen because of the extensive weather records and because of the involvement of Mn/DOT at that locality. Adverse weather conditions occur frequently at this location.

The weather investigation concentrated on the period 1987 through 1991. Visibility restrictions of 0.8 km (1/2 mi) or less were selected for examination. Glazing due to freezing rain and freezing drizzle were also included in the analysis. This particular category was chosen because traffic problems due to restricted visibility are most likely to occur under these conditions. Also snow accumulation, drift~~ing~~, and deposits on road surfaces are most likely with rate-of-fall values that cause visibility restrictions in this range.

The approach adopted involved examining the complete records of weather observations taken by skilled observers at National Weather Service stations. These records were used in order to get an accurate and complete count and duration of restrictions in a number of categories. The categories were as follows:

Table 1. Adverse weather conditions

Weather Condition	Type	Effects	Time to Problem	Comments
Fog	Radiation (ground fog)	Reduced visibility	Immediate	
	Precipitation	Reduced visibility	½-1 hour	
	Steam	Reduced visibility	15-20 min	Depends on wind
	Upslope	Reduced visibility	10-20 min	Can be an immediate problem to approaching motorist
	Advection	Reduced visibility	Varies	Usually immediate
Smoke	Process	Reduced visibility	Immediate	Depends on severity
	Forest fire	Reduced visibility	Immediate	Depends on wind and atmospheric conditions
Rain	Showers and thunderstorms	Poor visibility, skidding and flooding	Varies from immediate upwards	Heavy showers immediate; light showers may only slow traffic
	Steady rain	Poor visibility, skidding and flooding	Varies from immediate upwards	Light rain slows traffic; moderate to heavy rain can be immediate problem
	Freezing rain	Skidding	Immediate	Severe and dangerous
	Freezing drizzle	Skidding	Within 5 mins	
Snow	Major snows	Road blocks & skidding	Within 15 mins	
	Other significant	Road blocks & skidding	Within 15 mins	
	Lake snows	Road blocks & skidding	Immediate	In localized areas
	Blowing snow	Road blocks & skidding and poor visibility	Within 15 mins	

Table 1. Adverse weather conditions (continued)

Weather Condition	Type	Effects	Time to Problem	Comments
Wind	Gusts	Swerving and overturning	Variable	Depends on speed and variability
	Dust [arid]	Reduced visibility	Can be immediate	Can be observed in distance
	Dust [plains]	Reduced visibility	Can be immediate	Generally only an inconvenience but can be severe for short periods
Ice		Skidding	Immediate at 0 °C (32 °F)	Less of a problem at temperatures well below 0 °C (32 °F)

- Fog.
- Snow.
- Snow and fog.
- Glazing due to freezing rain or freezing drizzle.

The total hours and numbers of occurrence were logged by the calendar year. Five-year totals of each were then used in order to establish an average duration of each event. The results of the analysis are presented in table 2.

In considering table 2, it should be noted that observers sometimes include a combination of snow and fog as a visibility restriction. Although this combination can occur at temperatures around the freeze-thaw point, it does not occur with temperatures in the single digits. No correction for this was applied to the data in the review.

The table includes counts that are obviously out of the general range shown by accompanying data. These variations would be reduced if a longer period was analyzed. Nevertheless, the data will serve as a benchmark for use in forecasting during subsequent tasks of the study.

In addition to the visibility analysis, information on snow frequencies at Duluth was also assessed. Over the 5-year period under consideration, the results shown in table 3 were obtained.

Table 2. Adverse weather statistics for Duluth

Year	Fog		Snow and Fog		Snow		Glazing	
	Hours	# Events	Hours	# Events	Hours	# Events	Hours	# Events
1987	265	37	9	6	1	1	19	4
1988	158	43	32	8	14	4	66	9
1989	159	32	4	8	12	3	11	7
1990	242	43	3	2	4	1	65	6
1991	286	43	11	5	2	2	97	18
Total	1110	198	59	29	33	11	258	44
Avg.	5.6		2.0		3.0		5.9	

Table 3. Snow frequency at Duluth

Category	**Average Occurrence**
0.08-0.13 m (3-5 in)	3.8/yr
0.13-0.20 m (5-8 in)	1.6/yr
0.20 m (8 in) +	0.8/yr

These averages show that the more significant snowfalls are responsible for only a small proportion of winter maintenance problems. The lesser amounts are much more frequent and use a preponderance of maintenance funds.

CHAPTER 4. IMPACT ANALYSIS AND USER NEEDS

This chapter addresses the impacts of adverse environmental conditions on drivers through consideration of the driving function. The deterioration in driving performance is examined by investigating the effects of different weather situations. A safety assessment is also included. The remainder of the chapter focuses on the user needs of environmental sensor systems, from both a driver and State highway agency perspective.

EFFECT ON DRIVING PERFORMANCE

Environmental conditions have a major impact on motorists' driving performance. These impacts can be measured in terms of reduced mobility, reduced road safety, and increased driver stress levels during adverse weather conditions. These factors contribute to property damage cost, bodily injury, and loss of working hours. Environmental conditions directly affect the physical driving response of vehicles, as well as influencing the psychological and behavioral responses of drivers. The physical condition of the driving environment reduces the performance of the vehicle and increases the probability of a crash. Likewise, the increased intensity of the driving task during these periods makes driving more tiring and stressful, which in turn reduces the driver's maneuvering capabilities.

To avoid collisions with other road users, a driver must be able to perform a number of subtasks. The driver must be able to detect other vehicles, make judgments of speed and direction of other vehicles, predict the future behavior of other drivers, and adjust their own behavior. If there is the added burden of traveling in adverse weather, such as low visibility or slick surface conditions, the driving task becomes significantly more complicated. The driver must now take into consideration any reduced visual perception of the roadway, the unpredictability of the vehicle's maneuvering ability on slick roads, and the unpredictability of other drivers. These additional factors have a serious impact on the safety characteristics of the roadway and the demands on driving performance. The effects of adverse weather conditions on driving performance are discussed in the following paragraphs.

Rainfall causes poor visibility, loss of skid resistance and, at night, reflections from the wet road may distort drivers' visual perception of the roadway. Hail and ice can cause the most serious driving hazard for motorists. The loss of surface friction can cause drivers to completely lose control of their vehicles. Snow storms and snow drifts can reduce visibility, reduce surface friction, and cause road blockages. Wind hazards on roadways do not account for a high percentage of road crashes, but the effects of these conditions can be very severe. High gusting winds cause a loss in vehicle stability and reduce the surface friction of vehicles. Dense fog or smoke can reduce visibility levels to almost zero, causing drivers to speculate on the geometry of the roadway, travel at various speeds, or tailgate other vehicles.(23)

The effects of environmental conditions can be categorized in terms of the following:

- Reduced visibility.
- Reduced surface friction.
- Reduced vehicle stability.

Each of these conditions contributes to an overall reduction of road safety. Poor visibility can affect drivers' perceptions of the road and may blind drivers to other hazards in the roadway. Reduced surface friction directly affects the vehicle's maneuverability, making control of it difficult. Reduced vehicle stability also affects the vehicle's maneuvering ability. These factors or combinations of them are the direct cause of, or a contributing factor to, many crashes.

Visibility

A high percentage of crashes are attributed to inadequate perception of the roadway by drivers. Environmental conditions such as fog, snow, rain, and smoke are direct causes of reduced visibility. These conditions produce major safety hazards for drivers. In instances of low visibility, drivers should reduce the speed of travel and increase the distance between vehicles to compensate for variations in perception. Studies have shown that drivers do slow down when visibility levels decrease.(24) However, the response is often not sufficient to offset the effects of the low-visibility hazard.

Conditions of reduced visibility cause drivers to incorrectly perceive the highway environment and to react more slowly to changes in the roadway. For example, it will take a driver a longer period of time to notice that the vehicle ahead has slowed down or is approaching a stop. If sufficient headway is not maintained to compensate for the delayed perception, the driver will either crash into the vehicle or be forced to engage in a sudden braking or maneuvering task. With the visibility of other drivers also reduced, and given that environmental conditions causing reduced visibility often occur in combination with conditions causing low surface friction, this can be a major road hazard.(25)

In normal light conditions, drivers predict their maneuvering responses by looking ahead and monitoring braking reactions from vehicles several cars ahead. This additional visual perception allows drivers to travel relatively safely with shorter headways. Lower visibility affects drivers' perceptions of the road geometry and their recognition of road signs indicating bends in the road, or directional instructions to which the driver must respond. These perceptual differences often cause drivers to misjudge safe headway protocols and contribute to the hazardous traveling conditions during low-visibility situations.

The level of hazard produced by the environmental condition is dependent upon the level of visibility available to the driver. Under good environmental conditions, the range of visibility of an average driver is over 107 m (350 ft) and the meteorological definition of dense fog is levels below 396 m (1,300 ft).(26) This may have little or no effect on driving performance.(7) However, severe reductions in visibility can cause drivers difficulty in seeing lane markers or other vehicles traveling on the road.(26)

In most instances, driving behavior does not change significantly in low-visibility conditions.(7) The primary difficulty caused by fog, dust, or smoke conditions is in judging the geometry of the highway. In severe fog conditions, drivers often travel close to other vehicles as a means of forecasting the road. This can often lead to drivers over-responding to hazards by excessive braking, possibly resulting in skidding.(26)

The overall effect of fog on driving behavior varies for conventional roads and freeways. On conventional roads, statistics indicate that motor vehicle crashes actually decrease in fog conditions, while the fatality rate for motor vehicle crashes in freeway environments almost doubles. One explanation for this is that on conventional roads, there is an increased probability of overdriving because drivers have a heightened awareness of the road geometry. In freeway conditions, where the geometry of the roadway is relatively good, the consistency of driver reactions to the conditions is more varied, increasing the likelihood of crashes.(7)

The likelihood of multiple vehicle crashes is increased during fog conditions. In an investigation of driver responses in a multiple motor vehicle crash by the National Transportation Safety Board, the driver reactions to a sudden drop in visibility varied distinctly. Some drivers maintained highway speeds while others came to a complete stop. Drivers reported following the taillights of other vehicles to judge the geometry of the road. Drivers admitted to difficulty in determining if the taillights of vehicles were actually brake lights. Other drivers reported stopping their vehicles because of noises from other crashes, which caused additional crashes. Some drivers safely mitigated the fog at highway speeds, while others mitigated the road safety at reduced speeds of approximately 80 km/h (50 mi/h).

Overall, drivers did not know what action to take, especially after a crash occurred. Many drivers got out of vehicles to assess the situation in the low-visibility conditions.(27)

Another consideration in assessing the level of visibility hazards is the overall visual perception of the driver and the experience of the driver. Elderly drivers are often visually impaired and have slower reaction times than other drivers. Likewise, inexperienced drivers may make inappropriate choices in hazardous driving situations, increasing the effects of the visibility hazard.(26)

Surface Friction

Reduced surface friction can be caused by a number of environmental conditions. These include rain, snow, or ice on the highway. The most significant hazard under reduced surface friction conditions is that drivers are not readily able to evaluate the friction coefficient of the roadway to assess the braking distances applicable to the environment. The loss of friction amplifies the movement of the vehicle, increasing the distance to safely stop. Additionally, if the driver assesses the required braking maneuver incorrectly, the vehicle will begin to skid, decreasing the safe braking distance and increasing the likelihood of the driver losing control of the vehicle.(28)

The loss of maneuvering ability can have dangerous consequences in the roadway environment. An out-of-control vehicle on the roadway can create a situation in which other vehicles are forced to react to the developing scenario with little reaction time and in an already hazardous environment. These effects are further amplified on curved roads or in turning situations. Additionally, the coefficient of friction between a vehicle's tires and the roadway may be significantly reduced when the tire tread is low.(25)

Vehicle Instability

Vehicle instability is caused by severe crosswinds which occur during changes in barometric pressure. These conditions are common preceding or during thunderstorms. These lateral disturbances are particularly hazardous to small or lightweight vehicles. The forces generated from the crosswind create an environment in which the driver has to negotiate the wind forces as well as the roadway. Additionally, crosswind situations are usually dynamic, varying in intensity and over time. The constantly changing effects of the wind forces the driver to respond to an unpredictable environment. In this environment, a temporary loss of concentration can have serious consequences.

Crosswinds present a serious safety hazard because they can affect both the lateral forces on the vehicle and reduce the contact between the road and the vehicle. This is particularly hazardous during cornering maneuvers and maneuvers to compensate for the distortions. Drivers are often unaware of the effects of the vehicle-road contact and do not make the necessary speed adjustments to safely negotiate the roadway.

Wind hazards present a more significant problem to high-sided vehicles and for vehicles traveling on bridges or emerging from a tunnel. The wind force exerted on a vehicle is proportional to the square of the wind speed times the area of the vehicle exposed to the wind. The force of the wind is constantly changing and produces sharp fluctuations in wind direction. The dynamics of the wind forces and the motion of the vehicle are constantly changing and can be very difficult to mitigate.

Hazardous weather conditions increase the risk of all crash types, however, the risk of certain crash types is significantly higher under specific environmental conditions. These are outlined in table 4.

Table 4. Environmental crash risk

Environmental Condition	High-Risk Crash Type	Cause
Reduced visibility	Rear-end crashes Multivehicle crashes Roadway departure crashes	Tailgating Variable driving speeds Crash avoidance maneuvering Misjudging road geometry
Reduced vehicle traction	Intersection crashes Rear-end crashes Roadway departure crashes	Skidding Reduced vehicle control
Reduced vehicle stability	Rollover crashes Roadway departure crashes	Miscalculating turning maneuvers

SAFETY ASSESSMENT

The impact of adverse environmental conditions on road safety is evident in the number of crashes that occur under these conditions. The effect of these crashes can be measured in terms of traffic delay, property damage, and loss of life. Motor vehicle crashes are a leading cause of death and injury in the United States. In 1990, almost 44,500 lives were lost and over 5.4 million people were injured in motor vehicle crashes. The total monetary cost of motor vehicle crashes was estimated to be over $137 billion.(29)

Although environmental conditions are seldom reported as the direct causal factor for many crashes, these conditions are a contributing factor in a large number of crashes. According to the 1990 NASS records of crashes on U.S. highways, approximately 35 percent of all crashes occurred during slick road conditions or during periods of reduced visibility.(30) Statistics indicate that drivers are three times more likely to be involved in a crash during adverse weather conditions.(31)

Rear-end crashes account for 25 percent of all crashes in the United States. The 1990 National Highway Traffic Safety Administration (NHTSA) General Estimates System records report that 27 percent of rear-end crashes occurred during adverse environmental conditions. Of the 27 percent, 23 percent occurred in wet conditions and 4 percent in ice or snow conditions. Adverse environmental conditions were also a contributing factor in over 32 percent of single-vehicle roadway departures. Approximately 21 percent of these crashes occurred in wet conditions and almost 11 percent in ice or snow conditions. Environmental conditions are also contributing factors in 43 percent of intersection crossing path crashes and in 20 percent of lane change or merging crashes.(30)

The effect of adverse conditions on road safety varies from one region to another. In a study of annual crashes of passenger vehicles in the State of Michigan, adverse weather conditions and poor surface conditions were present in more than twice as many crashes as were dry roads. This type of correlation between vehicle crashes and adverse weather conditions is common for many regions across the United States.(31)

Advances in environmental sensor technology and in traveler information services may help to lessen the safety implications of adverse environmental conditions on highway transportation. Accurate detection of road hazards and real-time travel information can potentially reduce the effects of these environmental conditions by assisting motorists in avoiding hazardous areas or adjusting travel times, and increasing the efficiency of road maintenance crews.

DRIVER INFORMATION

The driver information requirements for road and weather information can be divided into two categories: tactile and strategic. Tactile information is required for short-term local travel planning and strategic information is used for long-range travel covering moderate to long distances and at least 24 h advanced planning.(3)

The purpose of traveler information services is to assist drivers in making safe and efficient travel decisions. Environmental hazard information provides drivers with information relating to current or predicted environmental conditions which may impact their travel plans. Drivers are primarily interested in information that will help them to minimize travel time and avoid potential hazards. Weather information can be utilized to adjust route selections or departure times, or to adjust driving behavior to safely mitigate upcoming hazards.

The driving public is usually the final link in the dissemination of weather advisories. Commercial radio and television are the primary sources of weather information to the public. These media usually cover a broad local area and do not provide detailed travel-related information. The information utilized is usually limited to information received from the National Weather Service and local airport weather stations. Information disseminated is often only updated hourly and broadcasts are usually limited to news broadcast times.

Other radio broadcasts such as the National Oceanographic and Atmospheric Administration weather radio and Highway Advisory Radio (HAR) provide continuous weather and related travel information. These radio broadcasts often include traffic information from local highway maintenance agencies or highway patrol agencies, such as road closings, detours, and traffic congestion information.

Cable television and videotex weather and traveler advisory services provide users with detailed weather and traffic information. Cable television broadcasts offer a 24-h national weather broadcast with brief local weather segments. In some instances, the cable service provides a continuous banner across the television screen with local information. Videotex and teletext services provide local weather and traveler information via modems. Local weather or travel information is also available through telephone services based on pretaped messages. This information is updated regularly, although most networks do not offer dynamic information.

Planning information must relate the overall regional characteristics with the temporal characteristics of the hazards. Drivers need to know what areas are affected and how long the condition is likely to exist. Information suggesting appropriate driving behavior may also be beneficial. The format and content of environmental advisories should take into consideration the users' application and the communication media.

Strategic travel information and general advisories, broadcast via TV and radio, should provide as much detail and predictive information of road hazards as possible. These advisories should include information relating the severity of the hazard, the predicted time and duration of the condition, and travel recommendations. Remote or localized communications media, such as variable message signs or HAR, provide tactile information. Advisories from these systems should be as concise as possible, indicating weather conditions and appropriate driving behavior such as "reduce speed" or "prepare to stop."

SHRP has conducted a study to develop guidelines for road weather information system communications.(3) The study identified driver information needs for general travel advisories. The study recommended that the following information be disseminated to drivers for general travel advisories.

- Present weather.
- Surface condition.
- Wind speed.
- Temperature.
- Visibility measurements.
- Precipitation type.
- Precipitation rate.
- Precipitation begin and end times.

These weather characteristics provide drivers with basic information to form travel itineraries. In more immediate hazardous situations, drivers require information that will assist in mitigating environmental hazards. In these circumstances, drivers only require information that affects their immediate driving needs. Providing drivers with relevant information or warnings that address their immediate tactile needs is difficult because it is not possible to monitor the entire roadway, and in order to provide effective warnings, the information must be accurate.(32) Inaccurate warnings will cause drivers to ignore future warnings. While it is possible to identify areas that are more likely to be effected by fog or flooding, all environmental conditions are essentially random, and the cost of monitoring remote areas and issuing tactile warnings such as appropriate travel speed or detours is great.

Ideally, drivers need to be given specific information on adverse weather conditions in the locality and on the route they propose to follow. This information needs to be available in real-time to be effective. Advances in driver information and communication systems offer significant opportunities to provide the required real-time, detailed travel advisories. IVHS can disseminate this information through in-vehicle display units communicating with roadside systems.(33)

The overall cost/benefit ratio of remote road weather information systems is difficult to assess. In a cost/benefit assessment of the SHRP A207 project, which examined the direct cost and benefits associated with road weather information systems, these systems were determined to be too costly and not accurate enough to provide effective warnings.(34) This cost/benefit analysis, however, did not take into consideration indirect benefits such as safety because those effects are difficult to quantify.

STATE NEEDS

The needs of State and municipal highway agencies vary from those of drivers in that they are responsible for operating and maintaining the highway infrastructure. Adverse environmental conditions have design, safety, and maintenance implications for the State agencies. To schedule their maintenance activities and provide travel advisories, these agencies can greatly benefit from accurate real-time environmental measurements.

One of the primary functions of State agencies is to ensure roads are kept open throughout the year, particularly during the winter. This involves responsibility for removing snow and ice from all public roadways. These activities are extremely expensive due to labor costs for plowing and applying chemicals or sand, and the cost of the chemicals. The timing of these activities can be extremely crucial, since applying chemicals too soon may result in the need to reapply more later. Keeping maintenance crews on standby when they are not needed is also expensive.

In certain situations, State agencies may tend to over-treat bridges and roadways to prevent ice formation and hence hazardous driving environments. These chemical treatments deteriorate the roadway and may eventually lead to more expensive maintenance costs in the warm season.

Better detection and measurement of environmental conditions that reduce visibility and stability can also be beneficial to State agencies. Although little can be done to eliminate these conditions, accurate detection and prediction of these conditions can assist State agencies in issuing more accurate travel advisories.

SHRP identified three short-term weather information uses of State maintenance agencies regarding ice and snow conditions. These include:

- Whether or not to change maintenance staff schedules.
- If or when to mount low blades or hoppers.
- What type of deicing chemicals and abrasive materials mix should be applied.

State agencies are interested in using environmental monitoring systems primarily to:

- Activate motorist warning systems such as variable or active message signs.
- Activate a snow and ice crew alert system.
- Activate automatic deicing systems such as chemical sprays or automatic road heating systems.
- Plan road construction activities.

The use of snow and ice monitoring equipment to improve State maintenance and planning activities was investigated for FHWA in the middle 1970's. Although the sensing technology available during that period was determined to be inadequate for most State applications, the study helped to define State requirements for environmental sensors. The study recommended that sensors based on hazard detection would be more beneficial for State applications than predictive sensors. Knowledge of the actual road surface condition was thought more desirable, since the identification of an actual hazard provides the State with measurable information on which to base State response decisions. However, at the time of the study, predictive sensors could not provide sufficient reliability and accuracy for State applications.(30)

The study concluded that the detector should:

- Perform reliably with a negligible false alarm rate.
- Distinguish distant levels of hazard detection.
- Function in the presence of chemicals likely to be found on the roadway.
- Be compatible with all standard snow removal equipment.

The accurate and reliable sensing of a condition in this context was defined as 99 percent correct. However, the degree of accuracy and reliability of the sensor would depend on the application of the information. Information obtained for travel advisories is less critical than information used to determine environmental treatment responses. The ability to distinguish levels of hazards allows State maintenance agencies to use the information to efficiently apply treatment. The more detailed the information, the greater the utility in assessing maintenance operations. The restrictions on interference from chemicals and snow plowing operations ensure that the system is capable of functioning in the harsh environments likely to be encountered.

Since this 1970's study, many States have implemented weather monitoring stations as discussed in chapter 2. Where a network of stations is operational, considerable savings in maintenance operations have been realized. The main difficulties with the current approaches appear to be the lack of localized, short-term weather forecasts to support the sensor information and the lack of compatibility between commercial systems. This latter aspect may be addressed by the development of open standards for road weather information systems.

CHAPTER 5. FUNCTIONAL REQUIREMENTS

This chapter describes the functional requirements of environmental sensors required for a generic condition-responsive driver warning and control system to support the needs of highway agencies and drivers. Development of the functional specification has been undertaken by considering the environmental conditions that need to be monitored and the information needs of drivers and highway agencies to improve road safety. Parameters required to identify particular adverse weather conditions have been defined. Functional requirements have been detailed for the sensors that measure these parameters.

The parameters to be monitored are discussed in the next section. This examines the potential parameters and assesses how directly useful they are as input to a driver information and warning system. Then performance criteria are described for sensors to measure the environmental parameters. These criteria, covering range, accuracy, calibration, reliability, and power, build on existing standards wherever possible.

The subsequent section covers the siting of the sensors on the highway network, and discusses the main factors affecting the positioning of the sensors to achieve effective coverage. This is followed by the data output requirements of the sensors. Operation and control aspects are then addressed.

PARAMETERS

Many meteorological parameters can potentially be measured. Some parameters are more useful for the general forecasting of weather conditions, while others are more suited to the needs of drivers and State highway agencies. For the latter, real-time information and near-term forecasts are key requirements. The sensors employed to monitor parameters may measure one or more parameters simultaneously and/or work in conjunction with other sensors.

Potentially useful parameters include the following:

- Atmospheric pressure.
- Ambient temperature.
- Wind speed, direction, and gust.
- Humidity, dew point temperature.
- Relative humidity.
- Precipitation type, rate, and depth.

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- Solar radiation/cloud cover.
- Visibility (fog, smoke, dust, etc).
- Pavement surface temperature.
- Pavement moisture.
- Snowy or icy pavement condition.
- Amount of deicing chemical present on pavement.

Atmospheric pressure readings are used as data input into meteorological models to forecast weather conditions. These readings are usually representative over a wide area. They therefore help to provide forecasts over an area, as opposed to the detection of specific meteorological phenomena related to pavement and driving conditions. For this reason atmospheric pressure is not considered to be of great importance for a driver information system.

Readings of air temperature represent a fundamental requirement in the forecasting of area-wide and local conditions. Ambient air temperature helps provide input to weather forecasts, gives a direct indication of local conditions and, in conjunction with other parameters, can be used to determine the onset of several meteorological conditions such as precipitation, reduced visibility, and ice.

Wind speed and direction represent useful parameters for meteorological monitoring and prediction. These parameters are also important in modeling the dispersion of air pollutants and predicting air pollution levels. Typically wind speed, average direction, and a factor representing the variation, or spread, in wind direction are determined. Monitoring of wind conditions at exposed sites where problems with high-sided vehicles can occur represents another important application. In this case, in addition to wind speed and direction, the wind gust factor can be significant in determining the potential hazard of vehicle instability.

To predict precipitation and reduced visibility, it is necessary to know the moisture content of the air. Sensors may be used to monitor relative humidity and/or dew point temperature.

It is very useful to be able to detect the occurrence of precipitation, including the type of precipitation, its rate, and the depth of precipitation on the ground or pavement. Detection of precipitation can be used to give warnings of reduced visibility and increased braking distances caused by wet or icy pavements. The depth of rain in particular locations can be used to inform drivers of floods.

Snow depth can be used to provide advisory driver information and assist State authorities in scheduling and prioritizing their snow clearance activities. An accurate measurement of the depth of snow on the highway may be beneficial to States in determining the response time and the type of plow needed. Inferences of snow depth may also be obtained from other measured parameters.

In some mountainous areas, monitoring snow depth on hillsides may assist in identifying the risk of avalanches. This may represent a more complex process as the spatial profile of snow depth and angle of inclination represent important factors in avalanche prediction. This may be achieved by having an array of sensors monitoring snow depth over a hillside, or alternatively, by using a scanning sensor to determine the snow profile. Data from these sensors could allow prediction of the stability of snow on a mountain slope. The accurate prediction of avalanches may also require knowledge of the state of the compacted snow (e.g., relatively uncompacted, large frozen mass, melting, etc.).

Solar radiation/cloud cover are useful parameters in meteorological predictions. Solar radiation can be used to predict the temperature rise at ground level. Cloud cover also influences the degree of cooling experienced over night. These factors are potentially useful in predicting the extent and duration of icy conditions. Therefore, they are important factors in planning maintenance activities.

Visibility is an important factor in traffic safety. There is, therefore, a requirement to be able to measure the degree of visibility and the extent of its coverage. An environmental sensor should be able to detect reduced visibility and quantify the visibility reduction. In advanced warnings of low visibility, drivers require information on the area subject to reduced visibility, its severity, and expected duration. To assist drivers further, it would be useful to identify the cause of the reduced visibility. In addition to detecting reduced visibility, sensors would therefore ideally be able to determine the type of aerosol responsible, for example fog, smog, smoke, dust, or precipitation. Drivers could then be informed of the existing condition.

In proximity warnings of low visibility, drivers require reactionary information like safe traveling speeds. As noted earlier in this report, a major hazard of low-visibility driving conditions is vehicles traveling at varying velocities. In these scenarios, the sensors must accurately detect visibility and initiate appropriate warnings. In instances when a lead vehicle is decelerating and the following vehicle is traveling at a constant velocity, the safe distance between vehicles is determined by the following algorithm:

$$GI = V_f^2/2a + T_D V_f - V_L^2/2a \qquad (1)$$

where

GI = gap interval (distance in feet)
V_f = velocity of the following vehicle
V_L = velocity of the lead vehicle
a = deceleration rate
T_D = time delay before driver initiates braking.

For instances in which the lead vehicle is stationary, the algorithm is as follows:

$$GI = V_f^2/2a + T_D V_f \qquad (2)$$

NHTSA-accepted values for braking deceleration rates of most vehicles excluding heavy trucks ranges from 0.5 g to 0.9 g with 0.7 g as the average braking deceleration rate in dry road conditions. The average time delay for drivers to initiate braking sequence is 2.05 s.

From a safety aspect, the ability to monitor, or predict, the skidding resistance of pavement surfaces is extremely useful to drivers. The degree of friction falls rapidly in wet and icy conditions and excessive wetness promotes aquaplaning. The passage of traffic can deposit a film of oil and tire rubber on the highway, which can build up during dry conditions and then form an extremely hazardous surface when rain falls. Ideally, sensors monitoring pavement surface conditions should monitor oil/rubber film build up, as well as wet and icy conditions. Pavement surface temperature and freezing point represent important factors in determining slippery or icy conditions. Consequently, there is a requirement for a sensor to monitor these parameters. A related factor is the latent heat below the pavement surface. In some applications it may also be desirable to monitor pavement sub-base temperatures. Similarly, the duration, or likelihood, of wet or icy pavements is related to the amount of solar energy falling on the pavement surface. This may be measured locally by a sensor, or estimated from meteorological predictions.

Sensors, whether monitoring fixed points, scanning, or mobile, should be able to produce a thermal map of the highway network. This can then be used to identify "cold" routes that need treating with deicing chemicals. Ideally, the rate of application of chemicals should be controlled so that thermally cold sections of the highway receive higher dosages of chemicals. Application rates could be determined by a thermal map stored in an onboard computer, or a thermal sensor connected to the vehicle.

Pavement moisture must also be monitored to identify slippery conditions. A sensor, or combination of sensors, is necessary to identify the presence of precipitation and its state. This allows the detection of wet, snowy, or icy conditions. In particular, icy pavements in the presence of water, perhaps due to thawing, present a very low coefficient of friction and a serious hazard to traffic safety.

Another important factor in determining pavement condition is the quantity of deicing chemicals already present on the pavement. A sensor able to monitor the presence and quantity of deicing chemicals can produce useful data for forecasting pavement conditions, as well as indicating whether it is necessary to apply additional deicing chemicals.

PERFORMANCE CRITERIA

This section outlines performance requirements for environmental sensors able to measure the parameters described above. Performance covers aspects such as accuracy, sampling rates, calibration, reliability and robustness, and power requirements. The performance indicators used below reflect existing standards or practice wherever appropriate, for example the Federal Aviation Administration (FAA) Advisory Circular(35) and the UK Department of Transport specification for the national ice prediction network.

The performance criteria have been divided into sections: range and accuracy, sampling rates, calibration, reliability and robustness, and power requirements.

Range and Accuracy

The range and accuracy requirements of sensors will vary according to the application. Large errors in certain measurements may not be of major significance, while for other parameters, like pavement temperature, large discrepancies could have serious consequences. Within the scope of this study, the team has suggested some representative values for the range and accuracy of different parameters.

The accuracy of the sensors should ideally match, or exceed, the values given below, while also satisfying the other functional and performance requirements described in this chapter. The level of accuracy required from sensors used to provide data for forecasts, should at least meet existing standards used in meteorology.

FAA Advisory Circular 150/5220-16A includes values for weather measurements taken by automatic weather observing systems. In the United Kingdom, the Department of Transport has developed a specification for a national ice prediction network. This covers parameters to be measured, their range of values, and the accuracy. Values from these specifications are shown in table 5.

For monitoring of pavement temperatures, the sensors should cover a temperature range of -30 °C to 66 °C (-22 °F to +150 °F), with an accuracy of ±0.28 °C (±0.5 °F) over the temperature range of -30 °C to 50.5 °C (-22 °F to +122 °F). These ranges and accuracy specifications were specified by Mn/DOT for the procurement of a network of road weather stations. These specifications are more stringent than those of the UK Department of Transport which are contained in table 5. Experience suggests that some of the problems with forecast packages are due to sensors unable to operate within the limits of ±0.28 °C (±0.5 °F).

Perry and Symons suggest wind measurements should be accurate to ±5 percent and relative humidity within ±2 percent.(23)

Sampling Rates

For meteorological forecasting purposes, the rate at which measurements are recorded is relatively slow compared to the sampling rates generally achievable by state-of-the-art technology. Typically, meteorological parameters should be recorded at least hourly. However, these measurements should represent the average value over the recording duration. Depending on the sensor technology, the reading may actually be an average value of many sample readings taken at a faster sampling rate. The sampling rate should be sufficiently fast to ensure that all significant transient fluctuations are captured and a representative average value is obtained over the measurement period.

Table 5. Range and accuracy specifications

Parameter	FAA Advisory		Department of Transport	
	Range	Accuracy	Range	Accuracy
Surface temperature	N/A	N/A	-25 °C to -15 °C (-13 °F to 5 °F) -15 °C to 15 °C (5 °F to 59 °F) 15 °C to 25 °C (59 °F to 77 °F)	±1 °C (± 2 °F) ±0.5 °C(± 1 °F) ±1 °C (± 2 °F)
Depth temperature	N/A	N/A	-25 °C to -15 °C (-13 °F to 5 °F) -15 °C to 15 °C (5 °F to 59 °F) 15 °C to 25 °C (59 °F to 77 °F)	±1 °C (± 2 °F) ±0.5 °C(± 1 °F) ±1 °C (± 2 °F)
Air temperature	-35 °C to 55 °C (-30 °F to 130 °F)	0.5 °C (1 °F) RMSE Max error 1 °C (2 °F)	-25 °C to -15 °C (-13 °F to 5 °F) -15 °C to 15 °C (5 °F to 59 °F) 15 °C to 25 °C (59 °F to 77 °F)	±1 °C (± 2 °F) ±0.5 °C(± 1 °F) ±1 °C (± 2 °F)
Dew point temperature	-35 °C to 32.5 °C (-30 °F to 90 °F)	Various[1]	-25 °C to -15 °C (-13 °F to 5 °F) -15 °C to 15 °C (5 °F to 59 °F) 15 °C to 25 °C (59 °F to 77 °F)	±1 °C (± 2 °F) ±0.5 °C(± 1 °F) ±1 °C (± 2 °F)
Visibility	< 0.4 km - 2 km (<¼ mi - 1¼ mi) 2.4 km - 2.8 km (1½ mi - 1¾ mi) 3.2 km - 4.0 km (2 mi - 2½ mi) 4.9 km - 5.7 km (3 mi - 3½ mi) 6.5 km - 16.2 km (4 mi - 10 mi)	± 4 km (± ¼ mi) 0.4 km, -0.8 km (¼ mi, -½ mi) ± 0.8 km (±½ mi) 0.8 km, -1.6 km (½ mi, -1 mi) ± 1.6 km (±1 mi)	N/A	N/A
Wind speed	2 to 85 knots	2 knots or 10% RMSE, max 15%	99 knots	± 2 knots [2]

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[1] Accuracy 1 °C (2 °F) dew point at -1 °C to 52.5 °C (30 °F to 90 °F) (80-100% relative humidity), max error 1.7 °C (3 °F)
Accuracy 1.7 °C (3 °F) dew point at -1 °C to 49 °C (30 °F to 120 °F) (15-75% relative humidity), max error 2.25 °C (4 °F)
Accuracy 2.25 °C (4 °F) dew point at -29 °C to -7 °C (-20 °F to 20 °F) (25-95% relative humidity), max error 2.8 °C (5 °F)

[2] At wind speeds greater than 5 knots measured over 10-minute periods.

To determine a sampling rate for a particular environmental parameter, the following factors should be considered:

- The rate at which the environmental parameter changes.
- The response time and degree of integration incorporated in the sensor.
- The rate at which measurements are to be recorded.

The rate at which an environmental parameter changes has a significant influence on the sampling rate required. For example, if the parameter changes relatively quickly, a fast sampling rate should be used, but for slowly changing parameters a slower rate is adequate.

The sampling rate may also be dependent on the characteristics of the sensor. Some sensors inherently integrate and/or average readings over the sampling period, therefore reducing the need for a fast sampling rate. Another aspect is the response time of the sensor. If an application requires instantaneous values of a rapidly-varying parameter, such as maximum wind gust speed, the sensor must respond faster than the monitored parameter. The sampling rate should be at least double the rate at which a parameter changes, in order to accurately track changes in the parameter.

The recording frequency required defines the absolute minimum sampling rate. The minimum sampling rate may be higher than the recording rate in order to obtain a representative average value.

For meteorological and air pollution observations, measurements are usually recorded hourly, half-hourly, or every 15 min. For some applications, they are recorded more frequently than every 15 min. Therefore, sensors should be able to provide measurements at least every 15 min. These measurements will represent the average value over the 15-min period.

Fog formation is usually rapid once started in air that is free from smoke pollution, and the visibility can fall from about 3.2 km (2 mi) to 180 m (600 ft) or less in under 10 min. Hence, for real-time advisory driver information, sensors should be able to record visibility measurements at least every 5 min.

For some applications, a faster real-time response may be desirable. Monitoring the slickness of pavement surfaces ideally requires immediate advisory driver information when conditions become hazardous. An alternative approach is for the monitoring system to take less frequent measurements of pavement conditions and use other meteorological factors to predict the onset of the hazardous condition. However, such an approach may require additional hardware to process the prediction algorithms and the predictions may be subject to error.

Calibration

Calibration of sensors is essential if the measured values are to be used directly. Although calibration is vital to achieve accurate sensor operation, the manpower required to calibrate an extensive network of sensors must be balanced against the overall benefits. The sensors requirements by being able to operate for long periods before requiring recalibration. The calibration process falls into one of the following:

- Initial calibration, perhaps under laboratory/controlled conditions.
- Onsite calibration (periodic recalibration).
- Periodic recalibration under laboratory/controlled conditions.

The methodology used for calibration is similar for all of the above possibilities. Typically, calibration involves a zero calibration and a span calibration. For a linearly-behaved sensor this defines offset and gradient scaling values. For a nonlinearly-behaved sensor the response function describing the relationship between the parameter's value and the sensor's output must be known and additional calibration points throughout the sensor's operating range may be required.

The zero calibration involves comparing the sensor's reading of a particular parameter with a known value for that parameter. The known value is sometimes zero, hence the term zero calibration, otherwise it may represent the minimum value to be monitored by the sensor. Zero calibration ensures the sensor's readings accurately correspond to absolute values of the parameter, as opposed to a constant offset between monitored and actual values over the range monitored. Similarly, the span calibration is normally carried out at the maximum value that the sensor will be required to monitor. Again, the sensor's reading is compared with the actual value of the monitored parameter.

If the zero and span calibrations agree with actual parameter values, then, provided the sensor has a linear response over its operating range, all measured values will reflect the actual parameters within the specified level of accuracy. For nonlinear sensors, the response function must be known and additional calibration points over the operating range will be needed for effective calibration.

However, the procedures for calibration require the parameter to be changed from a minimum to a maximum value. Clearly, such procedures can only readily be created in the laboratory. In situ calibration may be required for some sensors even though they have been calibrated in the laboratory. In this case, sensor readings can only be compared against the limited range of values available at the site, and so accurate operation over the sensor's entire range cannot be guaranteed.

Ideally, the sensor should be able to operate within its specified level of accuracy for long periods of time without recalibration. When recalibration is necessary, it should be possible to quickly calibrate the sensor on site. If the sensor must be calibrated in a laboratory environment, it should be relatively easy to remove the sensor from its mounting.

In order to reduce the calibration effort, the number of calibration points required for a sensor should be kept to a minimum. If, for example, the sensor has a linear behavior and its gradient scaling factor is known to remain constant over long periods, only one calibration point may be necessary to adjust the offset value.

The ideal sensor, with regard to calibration, is one which can perform an unattended automatic calibration and adjust its calibration in situ to ensure accurate measurements are achieved. Such a sensor may still need some manual intervention, but on a less frequent basis.

Reliability and Robustness

Environmental sensors for highway applications are required to operate unattended and continuously over long periods of time, and throughout adverse weather, pavement, and traffic conditions. In these situations the sensors need to maintain the specified levels of accuracy. For the systems to be effective, providing drivers with advisory messages and informing State agencies of severe weather conditions, it is important they maintain reliable operation throughout these periods.

Sensors must operate accurately in the most severe weather conditions. Their construction must be sufficiently robust to withstand the adverse weather conditions they are monitoring. In addition, sensors mounted in the pavement must operate reliably and accurately over the expected environmental, pavement, and traffic conditions. These sensors should be able to withstand thermal expansion and contraction of the pavement. Reliable operation should be maintained for all types and depths of precipitation, as well as ice on the pavement surface and the presence of deicing chemicals.

Sensors should have low maintenance requirements and a long life expectancy. The mean time between failures should be large and the mean time to repair or replace should be small. Preferably, sensors should not cause serious disruption to traffic flows when they need calibration, maintenance, or repair/replacement.

For an advisory driver information system to be effective, it is important that the driver perceives the system to be accurate and reliable. When a sensor is no longer operating correctly, it should be designed to fail in a way that is obvious.

Communications between sensors and data collection subsystems should be reliable, with detection and correction of data transmission errors. These should operate reliably over all weather conditions and not be susceptible to, or cause, electromagnetic interference.

Power Requirements

Power consumption of the sensors should be low to allow the option of powering the sensors by batteries or solar power. Many sensors are likely to be in continuous operation and so battery-powered operation alone is not practical, as this would entail significant manpower to change batteries over an extensive Statewide monitoring network.

Where sensors require main power, they should be able to operate reliably and cope with fluctuations in the power source. Power protection is essential, including lightning protection. Automatic reset of sensors following a power failure is a desirable function. For some applications, it may be necessary to ensure continuous sensor operation during power failures, and so sensors should be designed to operate with battery backup.

LOCATION

The siting of sensors depends on a number of factors, such as the application, required range of coverage, characteristics of the sensor, and characteristics and variability of the environmental parameter to be measured. In general, the environmental monitoring system should receive data from a network of sensors which provide a sufficient level of detail and are representative of the monitored area.

The level of detail required will vary with the environmental parameter being monitored. Many of the meteorological parameters used for forecasting purposes change relatively slowly over distance, so the distance between sensors monitoring these parameters can be relatively large. However, the site chosen for sensors should experience conditions typical of those over the area represented by the sensor.

One method for identifying the position of meteorological sensors is to assume the area concerned is relatively flat. A network of sensors can then be established based on a grid, with the size of the grid spacing reflecting the spatial variation in the monitored parameter and/or the overall system cost. In reality, the terrain may be complex and mountainous so at some points on the grid it may not be feasible to install sensors. In these cases, the sensors may be omitted, or placed at the nearest practical point to its theoretical position, because the area covered by the sensor is so remote and the potential benefits would not justify the cost. Extra sensors may also be deployed at sites known to have specific adverse weather conditions. For example, a low-lying area surrounded by hills may be susceptible to dense patches of fog, and would require additional sensors.

Once the theoretical positions have been determined, the actual sites can be selected based on the physical highway network. For convenience, the sensors should be located close to the road but not so they are influenced by passing vehicles or susceptible to damage from vehicles. Availability of power and communications can be determining factors, although not of primary consideration.

To detect pavement surface conditions, sensors need to be deployed along or in the highway. To provide complete coverage would require significant numbers of sensors. Therefore, highways need to be prioritized based on their importance and susceptibility to adverse weather conditions. These sensors can be superimposed on the grid of meteorological sensors described above. Where feasible, it is desirable for the pavement sensors to share the same housing, power, and communications as the meteorological sensors. Extra sensors may also be deployed at locations prone to specific environmental conditions.

An alternative strategy is the use of wide-range scanners and mobile sensors. A sensor able to scan a wide area offers major benefits in reducing the number of sensors required throughout the network and providing comprehensive coverage of the area. Examples of technologies able to satisfy this requirement are satellites and radar. Mobile sensors attached to vehicles also potentially offer comprehensive coverage of the highway network. For driver information purposes, the sensor may be fitted to the vehicle to scan the conditions ahead, providing total highway coverage for the driver. Integrating the output into mobile communication systems, such as those proposed in IVHS applications, will allow wider dissemination of the information.

The location of wind, temperature, humidity, and atmospheric pressure sensors used to forecast weather conditions can generally be separated by relatively large distances, as these parameters do not vary rapidly with distance. A significant amount of meteorological data can also be obtained from satellite and radar observations using various bands of the electromagnetic spectrum (e.g., visible, infrared, and microwave radiation). These technologies provide exceptional coverage from a very small number of sensors.

To monitor pavement conditions, sensor deployment should ideally provide total coverage of the highway. However, sensors mounted in the pavement can only monitor local conditions, which can vary along the road. This implies locating many sensors over a highway. Due to budget constraints and cost/benefit considerations, the number of pavement sensors is usually limited. It is therefore necessary to identify the most appropriate sites. The use of thermal mapping is one technique which has been developed to establish the number and correct location of pavement temperature sensors. According to Perry and Symons, a network of sensor sites across a region may only require one sensor site per 250 km^2 (100 mi^2) depending on road density and regional climatic variations.(23)

For avalanche prediction, the depth and profile of snow along the mountain needs to be known. To get an accurate picture would require an excessive number of sensor probes arranged in a grid across the mountain, or alternatively a limited number of scanning sensors. In practice, it may be necessary to have fewer sensors across the mountain and use interpolation and historical correlation data to predict snow depths and the likelihood of an avalanche.

The siting of sensors must be such that the sensor is able to perform accurately and reliably in its selected environment. The sensor should be mounted to obtain representative readings of the monitored environmental parameter and protected from damage in its environment.

DATA OUTPUT

The functional requirements for data output will depend on the application, the type of parameter being measured, and whether the sensor is connected to local or remote systems. To realize the maximum benefits of environmental sensor systems and emerging IVHS technologies, it is important that standard interfaces are utilized. The adoption of common hardware and communications protocols facilitates the exchange of weather information and provides a ready mechanism for future system enhancements.

Hardware Interface

Technologies vary widely across sensors monitoring the same or different parameters. However, the fundamental requirement is that all sensors represent their output as an electrical signal which can be converted into a standard format by electronic circuits. If the sensor is a relatively simple device with no processing power, the electrical signal generated will need to travel between the sensor and a local data collection subsystem, without suffering a significant deterioration in signal quality. Transmission of the signal should be based around a common specification so that a modular approach can be adopted between different types of sensor and data collection subsystem, or RPU.

For a sensor with limited processing ability, the transmission of data to the RPU is best accomplished by the use of a digital serial data link, such as RS232 for relatively short distances or a more robust serial interface for longer distances. The digital link should also incorporate an error detection/correction mechanism to ensure integrity of the data.

Where sensors and RPU's have reasonable processing capabilities, a common hardware and software interface should be adopted. This should be based on open communication standards. Again, data transmissions should incorporate an error detection mechanism and correct or retransmit corrupted data.

Both analog and digital data links must operate reliably in their roadside environment, particularly in the presence of severe environmental conditions such as storms, electrical discharges, ambient levels of electromagnetic fields and electromagnetic radiation (including radio and microwaves), and transient power surges and brownouts. The data transmission should also comply with all relevant regulations such as those governing electromagnetic compatibility and radiation.

Additional functional requirements will need to be specified if the environmental sensor systems are required to provide direct control or activation of advisory signs. This is not addressed within the scope of this study.

Software Interface and Communications Protocol

For digital data links between sensors and RPU's, the software interface should, as a minimum, ensure that data transmission errors are detected and corrected. A standard communications protocol should be adopted, providing an open systems approach. A communications protocol based on the International Standards Organizations OSI 7-layer model is recommended.

Data transmissions should comply with a common format which allows identification of the environmental parameter being monitored, its average value, period covered, and maximum and minimum values over the period. The sensor should be able to report its status and any faults detected. Off-scale measurements should also be identified. The protocol adopted should be compatible with the World Meteorological Organization FM 94 BUFR (Binary Universal Form for Data Representation) and FM 92 GRIB coding systems.

For sensors that communicate directly to a network infrastructure, as opposed to going via an RPU, the following additional requirements apply. As the sensor may be polled by a control center, the sensor must be able to store its measurements over the duration of the polling cycle and store its data for longer periods in the case of a communications failure.

The interface to the communications infrastructure, whether direct from the sensor or via an RPU, should support a standard communications protocol. This approach offers a number of distinct benefits:

- Sensors and RPU's can be provided by a range of vendors, allowing a wide range of products and features at competitive costs.
- Vendors' products can be mixed on the same system architecture, so that the most suitable sensors for each environmental parameter can be selected.
- The communications infrastructure can be shared with other data systems, for example air pollution sensors, traffic data collection systems, and IVHS.
- An open communications protocol gives the option of using alternative communication infrastructures and transmission media.

OPERATION AND CONTROL

Integral to any environmental sensor system for safe traffic operations are the operation and control aspects. The overall system has the task of gathering data from environmental sensors, processing this information to determine the current state-of-the-highway network, forecasting weather and pavement surface conditions, and providing advisory information to State highway authorities and drivers. A typical system is therefore likely to consist of the following components:

- A network of environmental sensors.
- RPU's.
- Communications infrastructure.
- Intelligent onsite controllers.
- Variable message signs for driver advisories.
- CPU and control center.
- Other advisory driver information systems, such as those supported by IVHS.

Operation and control elements of a generic condition-responsive driver warning and control system will be governed by the needs of the users and the agencies responsible for its functioning. For the State agencies charged with snow and ice control, the real-time information from pavement sensors will need to be combined with short-term meteorological forecasts to derive response strategies. Full integration of the available information, together with computer analyses and prediction, remains the ultimate aim. Limitations with near-term forecasting, however, mean that manual interpretation of data will remain a requirement in the system operation, at least in the short-term.

To allow accurate predictions of highway conditions, the control center will need to combine the highway sensor data with other meteorological data. This will require direct links with weather centers, and also with neighboring jurisdictions. Integration of the data sources is likely to be a key requirement.

Travel advisories will be the major output from the sensor system, providing real-time warnings to drivers as well as forecast information on potential hazard conditions. Environmental sensor information will be disseminated by a variety of approaches, including radio broadcasts, roadside variable message signs, and potentially by the activation of in-vehicle displays. System operation, therefore, needs to be flexible to enable both standard, preformatted messages and variable messages to be disseminated to drivers in real-time. For maximum benefits, the system needs to respond quickly, informing drivers of adverse road conditions as soon as they are detected or forecast.

SUMMARY

The functional requirements for a generic condition-responsive driver information and warning system are numerous. Several parameters and performance criteria have been identified which the sensors should satisfy. Other requirements relate to siting of sensors, data outputs, and operational and control aspects. These provide a platform from which a detailed specification can be developed. The main functional elements are summarized in table 6. In the table, requirements considered highly desirable are indicated by ✓✓. Requirements of lesser importance, but nonetheless desirable, are shown by ✓.

Table 6. Summary of functional requirements

Environmental Parameter									
Requirement	Air temp.	Wind	Humid.	Precip	Cloud cover	Visibility	Pavement		
							Temp.	Moisture	Chemical
Accuracy	✓	✓✓	✓	✓✓	✓	✓✓	✓✓	✓✓	✓✓
Reliability	✓✓	✓	✓	✓✓	✓	✓✓	✓✓	✓✓	✓
Open interface	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Real-time response		✓		✓✓		✓✓	✓✓	✓✓	✓
Wide-area coverage				✓✓		✓✓	✓✓	✓✓	✓
High spatial resolution						✓✓	✓✓	✓✓	
Identify type				✓✓		✓		✓✓	
Durability	✓	✓	✓	✓	✓	✓	✓✓	✓✓	✓✓
High cost/ benefit ratio	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Compact				✓		✓	✓✓	✓✓	✓✓
Low power	✓	✓	✓	✓	✓	✓✓	✓✓	✓✓	✓✓
Fully automatic	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Min. traffic impact for maintenance				✓			✓✓	✓✓	✓✓

CHAPTER 6. STATE-OF-THE-ART REVIEW

This chapter contains a state-of-the-art review of environmental sensor systems. It is divided into two sections: one covering the basic operating principles of the sensors, and the other presenting the review of commercial systems. Information contained in these sections has been obtained from literature searches, brochures, and technical reports. Manufacturers of systems worldwide were invited to provide information on their systems.

OPERATING PRINCIPLES

Environmental sensors can be categorized into several types based on their function. The main types are:

- Atmospheric.
- Pavement.
- Visibility.
- Wind.

Atmospheric sensors have been well-developed for the general meteorology market, with roadside weather stations available from a large number of vendors. Atmospheric sensors, therefore, are not discussed in detail.

Pavement Sensors

Pavement conditions can vary considerably from one location to another and over time. It is therefore necessary to utilize sensors located within the pavement to provide information on the present conditions. Data gathered by the pavement sensors can be used to predict pavement surface friction. Several factors determine the coefficient of friction, such as temperature, precipitation, and presence of deicing chemicals. In addition, atmospheric sensors allow prediction of future pavement conditions.

Pavement sensors can be divided into the following categories: passive, active, freezing point, vibration, microwave, and infrared.

Passive

Passive sensors are small, thermally passive, and are buried in the pavement with the surface exposed. The sensors are made of material with similar thermal properties and color to the pavement so that they will warm and cool in tandem with the pavement. They use a thermistor, resistance thermometer, or thermocouple to measure temperature. All of these approaches have been proven to be reliable and accurate. Temperature is normally measured at the pavement surface and below the surface. In some cases, a separate temperature sensor

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is buried a couple of feet below the surface. It is important to determine how much heat is flowing from the ground into the pavement to determine the amount of deicing chemicals to apply. The pavement sensors may also measure conductivity with electrodes to infer the concentration of deicing chemicals. Capacitance measure may also be used to determine the presence of moisture.

Active

Active sensors are fundamentally different from the passive type in that they take energy away from the sensor in order to predict future road surface conditions. An area on the surface of the sensor is cooled to approximately -16 °C (4 °F) below ambient. If frost or ice forms, it implies that moisture is present. Further reductions in pavement temperature may lead to icing on the roads. The sensors may also include a heated area to melt any dry frost, ice, or snow not detectable by conductivity.

Potential problems with these sensors are that they can be quite large, thereby having their own microclimate; the plates may possess different thermal characteristics than the highway; and they require a power source.

Freezing Point

Freezing point sensors directly measure the freezing point of any precipitation on the roadway. Road precipitation is funneled into a cup on the surface of the sensor, which is cyclically heated and cooled. The cooling cycle continues until latent heat release is detected. An advantage of this technique is that freezing point is measured independent of the type of deicing chemical used. A disadvantage is that the cup may tend to fill with debris.

Vibration

Vibration sensors are buried in the pavement and contain a surface plate, which is constantly vibrated. Analysis of the vibration signature can determine whether the road is dry, wet, or icy, as well as the thickness of the water or ice film.

Microwave

Microwave sensors employ a transmitter and receiver mounted above the roadway. The transmitter bounces microwaves off the roadway towards the receiver. If there is a film of water on the roadway, microwaves will bounce off both the surface of the water and the road surface. At the receiver, an interference pattern is created by the two reflections, which is analyzed to determine the film thickness and its salinity. It has been reported that this type of sensor can measure water film thickness up to 10 mm (3/8 in), but that icy roads cannot be identified.(1) One advantage of microwave sensors is that a fairly large section of roadway is analyzed, compared with pavement sensors. Sensors of this type can be readily installed and maintained as they do not involve digging up the roadway. However, there is concern that the technology may be too expensive for general use.

Infrared Combination

Another sensor type under development is a combination of infrared to measure temperature and a moisture sensor. The infrared sensor consists of a source and detector mounted approximately 7.6 m (25 ft) above the roadway, covering an area of about 3 m^2 (10 ft^2). The sensor works by looking at the diffuse reflected radiation in order to distinguish between dry, moist, wet, and snow-covered conditions. The moisture sensor is buried in the pavement but has a slightly raised area which allows the measurement of water depth to 3 mm (1/8 in). The pavement sensor measures temperature, along with the conductivity of the moisture. The combination of the surface readings and the infrared measurements is used to assess surface moisture and residual chemicals. A network of these systems is reported to be in operation in Germany.(3)

Infrared - Microwave

In the European DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe) program, the CROW project has developed a sensor which combines infrared and microwave approaches. Since microwave alone cannot determine icy conditions, infrared reflection is used to distinguish between dry, wet, and icy conditions. In addition, water levels and ice thickness up to 2 mm (5/64 in) can be distinguished from infrared reflections. The cost-effectiveness of this type of sensor has yet to be established.

Laser

Also within the CROW project, a laser imaging system has been developed. A laser scans the roadway and a CCD camera records the reflection. Image processing and identification techniques are used to determine road condition. Water thickness cannot be measured since the laser will bounce off the air to the water surface only. This technique is being considered for moving vehicle use.

Infrared Sensors

Infrared sensors are used to measure road temperature for thermography purposes, but are considered too expensive for continuous use in a road monitoring system. Further examination is needed to determine if future technological improvements could lower the cost of infrared sensors. One problem with infrared sensors is that they measure emissivity, not temperature. For a given surface, emissivity is proportional to temperature, but if the surface characteristics change due to precipitation, the emissivity changes. This property is being exploited by the infrared sensors mentioned above.

Road Friction

Measurement of road friction or skidding resistance has traditionally been undertaken with a vehicle and elaborate equipment. A violent application of the brakes for a period of 1 s at 49 km/h (30 mi/h) allows the skidding resistance to be measured with a decelerometer or, indirectly, in terms of stopping distance. An alternative is to use a brake trailer towed behind a vehicle or a side-slipping wheel. Portable devices are also available to measure road friction at specific points, but their use for adverse environmental monitoring is limited.

Recent developments by automotive companies have focused on traction sensors. These sensors determine the degree of slip between the road and wheel, such that if a slip condition is detected, the engine power is automatically switched to wheels with better traction. Traction is measured by determining the torque.

Development work has been carried out by Porsche in the European PROMETHEUS program to incorporate road friction measurement directly into vehicles, as described in chapter 4.

Summary

Most pavement sensors are point sensors, as they only indicate conditions at one specific point on the roadway. As a result, strategic placement of the sensors is critical to ensure pavement conditions are appropriately monitored. One method used to determine the best sites for sensor placement is thermal mapping. The process of thermally mapping sections of roadway involves the measurement of the spatial variation of pavement temperature under different weather conditions using an infrared temperature sensor. The road condition of an entire roadway can then be predicted from the point sensors along the road and the road thermography data base. Guidelines for siting road weather information sensors have been developed under SHRP.(34)

Visibility Sensors

Two key parameters are of interest in establishing the hazard associated with conditions of reduced visibility. These are the value of the horizontal visibility at a given point and its variation along the route. As with the pavement condition sensors, systems for measuring visibility can be divided into infrastructure-based and vehicle-based approaches. Infrastructure-based technologies are widely used, while future vehicle-based systems offer the potential to monitor sections of highway rather than limited points.

Visibility sensors operate on one of three main principles. These principles are luminance contrast, atmospheric transparency, and light scattering by airborne particles. In each approach the objective is to measure the atmospheric opacity by determining the extinction coefficient of light scattering and absorption in the visible range.

The first type of visibility sensor is the transmissometer, which consists of a laser source and receiver mounted so that the transmitter is aimed at the receiver. As the visibility of the atmosphere between the transmitter and receiver is reduced, the receiver will register less light in direct proportion to the reduced visibility. To avoid confusion with ambient light, the transmitter light source is modulated and the receiver synchronously demodulated. Any received light which is not modulating at the proper frequency is eliminated by this process. A modulation frequency is chosen (typically 1 to 3 kHz) which is not produced by natural atmospheric effects. To provide accurate readings over time requires the transmitter to be self-calibrating by use of a photo diode and servo feedback loop to keep the transmitter output constant. To get accurate readings, a large distance (baseline) is needed between transmitter and receiver.

Light scattering techniques or nephelometers also use a light transmitter and receiver; the receiver measures the scattered light instead of direct light. As visibility decreases, the scattered light increases. For the forward scatter technique, the receiver is placed (depending on the manufacturer) from 33 to 70° off the light source axis. The transmitter and receivers typically have no-dew windows with thermostat heaters on the inside and hoods outside. The transmitter consists of an near-infrared light source (typically a diode), projector lens, and photodiode. The photodiode monitors light source output to provide an electronic feedback to maintain constant power output. Some manufacturers locate the photodiode outside the window to compensate for dirty lenses. The light source is modulated at a frequency between 1 and 3 kHz so that the receiver can synchronously demodulate the input to distinguish between ambient and source light. The receiver typically uses a photodiode.

Most manufacturers claim that forward scatter sensors only require calibration on installation. The calibration technique consists of inserting a standard scattering medium in the optical path of the instrument. Pauwelussen et al., however, question the frequency of calibration required by this type of sensor.(28) Further investigation would be needed to resolve this issue.

One problem with the forward scatter technique is the effect of water particle size. In fog, the forward scatter sensor accurately measures visibility, but in rain, the measurement values are too low. The manufacturers mention the problem, but claim their instruments are compensated to alleviate the problem. Information on this compensation is vague and is probably an area of proprietary design. The reliability of one-angle nephelometers needs further investigation given the dependence on size of water droplets.

Another variant of the light scatter technique is to measure back scatter. The principle is the same as forward scatter except the receiver and transmitter are aligned on the same axis. A beam splitter is used inside the device to separate the transmitted and received light. The primary advantage of a back scatter sensor is that it is easy to mount on a vehicle. Such devices are experimental at this point, such as the work being performed by Volkswagen in the PROMETHEUS program. The largest issue here is to determine if there is a dependency on droplet size and whether it can be compensated for.

Another variant of the light scatter technique is to measure the scatter at all angles (integrating nephelometer). In the DRIVE program, the CROW project reported research and development of a prototype nephelometer. This consists of an omni-directional light source used with two receivers at different angles and a light trap or reflector at another angle. The report claims that visibility measurements with this instrument are independent of droplet size.(1) If this device can measure visibility more accurately than a one-angle nephelometer, it has excellent potential. Additional information on this sensor will be required to assess its full potential.

A study of road condition sensors by Schrack indicated that remote surveillance with video cameras was helpful under some conditions to verify what road condition sensors were indicating.(36) Video cameras are increasingly being used in traffic measurement with such systems as AUTOSCOPE™. It may be desirable to co-locate video surveillance centers with road condition centers for information sharing. Possibilities also exist for determining visibility from video images.

Wind Sensors

Wind measurement is a major element of roadside environmental monitoring systems. Parameters measured are wind velocity, direction, and variability. Some techniques seek to measure the wind directly, while others focus on alternative physical characteristics related to wind.

Fima et al.(37) suggest wind velocity can be determined by measuring the following parameters:

- Differential pressure.
- Aerodynamic force.
- Differential transit time of an ultrasonic wave (sonic anemometer).
- Vortex frequency generated by an obstacle placed in the air flow (vortex anemometer).
- Rotational speed of a vane (propeller anemometer).
- Generation of an ion stream by corona effect and measurement of the induced currents on different electrodes (ionic anemometer).
- Thermal transfer (hot wire or hot film anemometer).
- Aerosol velocity by laser anemometry.

Measurement of wind speed through differential pressure requires the use of a pressure tube, which allows calculation of both static and total pressure. Wind speed is derived through a simple equation relating these parameters to air velocity and density. For accurate measurement, the pressure tube must be aligned with the wind direction, and is therefore mounted on a vane. This can create problems over the response time of the vane alignment and vane oscillations under certain conditions.

A second technique for wind measurement is calculation of aerodynamic force. This typically utilizes a sphere mounted at the end of a balanced arm, allowing for rotation about two axes. Force sensors at the other end of the arm measure the corresponding wind force components. The force sensors must be covered with some type of case, which leads to potential stiffness problems at the interface of the case and the arm. A further problem with this type of system is ensuring its insensitivity to gravity, due to the balance of the sphere on the arm.

Sonic anemometers are commercially-available devices which give a very accurate measure of wind speed. Their operating method is based on the composition of sound wave velocity in still air and flow velocity. Each unit contains two transceivers, between which the propagation time of an ultrasonic pulse is measured. Wind velocity is then calculated according to the pulse propagation times in each direction. There are no moving parts within the device, supporting equipment reliability over extended operating periods. The principal disadvantages of sonic anemometers are their power requirements and high costs.

Another type of wind sensor with no moving parts is the vortex anemometer. This involves a cylindrical body which creates a series of vortices when subjected to a crosswind. Wind velocity is proportional to the vortex formation frequency. This can be measured using hot wire detection or amplitude modulation of an ultrasonic beam across the vortex trail. In practice, the cylindrical object may be placed inside a pipe, which must be aligned with the wind direction using a vane. This again leads to problems over excessive response time. An alternative approach involves the uses of two orthogonal sensors to measure components of wind velocity and thus calculate the overall speed and direction.

One of the simplest and most commonly-used types of wind sensor is the propeller anemometer. This allows wind velocity to be calculated through measurement of the propeller rotation frequency. If only one propeller is used it must be mounted on a vane and may be subject to long response times. Alternatively, two propellers can be used to measure axial wind components. Rotation of the propeller can be measured using an inductive position sensor. The main problem with this system is the potential for mechanical failure, particularly due to moisture or dust within the precision bearings.

A further type of anemometry is hot wire or hot film anemometry. These involve the calculation of wind speed through measurement of the cooling of an electrically-heated metallic wire or film. Wind speed is calculated using a known empirical relationship between air velocity, air temperature, current, and the electrical resistance of the material. Two sensors are generally required in order to calculate wind components and thus establish total wind speed. Hot wire probes are very accurate devices, often used in wind tunnel experiments. However, they are fragile and require complex calibration. Hot film sensors tend to be less accurate but are mechanically more reliable, making them more suitable for roadside use.

A final technique for wind measurement is laser anemometry. This involves focusing a laser beam on a small volume of interference fringes. Laser anemometry represents a precise measurement approach, but one which is potentially too complex and costly for widespread current use.

All of the techniques outlined above are applicable to wind measurement at a single, static point. However, wind measurement using an in-vehicle device is also a potentially valuable feature of future environmental monitoring systems. This would allow vehicles to act as probes in reporting on wind conditions. Vehicle-based wind measurement could also be particularly useful for providing warning messages in vulnerable areas, such as high-sided vehicles.

Investigations into vehicle-based wind measurement have recently been undertaken within the European DRIVE program. This reviewed the suitability of many of the approaches outlined above for use in the vehicle. Wind measurement from a vehicle is complicated in that movements of the vehicle itself, as well as adjacent vehicles, create aerodynamic disturbances. The exterior of the vehicle represents a harsh operating environment in which sensors will be subjected to vibration and impacts, in addition to conditions normally experienced at the roadside. Aesthetic consideration may also cause drivers to reject any type of wind measuring device which protrudes physically from the vehicle.

REVIEW OF COMMERCIAL SYSTEMS

A considerable range of commercial, environmental monitoring systems is available. The main systems suitable for highway applications are described below. Details are provided in terms of type of sensor.

Pavement Sensors

Climatronics (U.S.) - FRENSOR

This is an active device which is buried in the concrete and directly measures the freezing point using a peltier element. The device consists of a small cup which collects precipitation and cyclically (5-min cycle) freezes and melts the mixture to determine the freezing point. The temperature of the cup is measured and if an increase or stabilization of temperature is detected during the cool down cycle (representing latent heat release), that temperature is the freezing point. If the roadway is dry, the algorithms in the microprocessor detect and report this condition.

One-time calibration with pure water solution and known salt solution is required on installation. The device which is buried in the concrete is only able to collect data at one point on the road, so it is necessary to install multiple sensors at a site. The roadside microprocessor that accompanies the FRENSOR can support up to four sensors.

The manufacturer claims the tire traffic is constantly mixing the contents of the cup, keeping it representative of the surrounding roadway. Another problem is that the cup can fill with debris. The manufacturer claims the control software can determine when this happens and the reading can be rejected. Additional study is needed to determine if a site with multiple sensors will always have sufficient sensors free of debris to provide reliable measurements. An advantage of this device is that it directly measures the freezing point rather than inferring it from other measurements.

A Swedish National Road Administration COST 309 report indicates the freezing point is accurately measured by the FRENSOR.(38) The device also measures pavement temperature near the surface and 40 mm (1.5 in) below the surface. By comparing information from the FRENSOR and dewpoint temperature, it is possible to distinguish between dry, wet, frost, and ice conditions.

Surface Systems, Inc. (U.S.) - SCAN

The SCAN sensor is an in-pavement sensor. The sensor measures temperature, determines if the road surface is wet or dry using a capacitive technique, and measures conductivity to determine salinity. The sensor is thermally passive and fabricated using materials with the same thermal characteristics and color as the roadway. The capacitive sensor is located immediately below the surface of the sensor and depends on the difference between the dielectric constant of air and water. A thermistor measures temperature. Electrodes on the sensor surface measure conductivity across the sensor surface. Use of the sensor with a SCAN system consisting of a remote weather station and a central CPU can keep track of current road conditions and make forecasts. The system has been well tested and is in widespread use with over 200 installations reported. The cost of each ice detection station, including commissioning and installation, is approximately $35,000.

Vaisala (Finland) - Road Surface Sensor DRS12

This sensor, normally connected to a Vaisala MILOS weather station, is passive and buried in the roadway. The thermodynamic properties and thermal emissivity are designed to match the roadway so that the sensor's thermal measurements match the roadway. Temperature sensors are located at the top and bottom of the sensor so that both a surface and below-surface temperature are measured. The temperature measurements are used to determine the risk of icing and amount of chemical application if any. Electrodes on top of the sensor measure the conductivity of any surface water to estimate the salt concentration. For frozen conditions, capacitance is measured on the electrodes to give an indication of ice presence. The four sensors of the DRS12 can infer the following conditions: dewy, frosty, icy (white ice) or snowy, monocrystalline (transparent) ice, wet, wet and salty, dry, drying, and chemical.

AANDERAA Instruments - Road Surface Temperature Sensor (3304) and Conductivity Sensor (3330)

The conductivity sensor uses four copper electrodes to measure the conductivity of any moisture present on the sensor. The sensor must be located in the road shoulder, as only a thin film of moisture can be present. The conductivity is always measured at 1.1 °C (34 °F), with a heater used to warm the film of water.

The temperature sensor is mounted flush with the road surface in the lanes of travel. The sensor has a wear indicator to indicate when replacement is necessary. The sensing element is a platinum resistor in a Wheatstone half-bridge. Only the surface temperature is measured and not a below-grade temperature. The road temperature and conductivity together determine the freezing point.

Findlay Irvine (Scotland) - Road Surface Sensor

This surface sensor is mounted flush with the road surface and measures surface temperature, surface condition (dry, wet, ice/snow), and freezing point. Based on the limited information available, the sensor operates by chilling a portion of the sensor head until ice forms, which indicates the freezing temperature. The freezing temperature can be measured to four levels:

0 °C, -3 °C, -6 °C, and -10 °C (32 °, 27 °, 21 °, and 14 °F). In addition to a road surface temperature, a deep temperature sensor for measuring the temperature 300 mm (12 in) below the surface is included.

BG Engineering (Holland) - Road Condition Sensor

The device measures conductivity of the road surface. It is 60 mm (2.3 in) in diameter and consists of two concentric steel pipes. The sensor is mounted flush with the roadway and measures the conductivity of the roadway emulsion using the inner and outer pipe as electrodes. The sensor wears down with the roadway without affecting the performance of the sensor. A high value of conductivity indicates the road surface is wet and salty. A medium value indicates a wet surface and a low value indicates dry conditions. It is difficult to determine the difference between dry conditions and icy conditions since ice has low conductivity. One way around this is to use two sensors, one heated and one not. In icy conditions, the heated sensor will indicate wet and the other will not. This sensor yields limited information without additional information such as road and air temperature.(38)

Rails Company (Sweden) - Road Conditions Sensor

This company manufactures a device similar to that described above.

Vibrometer SA (Switzerland)

The Vibrometer is a steel pavement sensor which is 50 mm (2 in) in diameter. The presence of moisture is determined by constantly vibrating a surface plate. Analysis of the vibration determines if the road surface is dry, moist, or frozen. The thickness of the surface film can also be determined for water or ice. The surface plate is cooled and warmed using a peltier element. The phase change from ice to water is used to determine the freezing point rather than from water to ice to avoid problems with supercooled water.

Empirical data from the COST study show that a 3.5 °F (2 °C) error is introduced if using the phase change from water to ice and that the ice to water phase change was accurate to within 0.18 °F (0.1 °C).(38) The study also indicated the Vibrometer effectively distinguished between dry, moist, and wet conditions. How accurately the sensor measured water and ice films was not determined, but the study indicated there was a good correlation between indicated and actual film thickness. No indication was given to the durability of this sensor.

Hokkaido Development Bureau (Japan) - Dielectric Pavement Sensor

This sensor is buried in the pavement and measures capacitance, which is correlated to the salinity of the road surface. It has been reported that there is good correlation between salinity and capacitance, although the sensor is still experimental.

Boschung Mecatronic (Switzerland) - GFS2000 Ice Warning System

The ice warning system manufactured by Boschung Mecatronic consists of two sensors installed in the highway. A freezing-point sensor is used to determine the temperature of any water/chemical mixture found on the road surface. This is supplemented by a set of three ground probes. These are active sensors which are utilized to measure ground temperature and ice formation, as well as differentiating between dry, moist, and various wet states. The method of operation of these sensors is not disclosed in the information provided by the company.

Schrack Systems Inc. (Austria) - Road Condition Radar (RCR)

Road radar has the potential of measuring the thickness of the water layer and the salinity of the solution, from which the freezing point can be calculated. A radar transmitter bounces energy off the highway at a 60° angle of incidence into a microwave receiver. The signal processing electronics at the receiver can distinguish between reflections from the air-to-water interface and water-to-road interface. From these two reflections, the water thickness and salinity can be determined. Any interference from rain or fog is minimal because both reflections receive the same attenuation.

The radar device has an advantage over in-pavement sensors since it looks at a large area of the road across the width of the highway. Advantages over pavement sensors are that the pavement is not disturbed for installation, and a longer life can be obtained since the sensor does not wear down with traffic. The RCR can also measure water thickness which most pavement sensors cannot. Results from the DRIVE CROW project indicate a thickness of up to 10 mm (3/8 in) can be measured.(1)

The system is currently under prototype development. It is not known how economical the system will be or how robust the measurements will be under a variety of conditions.

RENSTAR - Road Temperature Monitoring System

The RENSTAR road temperature monitoring system model 991C is a vehicle-mounted noncontact device that detects surface conditions using an infrared thermometer. The device is externally-mounted on a vehicle; road temperatures are depicted on the dash-mounted digital display. The system has a 1-s cycle and a proposed accuracy of ±0.5 °C (±1 °F).

Visibility Sensors

AANDERAA Instruments - Visibility Sensor 3340

The 3340 measures visibility using a forward scatter technique. The measured range is from 50 m to 10 km (160 ft to 6 mi) with a claimed accuracy of ±20 percent. The device is very compact, measuring 92 mm by 79 mm (3.5 in by 3.1 in). Outside air is drawn into the device through vents and only tiny particles in the air (fog) effect the visibility measurement. It does not measure the reduced visibility caused by rain and snow.

Vaisala (Finland) - FD12P Visibility Sensor

The FD12P measures visibility and precipitation. Visibility is measured using a forward scattering technique. This technique uses an infrared transmitter and receiver where the axis of the receiver is 114 degrees different to the transmitter axis, as compared with a transmissometer whose receiver is directly opposite (180°) the transmitter. The forward scatter receiver will pick up more light as the visibility is reduced, the opposite of a transmissometer. To distinguish between ambient light and transmitter light, the source light is modulated at 2.5 kHz and synchronously demodulated by the receiver. Vaisala claims measuring visibility with a forward scattering device gives lower values than a transmissometer in rain and snow conditions, but that they have calibrated their device to compensate for this problem.

The FD12P also includes a precipitation monitor (traditional rain gauge). Between the precipitation monitor and the visibility meter, the control software can determine the type of precipitation (drizzle, rain, hail, sleet, and snow). The control software can also estimate the thickness of the water layer on roads. The output results are communicated via serial RS-232 ports. The FD12P is meant for a stationary location. Cleaning of the lenses is recommended every 3 to 6 months, but no other regular maintenance or calibration is required.

HSS - Visibility Sensor VF-500

The VF-500 uses the forward scatter technique. The offset angle of the sensor and receiver is 140°. The measured visibility range is 9 m to 10 km (30 ft to 6 mi) with an accuracy of 5 percent. The manufacturer claims the visibility can be measured for all forms of precipitation, but does not describe how different size water droplets are compensated for. The infrared source is modulated at 2 kHz to distinguish it from ambient light.

Maintenance requirements involve cleaning the sensor windows every 3 months. Unlike other manufacturers, HSS requires that the sensors be calibrated every 6 months. This may be because their specified accuracy is higher than other devices.

The output interface is RS-232. The instrument also has precipitation intensity options. HSS claims that for nighttime visibility measurements an optional ambient light sensor (ALS) is used. The ALS depends on knowledge of the average taillight intensity or some other target. No information was provided on why the ALS is necessary.

SCTI (U.S.) - Weather Identifier and Visibility Sensor (WIVIS)

This sensor, developed specifically for highway applications, measures visibility and precipitation. The visibility is measured using a forward scatter technique and precipitation is measured by analyzing the fluctuation of infrared beams. The same transmitter is used by the separate visibility and precipitation receivers. The precipitation receiver is 180° opposite the transmitter and the visibility receiver is off-axis. The forward scatter technique is essentially the same as used by Vaisala, but the precipitation measurement technique is unique.

The approach of analyzing the fluctuation of an infrared light beam relies on the fact that the amount of fluctuation is proportional to the intensity of the precipitation. Fluctuation frequencies as well as signal strength enable measurement and discrimination of rain and snow rates. The device gives continuous output of precipitation type, precipitation intensity, and visibility. Output from the device is on a RS-232 serial port. Sales literature indicates that optics require cleaning every six months, although no field calibration is required.

Wind Sensors

Furness Controls (UK) - Differential Pressure Transducers

Furness Controls manufactures a range of differential pressure transducers for climate control applications. Designed to measure low ranges (0 to 20 pascals), the transducer has high accuracy and repeatability with a stated resolution of 0.1 percent. An optional readout unit is available to display the measurements.

Kaijo Denki Co. (Japan) - DA/DAT Series

The DA and DAT series are ultrasonic anemometers-thermometers. The mode of operation is specified as time-sharing multiplex transmission/reception ultrasonic pulse emission. Design of the sensors allows determination of zero wind conditions, a rapid response time and the elimination of sound velocity error. An omnidirectional probe enables winds blowing from any direction to be measured up to 90 m/s (290 ft/s). Accuracy is stated as ±1 percent of the measured value and resolution is 5 mm/s (1/5 in/s).

J-Tec (U.S.) - VT1010 Solid State Anemometer

The VT1010 anemometer is a vortex type, designed to measure wind speed and direction without any moving parts. According to sales literature, the speed output consists of two pulse trains whose frequencies are proportional to the wind component speeds, while the direction is determined by two logic signals indicating component directions. Sensor accuracy is given as less than 3 percent of wind magnitude or two knots, whichever is greater. With no moving parts, no maintenance or calibration is required.

Höntzsch Instruments (Germany) - TAD

The company produces vane wheel anemometers for measuring wind flows. Wind speeds between 0.6 m/s and 40 m/s (2 ft/s and 130 ft/s) can be measured. CMOS electronics monitor the rotational speed of the vane. Accuracy is claimed to be 1.5 percent.

Cossonay (Switzerland) - Geotec Series 270

The GEOTEC Anemometer Series 270 includes hot film sensors for wind velocity and solid state transducers for atmospheric pressure. The hot film sensors determine a crosswind output voltage and headwind output voltage, from which the wind velocity and wind direction can be computed. Repeatability of measurements is given as ±1 percent.

TSI Incorporated (U.S.) - Model 202

The Model 202 anemometer is classified as an ionic anemometer. It is a dual axis version of the Model 201 which is installed on the M-1 Abrams Battle Tank. A high reliability rate is claimed as the sensor has no moving parts. The system is offered in ranges to 70 m/s (230 ft/s) together with linear or nonlinear outputs. Accuracy is stated as ±0.5 m/s (±1.6 ft/s), ±10 percent.

IRDAM (Switzerland) - Series 3022/3056

These sensors use the thermal field variation of a cylinder to measure wind velocity and wind direction. The speed range covered is 0 to 60 m/s (0 to 195 ft/s). According to the sales literature, the accuracy of the wind speed measurement is ±0.5 m/s (±1.6 ft/s), ±5 percent of actual wind, and wind direction ±2.5 degrees.

Micro Switch (U.S.) - AWM2000

Micro Switch, a division of Honeywell, developed the AWM2000 sensor in 1987 to measure mass air flow. The sensor uses integrated-circuit and thick-film technologies to achieve high sensitivity and rapid response. Physical and electrical microbridges are used in the sensor to measure the magnitude and direction of air flow.

Summary

This section has provided details of the main commercial systems available for monitoring pavement conditions, visibility, and wind direction and magnitude. Examples of the different technological approaches have been included where appropriate.

CHAPTER 7. RESEARCH AND DEVELOPMENT ACTIVITIES

The previous chapter covered the operating principles of different types of sensor systems and gave an overview of the major commercial systems. This chapter provides an outline of the main research and development initiatives into environmental sensor systems for safe traffic operations. The research activities are divided on a geographical basis covering the United States, Europe, and Japan.

U.S. INITIATIVES

In the United States much of the work into weather monitoring research for highway applications has come under SHRP or FHWA. Research performed by the Army, Air Force, and Navy also has applications to winter maintenance of highways, but this is not considered here.

SHRP

One of the main areas in SHRP has been research into snow removal and ice control. This area had the objective to provide safe, serviceable highways during winter conditions; reduce deterioration of bridges, pavements, and vehicles; and mitigate other adverse environmental consequences of snow and ice control.(39) The recommended research plan included studies into the prevention of ice-pavement bond, destruction of ice-pavement bond, development of improved displacement plows, improved methods of controlling blowing snow, and management of snow and ice control operations.

The study into management of snow and ice control operations had the specific objectives to adapt commercially-available equipment components to provide rapid assessment of storm warnings and pavement condition; develop procedures for improving allocation of limited resources; and evaluate alternative programs. Results from the study are contained in several reports, including "Strategy and Guidelines for Road Weather Information System Communications" and "Guidelines for Siting Road Weather Information System Sensors."(3,34) Widespread implementation of these guidelines should produce significant benefits.

Under the SHRP-IDEA program, a portable interactive weather information system has recently been developed. This is a numerical weather prediction model which customizes forecasts for a specific area by incorporating local topographic data and current weather information. SHRP is currently working towards developing a communications protocol and data format for RWLS.

FHWA

In addition to this study, FHWA issued a memorandum inviting States to participate in a research study entitled "Development of prototype adverse visibility warning and control systems for operational evaluations." This study, scheduled for the FY 1993 program, aims to install and evaluate a prototype visibility warning system for real-time application. System components will include visibility sensors, information processor, variable message signs, and communication links.

EUROPEAN INITIATIVES

In Europe, there are several research programs that include studies into environmental sensor systems. These comprise the PROMETHEUS program, COST, and DRIVE. These programs are described below.

PROMETHEUS

PROMETHEUS is part of the Eureka initiative and is a collaborative effort between major European automobile manufacturers and their respective governments. The $700 million research program is concerned with the creation of concepts and solutions to make vehicles safer and more economical. These will have less impact on the environment and will render the traffic system more efficient.

PROMETHEUS, initiated in 1986, combines basic research, conducted by universities and research institutes, and applied research, conducted by industry. This cooperation is being accomplished with the support of government agencies responsible for highway transportation and telecommunications. The research is divided into thematic projects which provide the technical input for specific subjects, such as sensing systems or man-machine interfaces. Common European Demonstrators (CED) provide platforms to monitor results and to compare different approaches in terms of performance, benefits, and costs.

There are three key areas being developed: safe driving, traffic flow harmonization, and travel and transportation management. Within the safe driving area there are several projects directly relevant to environmental sensor systems. These concern the use of mobile sensors to enhance vision and to detect loss of control during adverse weather conditions.

The vision enhancement CED is demonstrating systems to provide better visual information on highway and traffic conditions. The human eye can be easily dazzled at night when a vehicle passes in the opposite direction, and vision is also seriously impaired in adverse weather conditions. Image sensors can improve drivers' vision by collecting higher-quality information than available through human vision, provide a depth map of all obstacles for a head-up display, and produce data for the formation of an image with reduced visual noise. The vision enhancement group has been examining four separate approaches: ultraviolet illumination, thermal image using infrared cameras, infrared illumination and CCD camera, and gated intensified camera with pulsed illumination. Sensors from this project could have applications for measuring environmental conditions.

In other parts of the PROMETHEUS program (CED2 - Proper Vehicle Operation), research has focused on in-vehicle highway surface monitoring. Porsche has been looking at a system that assesses the difference between the friction potential and friction demand of the vehicle driving status. When the safety margin falls below a predefined limit, an in-vehicle warning device is activated. Volkswagen has been examining the use of vehicles to collect surface condition data and relay the information to roadside beacons. The roadside beacons can then provide a mechanism for disseminating the vehicle-derived data throughout the highway network. Volkswagen has also developed a visibility monitoring system based on an infrared laser beam. Back scatter signals from the beam are processed to derive the visibility range. The driver is then recommended an appropriate speed to reflect the prevailing conditions.

COST

The COST program began over 20 years ago. One of its projects, COST 30, had the specific aim of improving traffic safety and flow conditions using electronic traffic aids for detecting traffic conditions and communicating with drivers. This was split into nine research areas of which one, Theme 8, examined the relationship between highway traffic and weather. At the end of this study, a committee was established to coordinate further research and development work on highway meteorology. This led to several new projects including COST 309, which was set up in 1987 to investigate highway weather detection, forecasting, statistics, and service strategies.

In COST 309 there was involvement from 11 countries: Austria, Denmark, Finland, France, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom. Research was divided into different areas, with each area the responsibility of one country. Sweden looked at sensors and measuring systems, France the detection and prediction of fog, and other countries examined aspects such as weather radar and satellite information, effects of deicing agents, and dissemination of information to road users.

DRIVE

DRIVE is a European Community-funded initiative which is developing and demonstrating IVHS, with the aim of improving highway safety, increasing transportation efficiency, and reducing hazardous emissions from vehicles.

One of the projects in the DRIVE program is directly relevant to this study as it examined the monitoring of road weather conditions. The CROW project investigated systems to assist in reducing traffic accidents due to bad weather. It looked at improving data acquisition techniques and developed a system architecture to provide an integrated road and weather monitoring system. The main elements of CROW were:(1)

- A technique to predict the onset of aquaplaning based on extrapolation of radar imagery.
- A knowledge-based expert system to provide fog warnings.
- Prototype microwave, infrared, and laser-based sensing systems for monitoring the conditions of road surfaces.
- An integrated nephelometer to assess road visibility.

- A road/weather control center.

- An algorithm to define safe traffic levels in bad weather conditions, based on road, weather, and traffic data.

The results from the CROW project will be implemented in the GERDIEN demonstration project in the near future as part of DRIVE 2. The GERDIEN project aims to evaluate the operation of a number of monitoring systems within an integrated communications framework in the area of Rotterdam. Monitoring systems to be appraised include weather sensors, weigh-in-motion systems, variable message signs, and image analysis.

Sweden

In Sweden, the Swedish National Road Administration is continuing to initiate projects to improve winter highway maintenance services. Several projects have been proposed which will examine present monitoring methods, assess the effects of different quality levels, develop strategies to achieve a chosen quality level, and design mobile measuring equipment to record road conditions and status. For the latter equipment, the parameters to be measured include road surface wetness and type (ice, snow, rain, etc.), snow depth, road surface temperature, air temperature, uneveness of road, and surface friction.

OTHER DEVELOPMENTS

In Japan, there has been research into a vehicle-mounted sensor to determine variations in visibility. Takeuchi et al. describe a visibility sensor mounted on a vehicle to provide a motorist's eye level view of visibility conditions during blowing snow.(40) The sensor consists of a transmitter and receiver unit mounted at an angle. The transmitter projects a light which is reflected by airborne snow particles and measured by the receiver. The intensity of the measured light is in proportion to the snow concentration as well as visibility. It has been reported that the developed sensor compares favorably with the transmissometer type of visibility meter.

CHAPTER 8. FUNCTIONALITY ASSESSMENT

In the previous chapters, the background to environmental monitoring, addressing historical developments, current State activities, meteorological conditions which affect highway users, the impacts on users, and user needs were examined. A set of functional requirements has been developed based on this information. A state-of-the-art review has also been undertaken, covering commercial systems and research initiatives. This chapter brings together this information in a general assessment of the functionality of the sensor systems.

The assessment has involved an examination of the different sensor technologies to determine the extent to which they fulfill the functional requirements of a condition-responsive driver information and warning system. Information obtained on the various technologies has been used to perform a comparative assessment. Not all the required information was available, so estimates and assumptions have been made where appropriate. Verification of certain system parameters is proposed later in the study.

For each technology, the relative functionality offered by systems employing the technology was considered. A rating of high, medium, or low has been given for each functional aspect. It should be noted that these are relative ratings as opposed to an absolute rating. Although the approach adopted is necessarily subjective, it does provide a useful guide to current systems. More complex assessment approaches were considered but rejected, as detailed information on the performance of many technologies was not readily available.

Results from the assessment are contained in the figures below. For each figure, the following requirements were assessed:

- Accuracy - the sensor's ability to provide a high correlation between its measurements and actual conditions.
- Reliability - the sensor's ability to maintain its specified degree of accuracy over a typical range of severe weather, traffic, and other environmental conditions.
- Real-time response - the time taken to determine parameter given the needs of users.
- Wide-area coverage - the spatial area covered by a single sensor.
- High spatial resolution - the ability to provide measurements representative over a small area or point, so that accurate spatial profiles of an environmental parameter can be obtained.
- Durability - the ability of the sensor to operate for long unattended periods, requiring only occasional maintenance and/or calibration.
- High cost/benefit ratio - a high degree of benefit, satisfying all requirements, for a relatively low cost.

- Compact - relatively small size, for the given application.

- Low power consumption - offering the possibility of portable operation, battery powered, battery backup, solar power (in remote locations), etc.

- Minimal traffic disruption - minimal impact to traffic during installation, calibration and maintenance procedures.

- Identify type - for pavement moisture sensors, the ability to detect the type of moisture present, e.g., rain, snow, ice, frost, etc.

In figures 3 through 6, the ability of a particular sensor technology to meet a given requirement is given a rating of low, medium, or high. These are indicated by different degrees of shading in the boxes. In some cases, different variants of a particular technology may be able to meet a given requirement better than other variants of the same technology. Therefore, some technologies may have a range of scores, such as low to medium, and medium to high. Where the ability of a particular sensor technology to meet a given requirement is unknown, the box is left blank.

Figure 3 shows the ability of various technologies to meet the requirements for monitoring wind speed, direction, and gust. Figure 4 shows the ability of various technologies to meet the requirements for visibility monitoring. The ability of thermistors, resistance thermometers, thermocouples, and infrared sensors to meet the requirements for monitoring of pavement surface temperatures is shown in figure 5. Figure 6 shows the ability of various technologies to meet the requirements for pavement moisture/condition, road friction and freezing point sensors. The road friction sensor technology relates to on-vehicle devices or a towed trailer specifically designed for monitoring pavement surface friction. The electrical parameters technologies are based on measuring resistance/conductivity or a change in the sensor's capacitance.

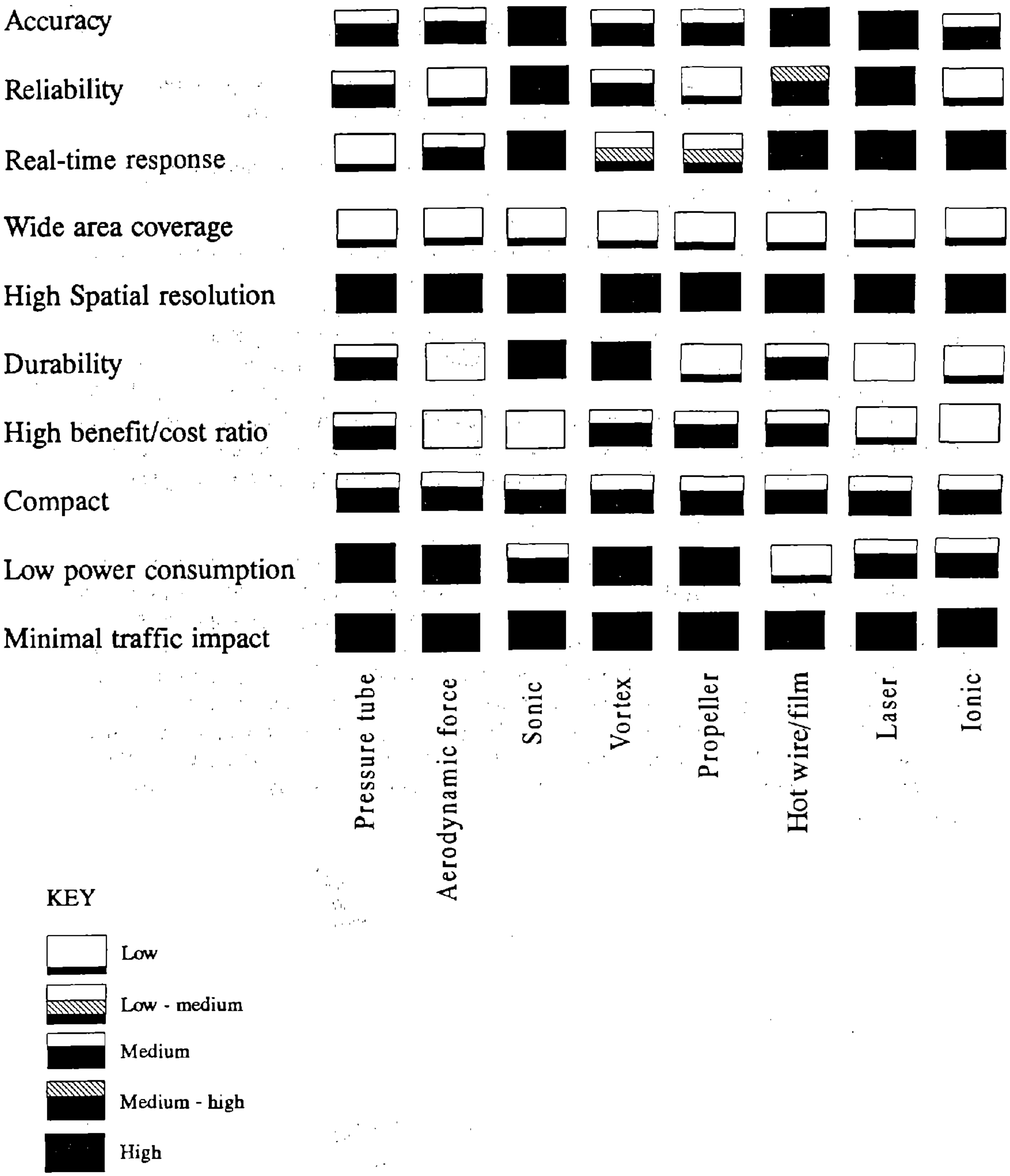


Figure 3. Wind monitoring sensors

		Light scattering/ nephelometer		
	Tansmissometer	Forward scatter	Back scatter	All angles
Accuracy	□	▧	□	□
Reliability	⬓	⬓	⬓	⬓
Real-time response	■	■	■	■
Wide area coverage	□	□	□	□
High Spatial resolution	⬓	⬓	⬓	⬓
Durability	▨	▧	▨	▨
High benefit/cost ratio	□	□	□	□
Compact	⬓	■	■	□
Low power consumption	□	□	□	□
Minimal traffic impact	■	■	■	■

KEY

□	Low
▧	Low - medium
⬓	Medium
▨	Medium - high
■	High

Figure 4. Visibility sensors

	Thermistor	Resistance thermometer	Thermocouple	Infrared
Accuracy	Medium - high	Medium - high	Medium - high	Low - medium
Reliability	High	High	High	High
Real-time response	High	High	High	High
Wide area coverage	Low	Low	Low	Medium - high
High Spatial resolution	High	High	High	Medium - high
Durability	High	High	High	Medium
High benefit/cost ratio	Medium	Medium	Medium	Low - medium
Compact	High	High	High	Low - medium
Low power consumption	High	High	High	Low - medium
Minimal traffic impact	Low	Low	Low	High

KEY

Low

Low - medium

Medium

Medium - high

High

Figure 5. Pavement temperature sensors

	Road friction	Freezing point latent heat detection	Vibration	Microwave	nfrared combination	IR-microwave	Laser imaging	Electrical params.
Accuracy	Low - medium	High	High	Medium	Medium - high	Medium - high	Low	Medium - high
Reliability	Low	Medium	Low - medium	Medium	Medium	Medium	Medium	Medium - high
Real-time response	High	Medium	High	High	High	High	High	High
Wide area coverage	High	Low	Low	Medium	Medium	Medium	High	Low
High Spatial resolution	High	High	High	☐	☐	☐	High	High
Durability	Medium	Low	☐	High	☐	☐	☐	High
High benefit/cost ratio	Low - medium	☐	☐	Low	☐	☐	☐	Medium
Compact	Medium - high	Medium	Medium	Low - medium	Low - medium	Low - medium	Low - medium	High
Low power consumption	High	Low	☐	☐	☐	☐	☐	High
Identify type	Low	Low	Low	Low	Low	High	Low	Medium
Minimal traffic impact	Medium - high	Low	Low	High	Low	High	High	Low

KEY

Low

Low - medium

Medium

Medium - high

High

Figure 6. Pavement moisture sensors

CHAPTER 9. EQUIPMENT PROFILES

BACKGROUND

All visibility sensor manufacturers identified through literature searches by the project team were approached to identify their interest in participating in a field test. A list of the solicited manufacturers is contained in appendix A. A number of mobile and stationary visibility sensor functional requirements were developed for the highway application. These were sent to the known vendors to allow identification of the suitability of their products. Five sensors were selected for stationary tests based upon manufacturer interest as follows:

- HSS Incorporated VR-301B-120 Digital Visibility Sensor.
- Belfort Instrument Model 6210 Visibility Sensor.
- Vaisala Visibility Meter FD-12.
- Sten Löfving Optical Sensors OPVD Visibility Sensor.
- Pharos Marine FD-320.

This chapter briefly describes each of the selected sensors in terms of method of visibility detection, physical attributes, cost, and special features of individual sensors. A diagram of each sensor is included. A chart summarizing the characteristics of the sensors is presented in table 7.

FIELD SENSOR PROFILES

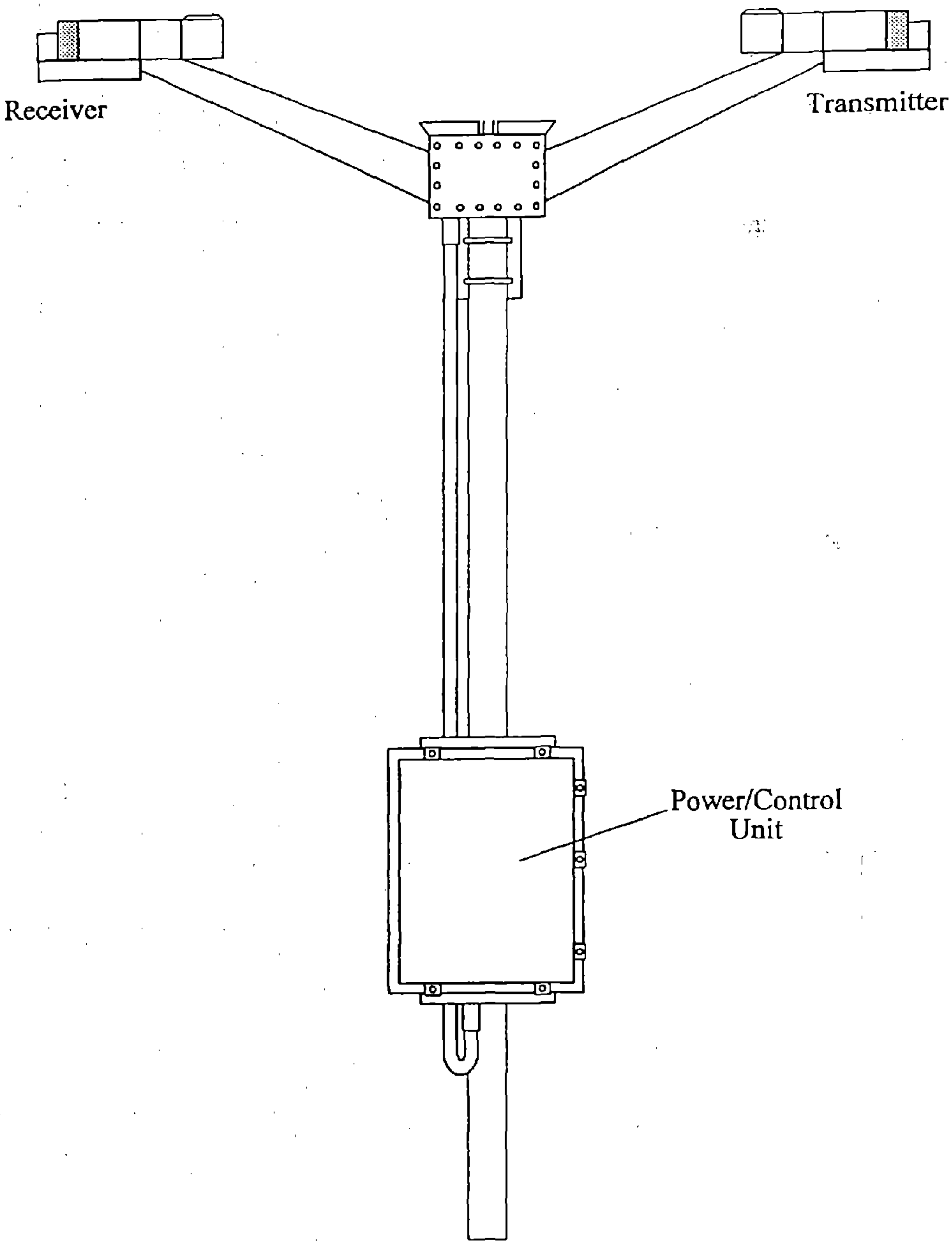
HSS VR-301B-120

The VR-301B unit consists of a sensor head with a transmitter and a forward scatter receiver mounted symmetrically on hardcoat anodized aluminum arms and a power/control unit. The system configuration is presented in figure 7. The sensor head is 1.26 m (58.5 in) long and weighs 11.5 kg (25 lb), while the power/control unit measures 0.43 m by 0.34 m by 0.13 m (20 in by 16 in by 6 in) and weighs 14.5 kg (32 lb). This unit houses the power supply, control electronics, data acquisition electronics, protective EMI filters, and surge arrestors for the power and signal lines.

Manufacturer specifications require the sensor head to be installed a minimum of 1.5 to 2.6 m (6 to 10 ft) above ground level. This was to be accomplished via a pole whose outer diameter measured from 60 to 70 mm (2 3/4 to 3 1/8 in). The power/control unit is most commonly mounted underneath the sensor on the same pole. The sensor is designed to operate from a 115 VAC power supply.

Table 7. Manufacturers' specifications for selected sensors

	HSS Inc. VR-301B-120 Digital Visibility Sensor	Belfort Instrument Model 6210 Visibility Sensor	Vaisala Visibility Meter FD-12	Sten Löfving Optical Sensors OPVD Visibility Sensor	Pharos Marine FD-320
Sampling zone	0.03 m^3 (1.13 ft^3)	0.02 m^3 (0.75 ft^3)			2 to 10 m (6.6 to 33 ft)
Sampling time	Variable		15 seconds	Not applicable	12 seconds
Operating temperature	-50 °C to +50 °C (-50 °F to 122 °F)	-55 °C to +55 °C (-67 °F to 131 °F)	-40 °C to +55 °C (-40 °F to 131 °F)	-30 °C to +30 °C (-20 °F to 86 °F)	-25 °C to +70 °C (-13 °F to 158 °F)
Power supply	115 VAC 50/60 Hz	+24 ± 2V DC 115/230 VAC 60/50 Hz	110/220 VAC ± 15%	24V DC	12V DC
Current drain	6W - Basic instrument 100W - De-icer heaters	4W - Electronics 10W - Window heaters	30VA Max 150VA with defrosting heaters	150mA	106mA Sampling 20mA Idle
Accuracy	±5%; 0 to 16 km (0 to 10 mi) ±10%; 16 to 30 km (10 to 18 mi)	± 10% reading	± 20% in natural, non-frozen fog ± 30% in precipitation		± 10% of threshold level
Operating threshold	10 m to 150 km (30 ft to 90 mi)	5.2 m to 59.6 km (17 ft to 37 mi)	10 m to 20 km (30 ft to 12 mi)	10 m to 3 km (33 ft to 1.8 mi)	Three independently adjustable thresholds
Signal source	Infrared	Visible	Infrared	Visible	Infrared
Sampling interval	Variable	60 seconds	60 seconds		Adjustable for 0.5 - 1.5 minutes
Light wavelength	890 nm	400 - 800 nm	875 nm	670 nm	940 nm
Pulse frequency	2 KHz	2 Hz	2.3 KHz	11 KHz	16 KHz



Note: approximate scale 10 mm = 52.5 mm (1 in = 2.10 in)

Figure 7. HSS sensor

The VR-301B utilizes the forward scatter approach for visibility determination. Forward scatter refers to the measurement of light scattered at angles less than 90° by particulates in the sample volume.

The HSS system uses a forward scatter angle coverage between 27 and 42°. For the VR-301B, the sample volume is defined by the intersection of a light beam projected by the infrared source in the transmitter with the field of view of the receiver.(41) An example of this process is shown in figure 8.

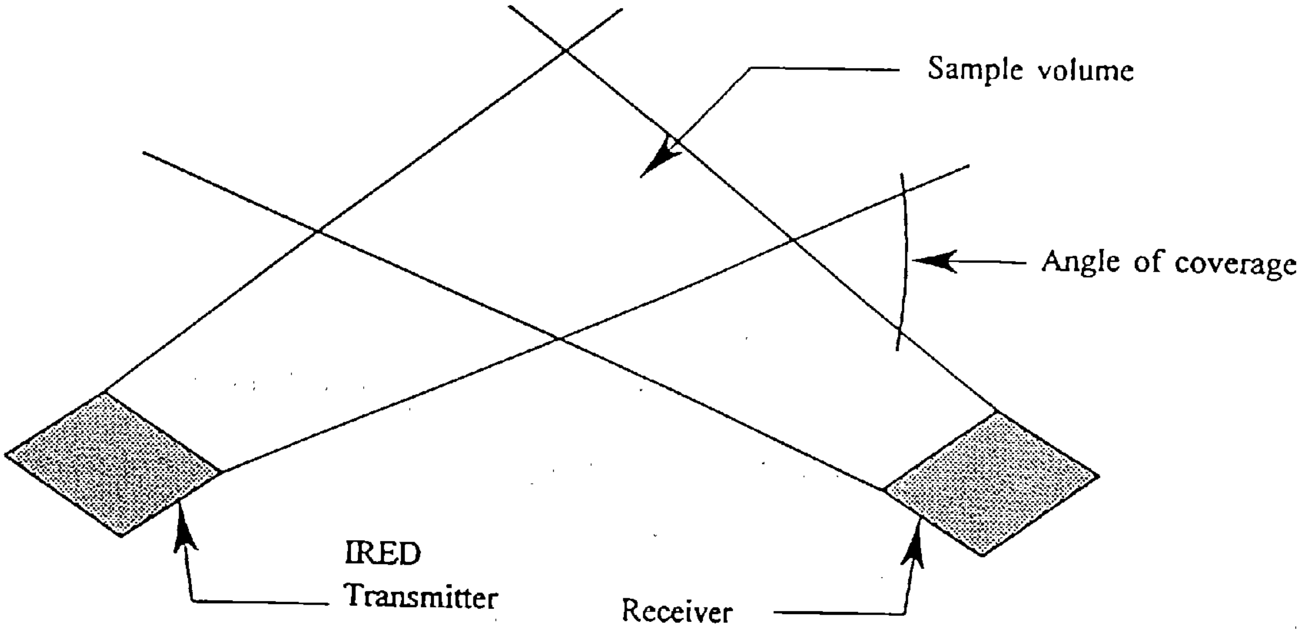
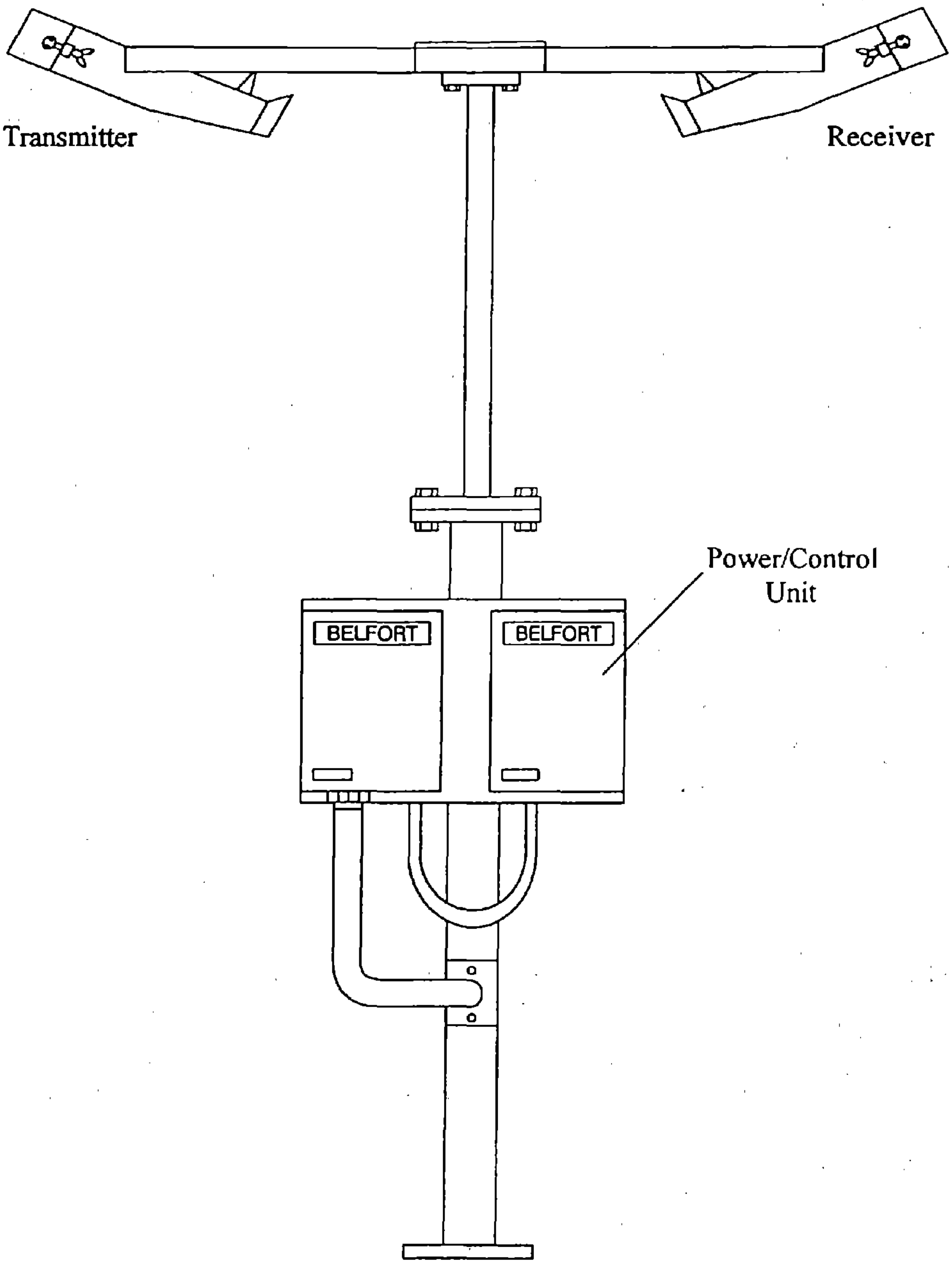


Figure 8. Basic principals of forward scatter visibility technique

In addition to visibility, the sensor can measure ambient light level, precipitation, and temperature. Dirt accumulating on the lenses is compensated for via a photodiode located inside the window. When contamination effects cause the sensor calibration to be altered by a value of greater than 8 percent, a maintenance flag appears on the output log. Additionally, heaters are present on both the transmitter and the receiver to prevent the onset of dew and ice. Outputs from the sensor are in digital form and are transmitted at the user-defined sampling interval.(41)

Belfort Model 6210

The Belfort 6210 also has a basic "T" configuration with sensor optics mounted at the ends of the cross bar and electronics attached on the main arm below the sample volume of the sensor. Figure 9 illustrates the basic configuration of the Belfort system.



Note: approximate scale 10 mm = 135 mm (1 in = 12.6 in)

Figure 9. Belfort sensor

The sensor optics, which are mounted at the ends of a cross arm approximately 1.5 m (60 in) in length, consist of a transmitter assembly and a receiver assembly. The transmitter assembly contains transmitter electronics, interface wiring, a xenon bulb, and an optical lens set. The bulb flashes to produce visible light which is focused through the optical lens into the scatter volume. The Belfort sensor also uses the forward scatter detection approach.

The receiver assembly includes the interface wiring, receiver electronics, and an optical lens group. The assembly detects the light which has been dispersed by particles in the scatter volume. This light is focused through the lens group onto a photodiode, which converts the light energy into electrical energy for processing. The processor utilizes two readings to conduct visibility calculations, a "light" reading gathered during the xenon bulb flash and a "dark" reading obtained between flashes. A trigger device is mounted at the transmitter assembly and sends a signal during the light reading enabling the processor to correctly select readings for calculation purposes.

Heaters are used on both transmitter and receiver assemblies to prevent the formation of dew or ice on the lenses. Manufacturer specifications recommend manual cleaning and inspection of the system every 3 months.(42)

The Belfort system has a total weight of approximately 43 kg (136 lb) and a height of 2.6 m (8.5 ft). However, the manufacturer notes that the scatter volume, or sample zone, should be at a height of approximately 4 m (13 ft). A mounting base of 1.4 m (4.5 ft) was required to elevate the sample zone to the proper location. The scatter volume is located 0.46 m (2.55 ft) below the top of the system.

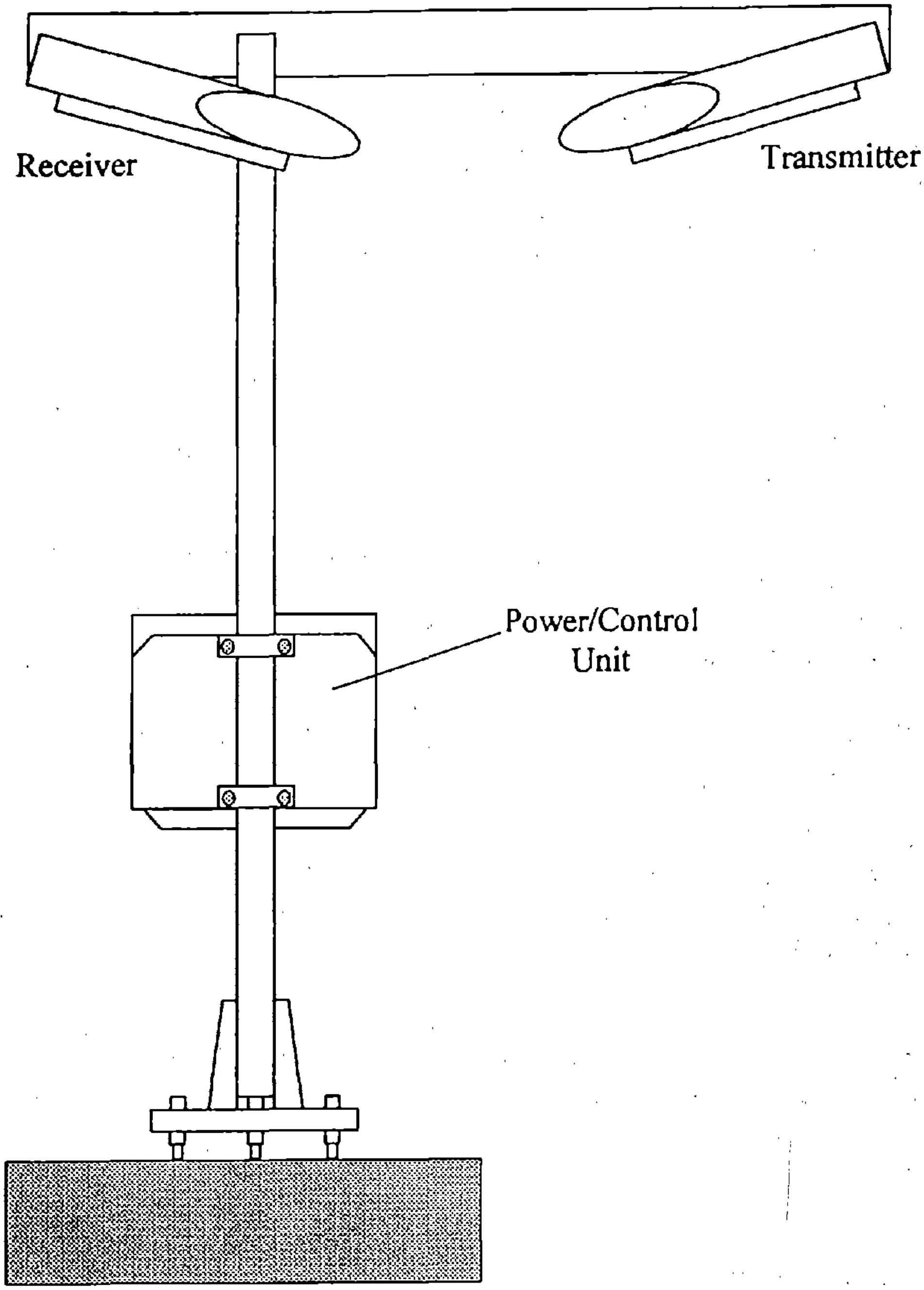
Vaisala FD12

The Vaisala FD12 system also utilizes the forward scatter technique and a "T" configuration. The optics are located at the ends of the cross arm and the electronics cabinet is attached to the mast support out of the range of the sample volume. Figure 10 depicts the Vaisala device's basic structure.

The receiver optics are offset at a permanent angle of 33°, respective to the transmitter assembly. Additionally, the entire optics unit is tilted 20° downward from horizontal. The transmitter assembly contains an infrared light emitting diode (LED) and an optical lens. A PIN-photodiode is also contained within the transmitter unit to monitor LED intensity for the purpose of offsetting the effects of temperature and aging upon the LED.

The receiver assembly contains another PIN-photodiode and detects scattered light present within the sample volume via a phase sensitive lock-in amplifier. The manufacturer states that background level effects will not contribute to the detection of the lock-in amplifier.

All data are measured in 15-s intervals for visibility calculations. The measurement period can be broken down as follows: 10 s allocated to signal measurement, 1 s for contamination measurement, and a 4-s offset measurement phase.



Note: approximate scale 10 mm = 142.5 mm (1 in = 13.25 in)

Figure 10. Vaisala sensor

Visibility calculations are conducted on signal frequencies which have been gathered and converted from currents by the PIN-photodiode. The raw data are then examined and a general pattern or profile is developed. Following the establishment of the signal profile, the precipitation algorithm is used to evaluate the most appropriate segment of the profile to be used for average signal calculations. Finally, the average signal value is inserted in a parameter within the calibrated transfer function to obtain an instantaneous visibility reading. This value is then averaged to derive 1-min readings.

Heaters are used to help prevent the build-up of dew or ice upon the transmitter and receiver lenses. The Vaisala system was the most compact of the forward scatter sensors with a total height of approximately 2.2 m (7.3 ft) and weight of about 35 kg (77 lb). No additional elevation of the device was required.(43)

Sten Löfving OPVD

The Sten Löfving OPVD sensor was, at the start of the project, a prototype device still undergoing development. For this reason, little information is currently available.

This device was the most compact sensor tested with approximate dimensions of 0.225 m by 0.75 m by 0.05 m (9 in by 3 in by 2 in) and a weight of approximately 1.0 kg (2.2 lb). A diagram of the OPVD sensor is shown in figure 11.

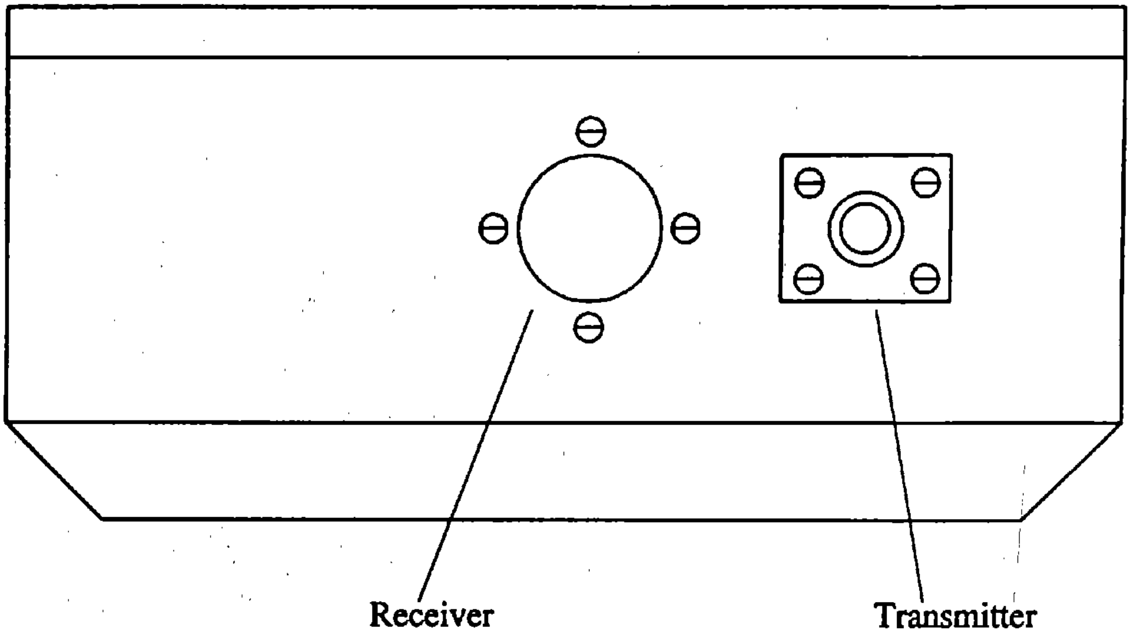
The sensor uses the back scatter visibility approach illustrated in figure 12. The device emits a narrow visible (670 nm) laser beam from the transmitter optic and then measures the amount or level of beam intensity which was reflected back by particulates present in the air. The sample volume is the path of the emitted light in front of the sensor. The sensor also has outputs for precipitation. Separate pulse outputs are reported for rain and snow. The system requires a 24V dc power supply.

Pharos Marine FD320

The Pharos Marine FD320 is a back scatter sensor. The device is contained within a single unit measuring 0.635 m by 0.48 m by 0.305 m (25.4 in by 19.2 in by 12.2 in) and weighing 12 kg (26.5 lb). A diagram of the sensor is shown in figure 13. A mounting pole, with an outside diameter no greater than 48 mm (1.9 in), is required for installation.

The back scatter visibility technique involves transmitting a signal, in this case infrared, into the atmosphere. The signal propagates out and is absorbed, refracted or reflected by particles present in the sample zone. A percentage of the reflected signal reflects back onto the receiver optics, where it passes through a lens and is focused onto a PIN-photodiode. This process is illustrated in figure 12.

The signal from the PIN-photodiode is processed by a wide-band width amplifier chain followed by a phase sensitive detector, an integrator, and a comparator. The result is then examined against the user-defined threshold values to determine whether or not a low visibility situation exists.



Note: approximate scale 10 mm = 16 mm (1 in = 1.48 in)

Figure 11. Sten Löfving sensor

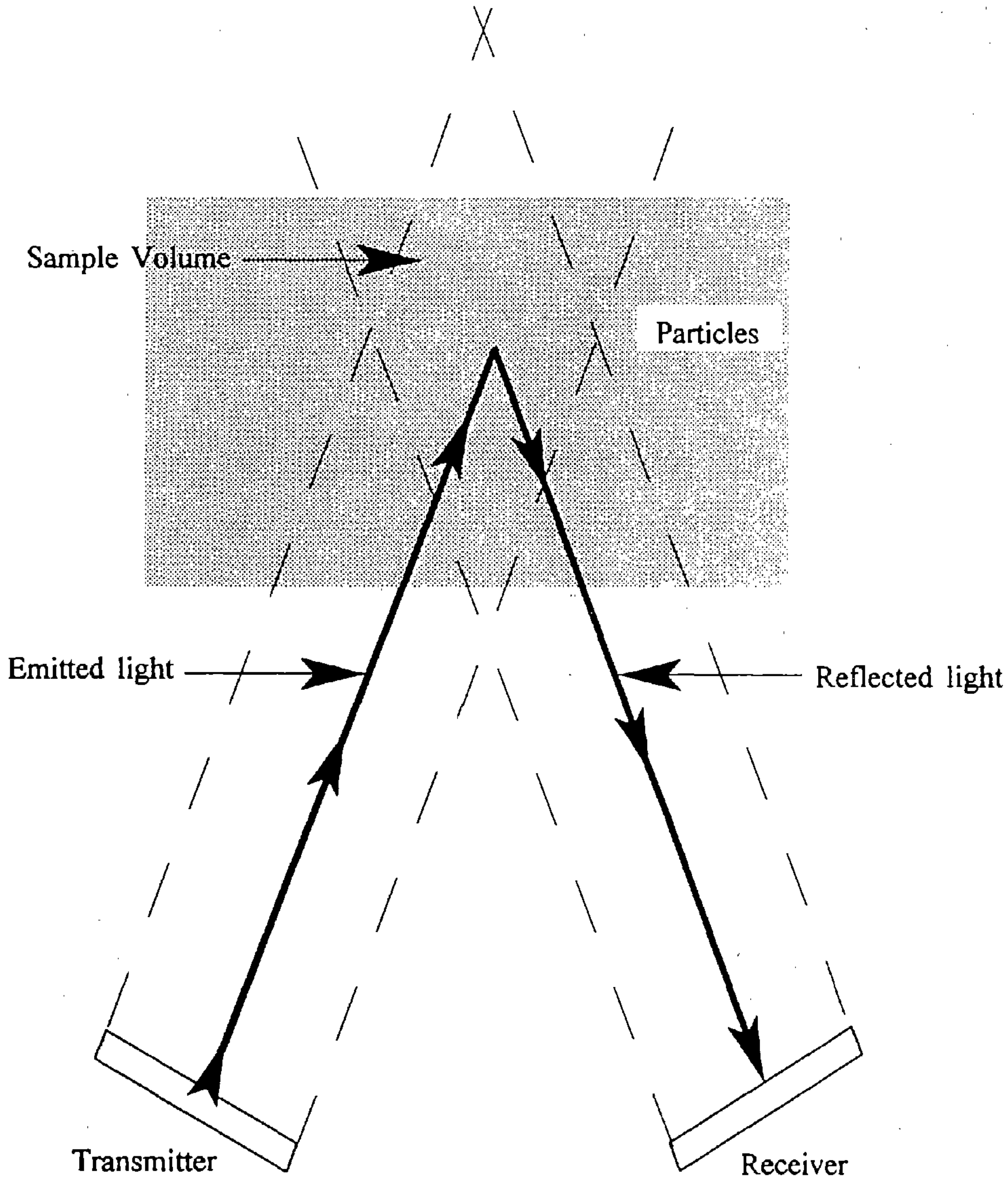
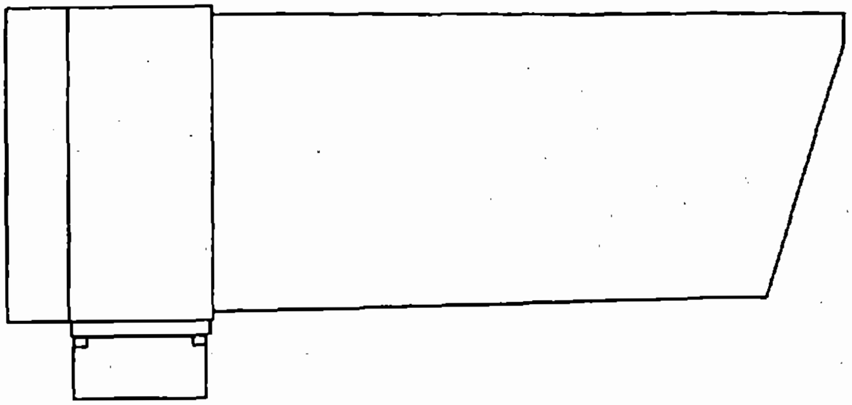
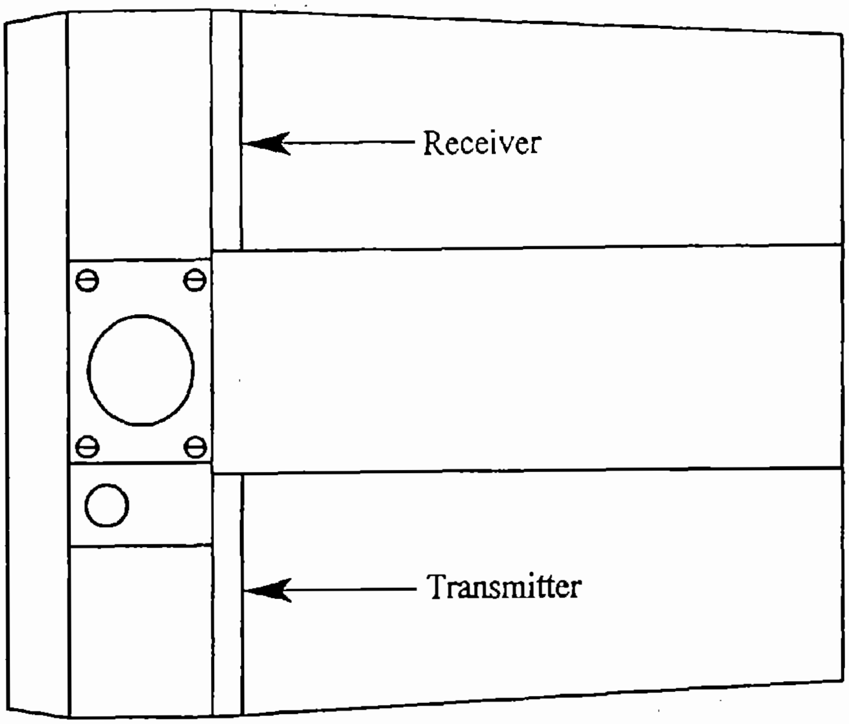


Figure 12. Principal elements of back scatter visibility measurement



Side view



Bottom view

Note: approximate scale 10 mm = 58 mm (1 in = 5.39 in)

Figure 13. Pharos Marine FD320 sensor

Optics contamination is controlled and compensated for in a unique fashion. Upon the completion of the 6-s firing sequence for the main optics, a pilot light is triggered for 6 s. This signal is carried via a fiber optic cable to a position directly in front of the receiver lens. The infrared signal is then processed in a similar manner to reflected light. Since all surfaces are exposed to the same environmental conditions, all will therefore be subject to the same attenuation levels. In this manner, the FD320 unit compensates for lens fouling and receiver gain change.(44)

CHAPTER 10. EVALUATION APPROACH

OVERVIEW

The evaluation of the sensors was carried out using two separate tests: functional tests and real-world tests. This chapter provides a description of the approach used in each test and the data collection activities, and describes the modifications made to the evaluation during the course of the test.

The functional tests examined the performance of each sensor under various simulated environmental conditions including: interference effects, contamination and environmental effects, and simulated reduced visibility. These tests were conducted prior to field deployment to ensure that all selected sensors met the agreed minimum functional requirements. Results from the functional tests provided essential information for field test deployment. Data obtained included: proper sensor placement, data transmission specifications, and power requirements.

The real-world tests examined the performance of the sensors over a longer period of time under real-world conditions. This included winter conditions and low visibility conditions. Vehicle speed data from the highway adjacent to the test site were also collected during the test.

FUNCTIONAL TESTS

Test Plan

The functional tests were conducted to evaluate the performance of the sensors under certain simulated conditions. These tests were performed at a Mn/DOT facility located in North Branch, Minnesota. This allowed the tests to be conducted in a controlled environment away from heavily-populated locations as well as major roads or freeway segments.

The tests implemented were based on the Visibility Sensor Evaluation Plan submitted to FHWA on April 9, 1993. This plan recommended conducting tests in the following areas:

- Interference effects.
- Simulated reduced visibility.
- Contamination effects.

Brief discussions of the test methodology and objectives associated with each of these test areas are given below.

Interference effects

Initial interference tests were undertaken to investigate the lateral clearance required between the sensor and other objects that could reflect optical signals. The remainder of these tests investigated the susceptibility of the visibility device to a number of possible sources of external interference. The interference sources tested included directly-reflected sunlight and vehicle headlights, as well as other visibility sensors. The output of the system under examination was monitored while using the interference sources, both individually and in combination.

Simulated reduced visibility

For this test, visibility in the vicinity of the sensors was manually reduced and the output of the sensor systems noted. Variations over time and variations with different intensity of reduced visibility were monitored. Time required to identify visibility changes was noted as well as time necessary to recover from extreme visibility reduction conditions. Visibility reduction was achieved via the generation of smoke. Due to the difficulty in controlling the consistency and coverage of the smoke production, a test site away from populated areas was used.

Contamination effects

These tests examined the effect of dirt and water on the exterior of the optical equipment. A series of transparent plates of varying levels of contamination were created prior to the dirt test. A clean plate was used to check for unexpected attenuation or scattering effects. Water was tested by splashing or spraying the optical equipment while attempting to simulate possible real-world occurrences.

A functional test plan was developed to address each test parameter in detail. A copy of this test plan is contained in appendix B. Also included in the test plan are any modifications made by the test supervisor during the course of the testing.

REAL-WORLD TESTS

Equipment

The site chosen for the real-world tests was Thomson Hill in Duluth, Minnesota. The site is located at the side of Interstate 35 northbound approximately 8 km (5 mi) south of Duluth. The site selection was based on the analysis of historical data and consideration of the test logistics. The following factors led to this selection:

- The site was located near to the lake shore and would experience frequent advection fog due to adiabatic cooling of onshore winds.

- The area over the brow of the hill provides a bowl for the formation of radiation fog which would affect the chosen site.
- The conditions at the site are such that during heavy snowfall there was a high probability that visibility would be significantly reduced due to blowing snow.
- The site has been historically noted to be the location of extremes in icing, wind, turbulence, and fog occurrence.
- The site is particularly prone to post-thunderstorm fog which may permit advance prediction of fog and enable a site visit during low visibility conditions.
- There is a meteorological sensing system installed at the site that could provide useful additional site data. There is also access to power and communications facilities.

Based upon the results from the functional tests, a deployment plan was devised in order to maximize the available space while ensuring that no interference effects between sensors were experienced. This plan was developed around the predetermined position of a modular building, provided by Mn/DOT, to house the computer system and all communications media. The modular building was equipped with heating and air conditioning capabilities to provide the appropriate environment for the computer equipment.

A video camera was attached to a 16.5-m (55-ft) telephone pole provided by Mn/DOT in order to allow for remote inspection of weather conditions at the test site. A series of targets were then placed within the range of the camera to allow for initial visibility readings. The targets were 0.432 m by 0.432 m (18 in by 18 in) with a nonreflective black background. A 0.192-m (8-in)-tall numeral was placed on each target to identify its location. The numeral was made of a white reflective material. The targets were placed on mounting poles at a series of distances measured from the video camera as follows:

Target	Distance (m) / (ft)
1	5 / 16.5
2	10.5 / 35
3	20.1 / 66.3
4	32.7 / 108
5	67 / 221
6	80 / 265
7	100 / 330
8	150 / 495
9	200 / 660

Targets #2 through #5 were placed according to the minimum braking distances required for a vehicle traveling at 32, 48, 64, and 80 km/h (20, 30, 40, and 50 mi/h). The remaining targets (#1, #6 through #9) were positioned to fill any gaps which may have remained after placement of the braking distance targets.

In addition to the video camera, the AUTOSCOPE™ system was placed at the top of the pole to gather traffic speeds for comparison against visibility conditions. Figure 14 presents an overview of the test facility.

The computer equipment housed in the modular building was responsible for gathering and storing data from each of the sensors, the video camera, and the AUTOSCOPE™ system. The computer was equipped with serial ports, an analog-to-digital converter, and video frame grabbing capability. All data were stored on the computer's hard disk drive until they were downloaded remotely via modem.

The total cost for preparation of the test site and installation of all required sources such as electrical power for the sensors and computer equipment as well as phone service for modem access was approximately $11,500. A detailed cost breakdown is depicted in table 8.

Table 8. Installation cost breakdown

Labor Costs	Subcontractor and Consultant Costs	Other Direct Costs	Total
$ 4,800.00	$ 3,693.43	$ 2,993.85	$ 11,487.28

Manual Data Collection Procedures

To ensure that data were collected in a timely and efficient manner, the cooperation of all team members was required. The data collection procedures were developed as a collaborative effort. Due to the dynamic nature of the test, data collection procedures were continuously reviewed to ensure that team members were aware of their responsibilities and that the most efficient methods were being utilized.

The objectives for the manual data collection element were to:

- Collect manual observations of visibility to compare with outputs obtained from the sensors during low visibility conditions.
- Identify onsite problems with sensors or environmental conditions present which are causing the sensors to malfunction.
- Perform simple corrective activities if required.

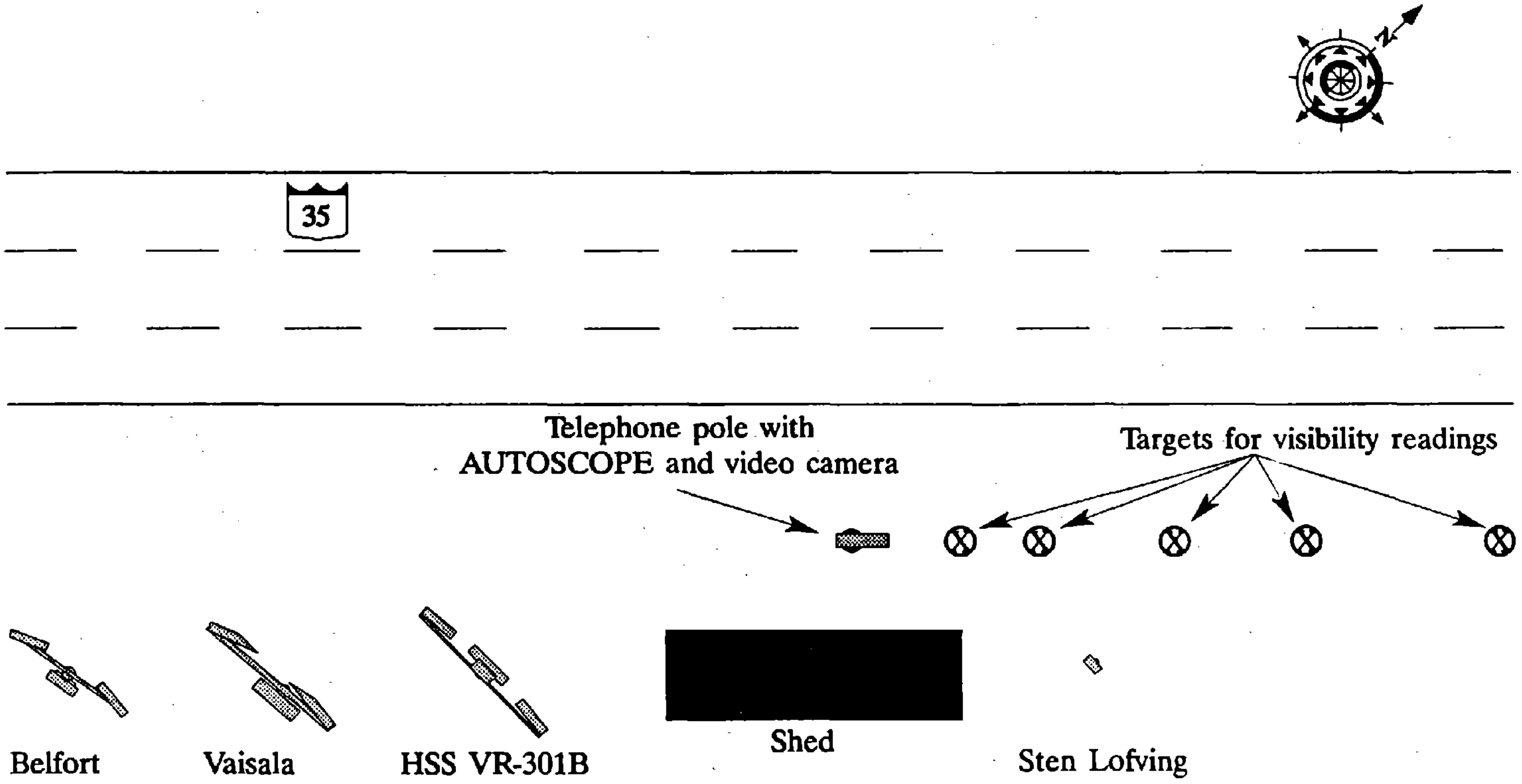


Figure 14. Thomson Hill environmental sensor layout (not to scale)

- Maintain a log of all maintenance or similar type activities.

The process for gathering low visibility data began with daily weather forecasts prepared by the project meteorologist. The forecasts provided detailed information regarding that day's weather, including percentage chance of low visibility in the test range and a weekly forecast for possible low visibility at the test site. Sample forecasts are included in appendix C. The forecasts were faxed to all team members before 8:00 am CST in order to maximize time prior to low visibility occurrences. Based upon the conditions identified in the daily weather update, the Mn/DOT dispatcher initiated a visibility monitoring process at the Thomson Hill site. This monitoring was conducted remotely via computer, utilizing a software program which allows for direct communication with the onsite computer and video systems.

During the monitoring process, if a low visibility condition was observed, due to any type of inclement weather, the dispatcher contacted the Mn/DOT observer and requested a visit to the site. The physical characteristics of the test site and the surrounding environment resulted in sporadic episodes of low visibility occurring without warning. The Mn/DOT observer was also requested to visit the site to conduct manual observations when reports of such conditions were given by any authorized transportation-related representative such as Mn/DOT employees or State Highway officers.

Manual observations were conducted via a specific procedure developed according to guidelines outlined by the National Weather Service. Visibility readings were taken by positioning an observer adjacent to the video camera mounting pole and identifying the farthest of the numbered targets which could be seen with the naked eye. The observer was required to note the furthest sign for which the outline was visible. Where possible, the manual observations were noted in 2-min intervals during a low visibility condition. The data were recorded on the data collection sheets shown in appendix D.

To ensure that the data automatically recorded from the sensors could be matched against the manual observations, the Mn/DOT observer identified the time on the data collection computer and recorded it on the data collection sheets. Manual data were collected for a period of at least 2 1/2 h or until the low visibility condition dissipated.

As part of the maintenance and preventive care process of the evaluation plan, the sensor outputs were continually reviewed to identify any abnormal readings. To assist the Mn/DOT dispatchers in identifying abnormal readings, table 9 was provided.

If a sensor displayed abnormal readings during the test, a Mn/DOT representative was dispatched to the test site to conduct a physical examination of the sensor in question. If an obvious cause such as ice or dirt build-up on the sensor options was noticed, rectifying actions were taken. However, if the cause was not obvious, the test supervisor was contacted to investigate and make any necessary repairs. An activity log was placed inside the shed to record all visits to the test site and for the purpose of documenting actions taken while at the site.

Table 9. Abnormal sensor readings

Suspect Sensor Reading	Other Sensor Readings (or manual readings)			
	<500	500-2000	2000-20000	>20000
<500	OK	OK	Abnormal	Abnormal
500-2000	OK	OK	OK	Abnormal
>2000	Abnormal	OK	OK	OK

CHAPTER 11. RESULTS OF FUNCTIONAL TESTS

Results of the functional tests for each sensor tested are presented below. This section also provides a brief description of any features that were unique to a particular sensor and identified during the functional testing process.

HSS VR-301B

Interference Effects

Sensor	Interference Effects		
	Lateral Clearance Required	Reflected Sunlight	Vehicle Headlight
HSS VR-301B	4.32 m (14.5 ft)	No effect	No effect

The required lateral clearance for the HSS device was found to be an area of 4.32 m (14.5 ft) in radius from the base of the device as shown in figure 15. The sensor was not affected by either sunlight or vehicle headlights directed into the sensor optics.

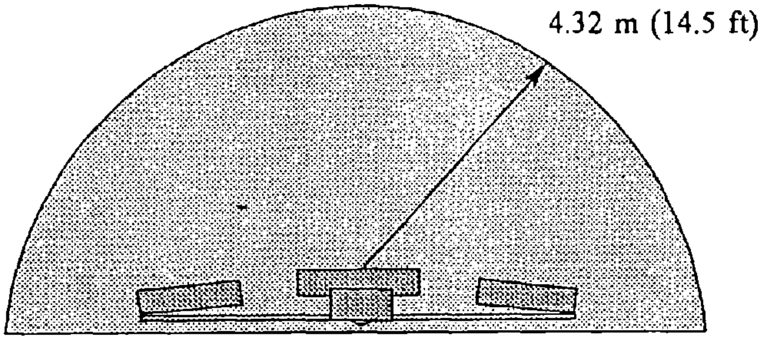


Figure 15. Required lateral clearance for HSS sensor

Simulated Reduced Visibility

Sensor	Simulated Reduced Visibility		
	Initial Reading	Diffused Smoke Reading	Intense Smoke Reading
HSS VR-301B	150 km (90 mi)	0.11 km (0.07 mi) @ 1 min	0.05 km (0.03 mi) @ 1 min

The reduced visibility test was conducted in two parts, a diffused smoke condition and an intense smoke condition. This was done to examine the sensitivity of the device. The sensor was first subjected to an intense smoke environment to examine the time required to identify the reduced visibility condition and then by a diffused smoke condition to examine how the sensor reacts to a much lesser degree of contamination present in the air.

As may be observed in table 10, the HSS device required only 1 min to detect the smoke effects, reducing visibility from 150 km to 0.05 km (90 mi to 0.03 mi). When the smoke-producing machine was turned off, the HSS sensor immediately noted an increased visibility condition going from 0.054 km to 0.457 km (0.03 mi to 0.27 mi). The sensor required only 1 min to return to the initial visibility condition of 150 km (90 mi).

Table 10. Reduced visibility results for HSS sensor during intense smoke conditions

	Time (minutes)	Visibility (km) / (mi)
Smoke on	0	150.0000 / 90.0
	1	0.0540 / 0.03
	2	0.0403 / 0.02
	3	0.0268 / 0.02
	4	0.0384/ 0.02
	5	0.0543 / 0.03
Smoke off	6	0.4573 / 0.27
	7	150.0000 / 90.0
	8	150.0000 / 90.0
	9	150.0000 / 90.0
	10	150.0000 / 90.0

Contamination Effects

Sensor	Test Configuration (Optics Covered)	Contamination Effects				
		Light Dirt	Medium Dirt	Heavy Dirt	Water	Water & Dirt
HSS VR-301B	Transmitter only	No effect	Visibility readings reduced by 50%	Visibility reduced in excess of 70%	No effect	No effect
	Receiver only	No effect	Minor effect noted	Visibility reduced 60%	No effect	No effect
	Transmitter & receiver	No effect	No effect	Minor effect noted	Precipitation detected & visibility reduced	N/A

The dirt test was conducted via a multi-phase method of placing the contamination plates in both optics as well as each optic, receiver, and transmitter, individually as the results noted.

The medium dirt test produced interesting results. When the contaminated plate was inserted in front of the transmitter optic only, visibility dropped by 50 percent as can be seen in table 11. Testing of the receiver unit found only temporary visibility reductions, whereby the sensor noted an effect and then self corrected for the presence of contamination on the optic. The sensor was able to self-adjust for the presence of contamination effects when placed in front of both optics.

Table 11. Contamination test results - HSS sensor

	Medium dirt level transmitter only	Heavy dirt level receiver only
Time (minutes)	Visibility (km) / (mi)	Visibility (km) / (mi)
0	150.00 / 90.0	150.00 / 90
1	27.27 / 16.4	17.65 / 10.6
2	75.00 / 45	50.00 / 30
3	75.00 / 45	50.00 / 30
4	75.00 / 45	50.00 / 30
5	75.00 / 45	50.00 / 30

Similar results occurred during the heavy dirt level tests, except for more pronounced visibility restrictions for each optic unit individually and a minor effect when placed before both optics.

The HSS sensor produced an effect worth noting during the contamination tests. When a contamination plate was initially placed in front of the optic unit, the sensor detected a greatly reduced visibility condition, however, the unit quickly initiated a self-correction process which reacted and attempted to adjust for the contamination present. This effect is clearly depicted in table 11.

When water was applied to the transmitter and receiver optics, the HSS sensor correctly identified a precipitation condition and visibility was reduced. It should be noted that when water was being applied to each optic, some streaming occurred which prevented a uniform coating from being achieved. Numerous attempts were made, but it was found to be impossible to prevent the streaming effect. This effect prevented an accurate calculation of the percent reduced visibility.

According to the test plan, the water and dirt test was only performed when the water-only test depicted no effect. This test was not conducted on the HSS sensor as it was affected by water.

VAISALA FD12

Interference Effects

Sensor	Interference Effects		
	Lateral Clearance Required	Reflected Sunlight	Vehicle Headlight
Vaisala FD12	5.76 m (19 ft)	Insignificant effects noted	Noticeable visibility reductions

The Vaisala device required a semicircular area of clearance identical to the requirements of the HSS sensor depicted in figure 15. A slight visibility reduction was noted by the sensor when sunlight was reflected into the optics. When the data were analyzed, however, the effect was found to be insignificant.

The test of vehicle headlights was performed in accordance with the lateral clearance test methodology. The headlight was positioned at the previously determined clearance distance and then shown back at the sensor unit at 30° increments for the entire 180° arc clearance area. Insignificant effects were noted until the headlight was shown into the sensor optics at 120° and 150°. As can be seen in table 12, a reduction in observed visibility was recorded. As the effect only occurred when light was shown directly into the receiver optics and only in close proximity to the sensor, it was decided to note this result for possible further investigation during the field test.

Table 12. Results of headlight test for Vaisala sensor

Time (min.)	180° Visibility (m)	150° Visibility (m)	120° Visibility (m)	90° Visibility (m)	60° Visibility (m)	30° Visibility (m)	0° Visibility (m)
0.50	37504	32360	27386	27367	45421	19805	38942
1.00	36376	29734	30956	27983	40284	21329	35932
1.50	35032	21981	31989	30121	31912	26653	35037
2.00	38163	18995	27759	32972	25649	34563	36744
2.50	42349	19973	20852	30101	25473	37228	37597
3.00	36801	22509	19329	29358	28609	31872	36462
3.50	35714	22453	23761	32244	30807	31160	35174
4.00	38914	23392	27050	37140	38279	36037	37695
4.50	40031	27216	24129	40944	35772	32867	35050
5.00	35998	26594	23982	43432	24476	28199	33350
Average	37689	24521	25719	33166	32688	29971	36198

Note: The 180° arc for vehicle headlight testing initiated at the right and proceeded counter-clockwise.

Contamination Effects

Sensor	Test Configuration (Optics Covered)	Contamination Effects				
		Light Dirt	Medium Dirt	Heavy Dirt	Water	Water & Light Dirt
Vaisala FD12	Transmitter only	No effect	No effect	Contamination detected sensor defaults to alarm mode	No effect	No effect
	Receiver only	No effect	Contamination detected sensor defaults to alarm mode	Contamination detected sensor defaults to alarm mode	No effect	No effect
	Transmitter & receiver	No effect	Contamination detected sensor defaults to alarm mode	Contamination detected sensor defaults to alarm mode	No effect	Reduced visibility observed

The Vaisala sensor was found to be the most sensitive of the sensors examined. When a medium-level contaminate plate was set in front of the receiver optics, the FD12 unit produced an alarm flag and stopped recording visibility conditions. This event persisted in the combined configuration at the medium dirt level as well as all optic combinations when the heavy contamination level test was conducted.

The system proved to be dynamic when the water and light dirt test was administered. The Vaisala system indicated a slightly reduced visibility condition, but did not go into an alarm mode and continued to monitor and record visibility conditions.

STEN LÖFVING OPVD SENSOR

Interference Effects

Sensor	Interference Effects		
	Lateral Clearance Required	Reflected Sunlight	Vehicle Headlight
Sten Löfving OPVD	32 m (105.6 ft)	Sunlight effect found insignificant	No effect

The required clearance area for the OPVD sensor was found to be a beam-like shape with a width of approximately 0.1 m (4 in) and a distance of 32 m (105.6 ft). A diagram of the required area is shown in figure 16. This area requirement was found to be a result of the back scatter visibility technique utilized by this device.

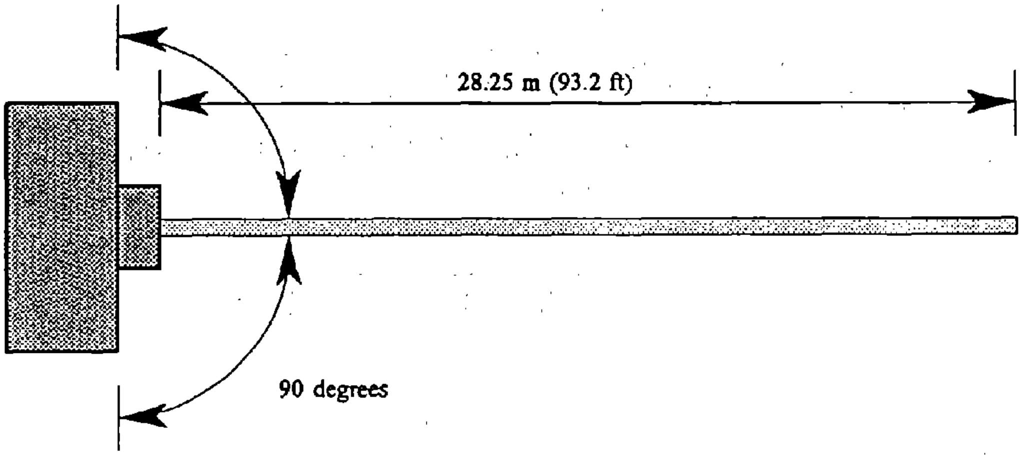


Figure 16. Required lateral clearance for Sten Löfving sensor

Figure 17 illustrates the effects of placing an object inside of the required clearance area. At 26 and 29 m (86 and 96 ft), definite interference effects are recorded by the Sten Löfving sensor, however, when the reflective object was placed at 32 m (105.6 ft), only a very negligible effect is noted.

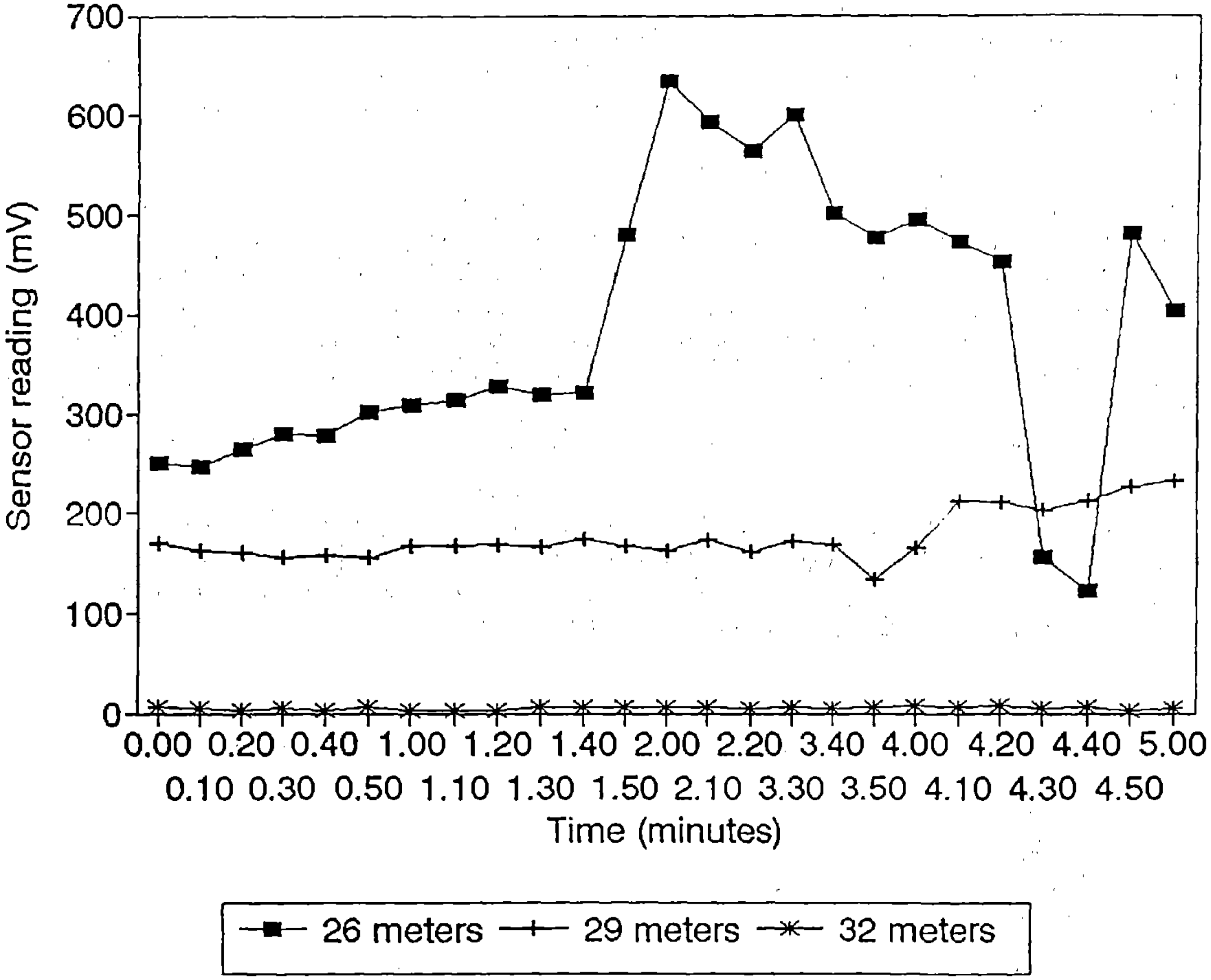


Figure 17. Lateral clearance test with object at fixed distances
for Sten Löfving sensor

It was found that both sunlight and vehicle headlights shown into the optics of the OPVD sensor had insignificant effects.

Simulated Reduced Visibility

Sensor	Simulated Reduced Visibility		
	Initial Reading	Diffused Smoke Reading	Intense Smoke Reading
Sten Löfving OPVD		103 mV @ 50 seconds	720 mV @ 10 seconds

The Sten Löfving sensor was among the quickest of the sensors examined to detect reduced visibility conditions. The OPVD device reported lower visibility at its first poll, a period of 10 s, during intense conditions produced by fog. The sensor was considerably slower to react to a diffused smoke condition, reacting and detecting the presence of fog in 50 s. This figure, however, compares very well with the reaction rates for the remaining sensors examined as part of this test.

Contamination Effects

Sensor	Test Configuration (Optics Covered)	Contamination Effects				
		Light Dirt	Medium Dirt	Heavy Dirt	Water	Water & Dirt
Sten Löfving OPVD	Transmitter only	No effect	No effect	Reduced visibility	No effect	No effect
	Receiver only	No effect	No effect	Reduced visibility	No effect	No effect
	Transmitter & receiver	No effect	No effect	Severely reduced visibility	No effect	No effect

The OPVD sensor proved to be one of the more robust devices, only identifying a reduced visibility condition during the heavy contamination test. Visibility reductions were most significant when heavy contamination plates were placed on both optics. The sensor was not affected by the presence of water or water and dirt combined on the lens.

PHAROS MARINE FD-320

The Pharos Marine sensor reported visibility conditions differently from the other sensors examined in this study. The FD-320 device has three visibility threshold levels which the user sets from within the sensor's measuring range of 50-1,000 m (165-3,300 ft). Based upon input from the manufacturer, the values chosen for the field test were: 100, 300, and 500 m (330, 990 and 1,650 ft).

When visibility conditions fall below 500 m (1,650 ft), a fog #1 alert is given. If the condition persists for two consecutive measurement cycles, an alarm #1 is given in addition to the alert. This procedure is repeated for visibility conditions which fall below 300 and 100 m (330 and 990 ft), with fog #2 and alarm #2 as well as fog #3 and alarm #3 being activated.

Interference Effects

Sensor	Interference Effects		
	Lateral Clearance Required	Reflected Sunlight	Vehicle Headlight
Pharos Marine FD-320	43.2 m (142.6 ft)	Placed sensor into fault mode	No effect

The Pharos Marine device required the largest clearance area, extending more than 43 m (142 ft) out from the sensor. The FD-320 sensor clearance area resembled that shown in figure 16 for the Sten Löfving device. Sunlight reflected into the optics of the device placed it into a "fault" mode requiring rebooting of the system, and thus precluding any visibility readings from being obtained.

Simulated Reduced Visibility

Sensor	Simulated Reduced Visibility		
	Initial Reading	Light Smoke Reading	Intense Smoke Reading
Pharos Marine FD-320	No alarms - visibility above 500 m (1,650 ft)	Fog detected on Alarm #1 @ 30 seconds	Fog detected on Alarm #1 @ 30 seconds

The Pharos Marine system detected the reduced visibility condition caused by intense smoke and reported such findings in 30 seconds. The system detected a visibility condition between 300 and 100 m (990 and 330 ft) for the duration of the test. The FD-320 required just over

1 m to return to clear visibility conditions after the removal of the smoke-producing machine. During the diffused smoke test, the Pharos Marine sensor again detected reduced visibility in 30 s. Due to nonuniformity of the smoke in this test, the FD-320 reported visibilities ranging from below 500 m to 100 m (1,650 to 330 ft) during the test period. The sensor reported clear visibility conditions 1 min after the smoke machine was turned off.

Contamination Effects

Sensor	Test Configuration (Optics Covered)	Contamination Effects				
		Light Dirt	Medium Dirt	Heavy Dirt	Water	Water & Dirt
Pharos Marine FD-320	Transmitter only	No effect	No effect	No effect	No effect	No effect
	Receiver only	No effect	Placed system into fault mode	Placed system into fault mode	No effect	No effect
	Transmitter & receiver	No effect	Placed system into fault mode	Placed system into fault mode	No effect	No effect

The Pharos Marine system produced interesting results from the contaminates test. While the light dirt test had no effect upon the device, the medium and heavy levels placed the sensor into the "fault" mode, again requiring system rebooting and precluding any data from being collected. The point of interest was that this effect did not occur when the plates were set only in front of the transmitter optics. During these tests, the system responded normally and continued to collect and report on visibility conditions. The water test as well as the water and dirt test were found to have no effects on the FD-320 device.

CHAPTER 12. DATA ANALYSIS

OVERVIEW

This chapter explains the methodology used to analyze the data collected in the real-world testing of stationary visibility sensors. The analysis of sensors in real-world testing is primarily directed at visibilities below 200 m (660 ft). This threshold distance is based on an approximate worst case stopping distance for a vehicle traveling at a speed of 88 km/h (55 mi/h).

As discussed in chapter 10, the visual inspection of the targets placed along the roadside forms the primary baseline data against which the sensor-reported visibilities were assessed. These targets were strategically placed at stopping sight distances corresponding to a range of speeds. It has been assumed that observation of these targets would closely approximate a person driving a motor vehicle through the same conditions.

The initial analysis consisted of a direct comparison between each sensor's reported data and the visibility reported by the on-site observer. This initial comparison determined that a series of anomalies existed between the sensors data and the manual observations. Some correlation was found to exist between the anomalies and the person making the observation. Based upon these findings, the evaluation team examined and compared the manual observations with the stored video images for the same time period. It was identified that there were similar anomalies between the manual observations and the visibilities determined by the video image Thus, it was determined that the analysis would utilize the video images rather than the onsite observations as the baseline data. This methodology has many benefits including:

1. The pictures taken at the site are stored digitally via the onsite computer with a file name that corresponds to the time at which the picture was taken. The sensor-reported visibilities are also stored in a file with a field identifying the computer time at which the sensor reported the visibility. This correlation of picture and sensor time ensures that no human error entered into the transcription of data.

2. It has been identified throughout the real-world testing, and confirmed by the consultant meteorologist that, at the test location, the time required for visibility to change significantly is very short, sometimes less than a minute. Each of the pictures taken at the site were within 30 s of the sensor-reported visibility. There is therefore a much higher probability that the visibilities recorded by the sensors and those observed in the pictures are the result of the same conditions.

3. The use and evaluation of pictures taken at the site ensure that only a single observer is determining the visibility. Four different Mn/DOT personnel made manual observations of visibility during the test period. It is apparent

that the observers were not consistent in their interpretation of the visibility conditions.

4. The video pictures are unaffected by wind gust or other environmental affects which may alter an observer's interpretation of the visibility distance. The video pictures taken at the site therefore more closely approximate the conditions that would be observed by a person driving a vehicle.

5. More data are available for analysis. While manual observations were taken each time a low-visibility condition could be predicted in advance of the occurrence, observers were not on site for all low-visibility developments.

IDENTIFICATION OF VISIBILITY RANGE FROM VIDEO IMAGES

The baseline visibility used for this analysis is represented by a range of visibilities rather than a single visibility. The range of visibilities is identified from the furthest roadside target that can be seen on the video image. The following example displays why a range, and not a single target distance, is utilized in the analysis:

> Target # 3 is located at a distance of 20.1 m (66.3 ft) from the sensors, while target # 4 is located at a distance of 32.7 m (108 ft) from the sensors. If the furthest roadside target, visible in the video image, is target # 3, then the actual visibility distance may not be exactly 20.1 m (66.3 ft), but rather some distance between 20.1 m and 32.7 m (66.3 ft and 108 ft). This resultant range of visibilities is an effect of the separation distance between visibility targets. A distance of 31 m (102 ft), for example, would allow the observer to see target # 3 but not target # 4.

To facilitate the analysis described in chapter 10, video pictures were examined throughout the test to identify when low-visibility conditions occurred. When low-visibility conditions were identified (i.e., roadside target # 9 could not be seen), video pictures were downloaded and saved on computer disks for future review and comparison. If any of the video pictures appeared to be unclear as a result of snow or dew covering the camera's lens or from the image being too dark as a result of poor sunlight, the video image was placed in a separate file and was not used for the analysis.

Following the identification of low-visibility occurrences, the video images were reviewed to determine the furthest roadside target visible in each of the video pictures. The basis for identifying a visible target was the same as that identified in the procedures for onsite observations. These procedures stated that the outline of the furthest target must be seen by the observer. After observing the image on the computer's video monitor, a high resolution copy was printed using a laser printer and the observation confirmed. Examples of video images for both low visibility (<200 m) and good visibility (>200 m) can be found in appendix K.

COMPARISON OF OBSERVED VISIBILITIES TO SENSOR-REPORTED VISIBILITIES

A direct comparison was made for each low-visibility occurrence identified in the video images. The results presented in chapter 13 identify the total number of visibility occurrences assessed for each sensor, the number of times the sensor-reported visibility was within the range of visibilities identified through examination of the video images, and the average number of reported visibilities that were within the range of the manual observations, for each sensor.

Each anomaly between sensor-reported visibilities and the visibility range identified through examination of video images is assessed by determining the absolute and percentage difference between the visibility distances.

Following the direct comparison of sensor-reported visibilities and manual visibilities, each sensor is recalibrated. The calibration methodology employed is a straight linear calibration, derived from multiplying the sensor-reported visibility by a scalar constant. The scalar constant chosen maximizes the percentage of sensor-reported visibilities that will be within the range identified through examination of the video images.

VISIBILITY IMPACTS ON SPEED

The AUTOSCOPE™ system provided at the site collected vehicle speeds during the test periods. To investigate the impact of visibility on vehicle speed, a series of graphs of speed versus visibility were plotted. These plots utilize data from a sample of the low-visibility days: December 16, May 29, June 6, June 27, and June 5. The plots utilize data from the complete day to provide both good and poor visibility data points.

CHAPTER 13. EVALUATION RESULTS

OVERVIEW

This chapter presents the results of the real-world testing of visibility sensors and provides a quantitative assessment of the visibility sensors. This assessment determines whether sensor-reported visibilities were within the range of visibilities identified through review of the video images recorded at the test site. The assessment also determines whether the sensor-reported visibilities were within the minimum requirements specified in the test plan. These requirements specified that the sensors reported visibilities should be within ±20 percent of the visibilities identified through manual observations.

The Pharos Marine sensor did not participate in the real-world tests due to a failure in the sensor's communications terminal prohibiting transmission of signals.

The section following this overview identifies the date, time, and type of low-visibility obstruction for each of the low-visibility occurrences used to analyze the sensors. This section provides information on some of the anomalies between sensor-reported visibilities and visibility distances identified through manual observations. Then the results of the direct comparison of sensor-reported visibility distances with visibility distances determined through manual observations are presented. The next section presents the results of comparing the sensor-reported visibility distances with manual observations after the sensor data have been recalibrated. The subsequent section identifies sensor failures observed during the real-world testing, followed by the results of comparing vehicle speed data, collected with the AUTOSCOPE™ test equipment, with visibilities identified by the sensors.

LOW-VISIBILITY OCCURRENCES

Thirteen low-visibility conditions were analyzed to evaluate each of the sensors. The date, time, and conditions for each of the low-visibility occurrences are presented in table 13.

The visibility conditions presented in table 13 are based on observations made by onsite personnel and examination of video images recorded at the test site. The conditions have been confirmed by the consultant meteorologist through contact with the National Weather Service and meteorological observations made at the site.

An exception to the comparison of visibility distances acquired through review of the video images with visibilities reported by the sensors was identified for the low-visibility occurrence on February 25, 1994. This is the only low-visibility occurrence identified in which the resultant low visibility was caused by blowing snow. After assessing the meteorological conditions at the test site, the consultant meteorologist stated that the low-visibility resulted from conditions that may have reduced the visibility at the height at which the targets are

Table 13. Low-visibility occurrences

Date	Time	Type of Visibility Obstruction
December 4, 1993	8:30 am - 2:05 pm	Fog
December 14, 1993	9:00 am - 11:45 am	Fog
December 16, 1993	8:30 am - 5:30 pm	Fog
December 17, 1993	9:00 am - 11:00 am	Fog
February 25, 1994	8:00 am -12:40 pm	Snow, blowing snow
March 1, 1994	10:20 am - 10:45 am	Fog
May 29, 1994	6:10 am - 8:10 am	Fog
May 30, 1994	5:00 pm - 5:25 pm	Fog
June 5, 1994	7:15 am - 7:40 am	Fog
June 6, 1994	5:30 am - 9:05 pm	Fog
June 24, 1994	5:00 am - 6:20 am	Fog
June 27, 1994	4:40 pm - 5:25 pm	Fog
July 5, 1994	5:30 am - 7:45 am	Fog

located, but may not have produced the same low visibility conditions at the height at which the sensors were located. The consultant meteorologist made this assessment based on the following facts:

- Reported snow depth was about 0.6 m (24 in) in the Duluth area. Added to that is the additional depth of snow plowed into the area of the visibility makers. That brings the snow surface very close to the markers.

- Atmospheric temperatures were -12 °C (10 °F) or less across the area; the dew point temperature spread was 3 ° to 5 °. Road surface temperatures varied from -10 °C to -7.8 °C (14 °F to 18 °F). From this set of conditions a snow-surface temperature very close to the atmospheric readings can be assumed.

- Wind readings were from the east at 32 km/h (20 mi/h) or more, with frequent gusts. Snow was falling. Visibility readings at the Weather Service and at the test site were caused by snow and blowing snow.

- An east wind at the test site is subjected to the laws of fluid-flow at the surface. This results in lowered pressure and an increase in velocity in the very narrow band that extends from the surface to perhaps 0.6 m (2 ft) above the surface.

- Snow particles at the surface tend to break loose when there is a combination of a snow-surface temperature near the atmospheric wet-bulb temperature and a strong wind.

- The sensors were located several feet higher than the visibility markers.

The conditions identified by the consultant meteorologist do not preclude the sensors from reporting the visibilities at the height of the targets, but rather explains the discrepancy identified between the visibilities reported by sensors and those identified through review of the video images.

SENSOR ACCURACIES

Table 14 presents the results of comparing sensor-reported visibility distances with manually-observed visibility distances.

Table 14. Sensor accuracies

	Belfort 6210	HSS 301B	Sten Löfving OPVD	Vaisala FD12
Total number of visibility occurrences assessed	233	235	134	212
Number of visibility measurements which coincided with manual visibility range	91	129	60	27
Average	39.1%	54.9%	44.8%	12.7%

The accuracies presented in table 14 are based on the 13 days of low-visibility conditions identified in table 13. As displayed in table 14, the total number of visibility occurrences were not equal for each of the sensors. This is a result of either sensors not being operational or data collection problems by the onsite computer. As explained below, the Sten Löfving OPVD sensor was not operational during the period of December through March. A data collection problem occurred in the downloading of Vaisala FD12 data on June 6 from

5:30 am until 6:50 am. Similarly, a data collection problem occurred in the downloading of Belfort 301B data on February 25 at 8:55 am and on June 5 at 7:15 am.

The sensor-reported visibilities for each day identified in table 14 are presented in appendix K.

CALIBRATION OF SENSORS

After the initial assessment of sensor-reported visibilities, it was identified that all sensors responded similarly to the conditions at the test site and differed from the visibilities identified through examination of video images by an order of magnitude of one. As a result, each of the sensors' data were recalibrated in an attempt to maximize the number of reported visibilities which corresponded with the visibility range identified through examination of the video images. The resulting calibration factor and sensor accuracies are displayed in table 15.

Table 15. Accuracy of sensor after calibration

	Belfort 6210	HSS 301B	Sten Löfving OPVD	Vaisala FD12
Calibration factor	.83	1.06	1.09	.51
Total number of visibility occurrences assessed	233	235	134	212
Number of visibility measurements which coincided with manual visibility range	133	133	61	96
Average	57.1%	56.6%	45.5%	45.3%

As displayed in table 15, the sensor accuracies improved significantly after being calibrated. An assessment of each sensor's calibration for each of the low-visibility occurrences identified in table 13 can be found in appendix G.

Table 16 presents the absolute and percentage difference between sensor-reported visibility distances and visibility distances obtained through manual observations.

As displayed in table 16, the average percent differences between sensor-reported visibility and manual observations are less than 20 percent for three of the four sensors.

Tables presenting the results of each sensor's accuracies after calibration, for each of the low-visibility occurrences identified in table 13, can be found in appendix H.

Table 16. Comparison of manual and sensor data

	Absolute Difference				% Difference			
	Vaisala	Belfort	HSS	Sten	Vaisala	Belfort	HSS	Sten
December 4, 1994	7.1	6.7	2.4		5.8%	5.3%	2.7%	
December 14, 1994	50.6	32.0	52.9		32.6%	21.1%	33.1%	
December 16, 1994	1.46	0	1		1.0%	0.0%	0.7%	
December 17, 1994	9.2	10.5	6.5		6.1%	7.1%	4.9%	
February 25, 1994		118.5	329.3			61.4%	176.1%	
March 1, 1994	71.7	7.8	67.0		36.7%	3.9%	34.0%	
May 29, 1994	2.0	8.2	2.4	48.9	2.4%	6.0%	1.8%	27.3%
May 30, 1994	1.2	0.003	2.7	23.2	0.8%	0.004%	1.8%	19.3%
June 5, 1994		12.8	9.7	30.0		12.8%	9.7%	30.1%
June 6, 1994	32.1	7.1	8.3	98.9	20.3%	5.8%	6.9%	59.2%
June 24, 1994	8.5	18.6	8.1	73.0	8.9%	11.1%	5.2%	43.7%
June 27, 1994	12.0	20.0	19.8	31.1	8.0%	12.3%	12.6%	17.7%
July 5, 1994	3.857	8.63	5.722	10.657	3.9%	8.9%	5.7%	10.7%
Average	17.7	35.5	88.0	60.9	17.80%	24.05%	52.14%	44.65%
Average (w.out 2/25/94)	17.7	8.6	10.3	60.9	17.80%	12.16%	12.92%	44.65%

SENSOR FAILURES

Three of the sensors failed to report visibilities during some portion of the real-world testing. These sensors are the Belfort 6210, the Sten Löfving OPVD, and the Vaisala FD12.

On April 26, 1994, the Belfort 6210 visibility sensor was struck by lightning during a thunderstorm. The sensor's serial board was damaged and needed replacement. Following the evaluation team's assessment of the lightning strike on April 27, the sensor vendor was contacted. The vendor supplied a new serial board and instructed the evaluation team on the installation procedures. Subsequently, the sensor was working again on May 9, 1994.

The failure of the Sten Löfving sensor during the real-world testing was determined to be a result of a connection becoming loose during the initial installation of the sensor at the Duluth test site. The sensor was subsequently removed and repaired by project team members after consulting with the manufacturer.

On five separate occasions, the Vaisala FD12 sensor failed to report visibilities as a result of the sensor lens becoming fouled from snow and ice forming on the optics unit. During these occurrences, the sensor would report a visibility of 0 m and a hardware failure. The failures were determined to be the result of the heaters within the optics units either not producing enough heat to melt the snow and ice, or the heating unit was not functioning properly. Each of the occurrences required the dispatch of Mn/DOT personnel to the test site to brush off the snow or wipe the sensor's optics. The other sensors did not succumb to this problem as a result of having the transmitter and receiver hoods located at an angle which would keep snow from collecting on the transmitter/receiver or having a more powerful hood heater.

In cold weather climates, a combination of a powerful hood heater and the transmitter/receiver being located at an angle which does not allow snow to collect would be the best solution to prevent lens fouling. (It should be noted that the Vaisala sensor reported the hardware failure allowing maintenance personnel to be dispatched when the situation occurred).

Table 17 gives a brief summary for each of the sensor failures, including total down time and repair costs.

Table 17. Summary of sensor failures during real-world testing

Sensor	Failed	On-line	Problem & Response Taken	Repair Costs
Belfort	4/25/94	5/9/94	Sensor struck by lightning. Serial card destroyed. Vendor contacted and new board sent and installed.	Board provided by vendor free of cost. Contractor - 2 hours to install new board.
Sten Löfving	11/4/93	4/6/94	System reporting extraneous results. Sensor taken down for repair 2/28/94. Manufacturers fixed loose ground connection.	Contractor - 3 hours to remove and reinstall sensor
System	4/25/94	4/28/94 Communications returned to HSS & Vaisala	Communications down due to lighting strike. Image Sensing Systems replaced modem and serial card.	Repair by Image Sensing Systems - $1,140.00
Vaisala	11/23/93	11/23/94	Sensor reported failure due to lens fouling. System self-corrected. No action taken to repair.	
	11/25/93	11/25/93		
	1/06/94	1/07/94		
	1/25/94	1/25/94		
	1/26/94	1/27/94	Sensor failed to transmit data.	
	1/28/94	2/11/94	Zero visibility reported on numerous lengthy periods. Mn/DOT personnel dispatched to inspect system & clear lenses	Mn/DOT - 1 hour to clean off lenses
	2/23/94	2/23/94	Zero visibility reported during clear conditions. System self-corrected. No action taken.	
	3/23/94	3/24/94		
	4/28/94	4/29/94		

VISIBILITY IMPACTS ON SPEED

In order to effectively analyze driving speed changes for different visibilities, the average speed for a range of visibilities was calculated. Similar quantities of data from good visibility and poor visibility periods were used for the analysis. Table 18 presents the resulting data points.

Table 18. Average speed and visibility range data

Average speed (km/h)	Visibility range (m)	Sample size
100.456	up to 54	46
101.3936	54-71	115
103.5732	71-93	117
104.198	93-122	132
107.9103	122-159	79
108.8042	159-208	98
108.3094	208-271	82
106.663	271-348	50
108.6435	348-458	46
110.7616	458-603	38
109.8732	603-787	53
107.9315	787-1020	27
112.632	1020-1449	30
112.3651	1449-1898	39
112.2224	1898-2439	41
109.8929	2439-3225	49
112.4172	3225-4225	75
112.1614	4225-5555	85
112.7197	5555-7317	118
112.3692	7317-9677	130
110.7677	9677-12500	101
110.8051	12500-16666	126
114.1233	16666-21428	133
115.5513	21428-27272	281
113.7639	27272-37499	233
111.2217	37499-50000	115
111.2014	50000-74999	106

Table 18. Average speed and visibility range data (continued)

110.0173	74999-100000	62
108.0483	100000-149999	208

The plots of vehicle speed versus visibility for the test are shown in figure 18. These plots were generated using data from days with low visibility due primarily to fog (December 4 and December 16, 1993; and March 1, May 29, May 30, June 5, June 6, June 24, June 27, and July 5, 1994). Those days which included visibility restrictions due to snow or blowing snow were not included in this analysis since vehicle speeds on these days varied to a much greater extent. The speed variation due to snow is illustrated in figure 19, which presents a plot of the 5-min average speeds throughout the day on February 25, 1994.

From these data, it can be seen that the impact of snow on driving conditions is much greater than the impact of low visibilities. Visibility reductions to less than 70 m (231 ft) caused only a 5 to 10 km/h (3 to 6 mi/h) average speed reduction.

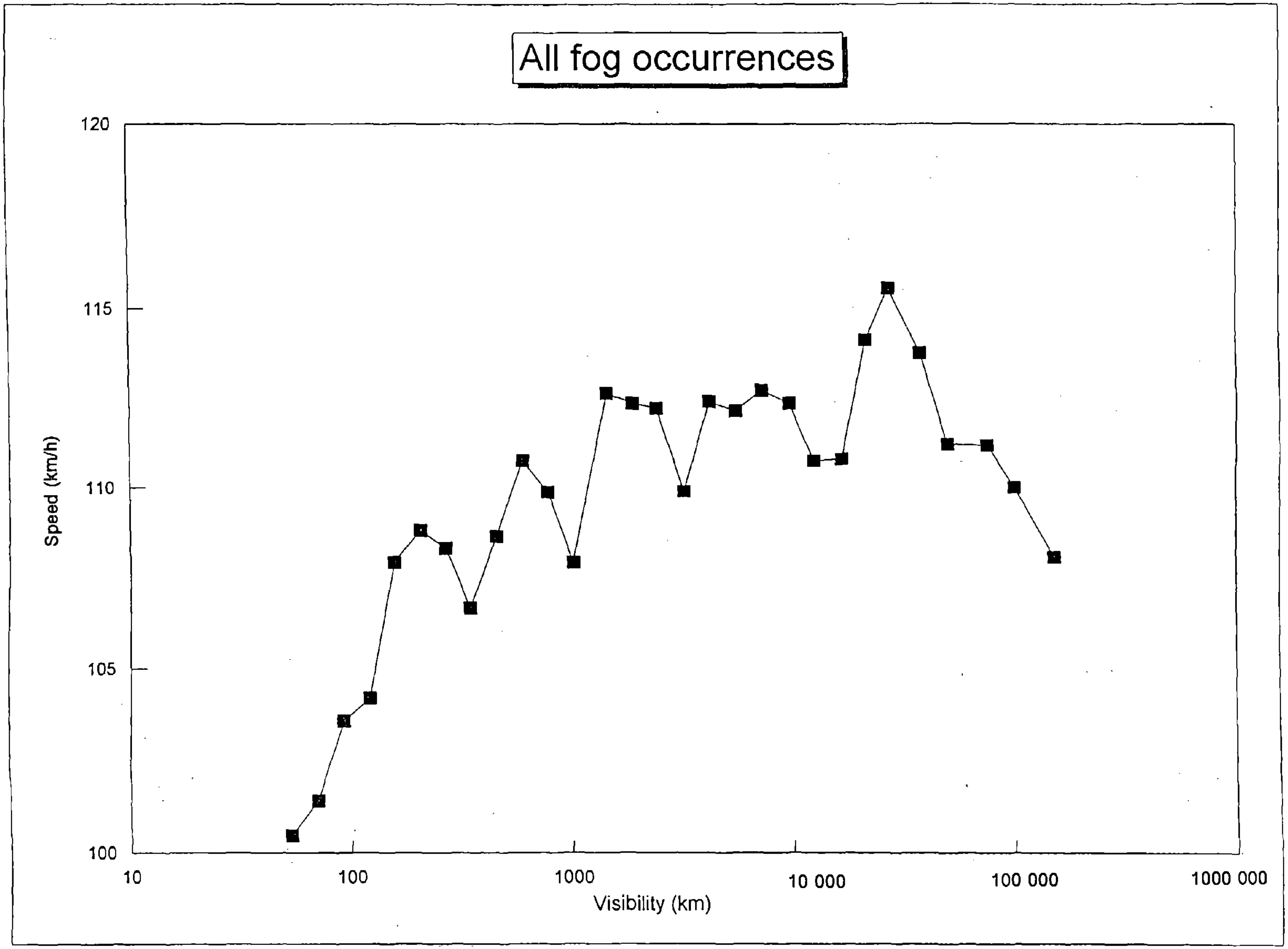


Figure 18. Vehicle speed versus visibility

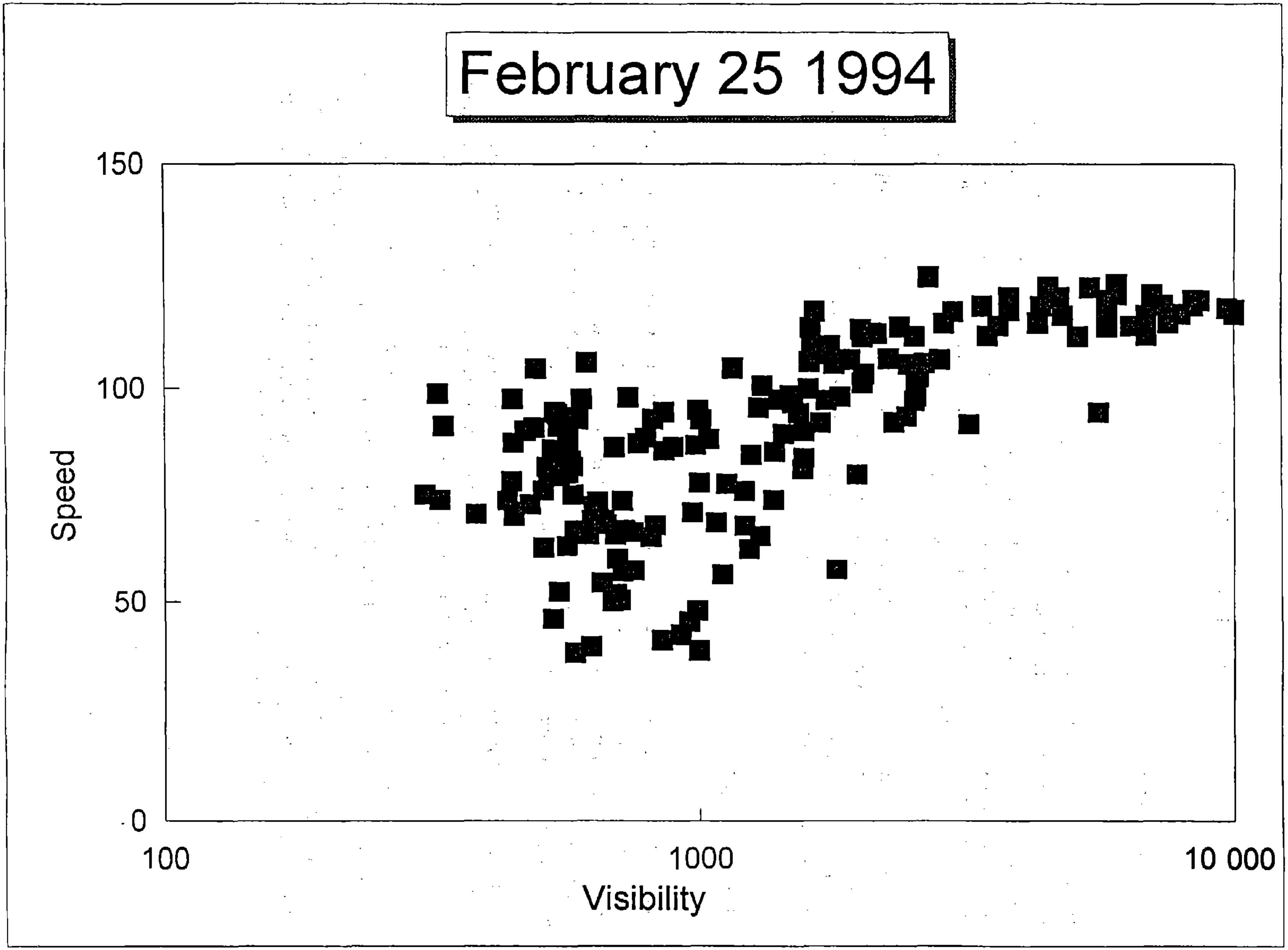


Figure 19. Five-minute average speeds

CHAPTER 14. MOBILE VISIBILITY SENSOR

INTRODUCTION

Developing an accurate and useful representation of conditions of reduced visibility involves the detection of limited visibility at a number of varying locations. There is potential for achieving this using a large network of stationary sensors, a smaller number of stationary sensors combined with predictive modeling, or possibly a small number of mobile sensors. In order to investigate the feasibility of the latter method, a mobile visibility sensor was tested. The only mobile sensor offered for testing was the AVM III developed by HSS Inc.

In order to undertake this evaluation, the 15 mobile visibility sensor functional requirements were classified into three categories: operational performance of the sensor; qualitative performance measures; and quantitative performance measures. A matrix identifying each functional requirement and its associated category is shown in table 19.

SENSOR DESCRIPTION

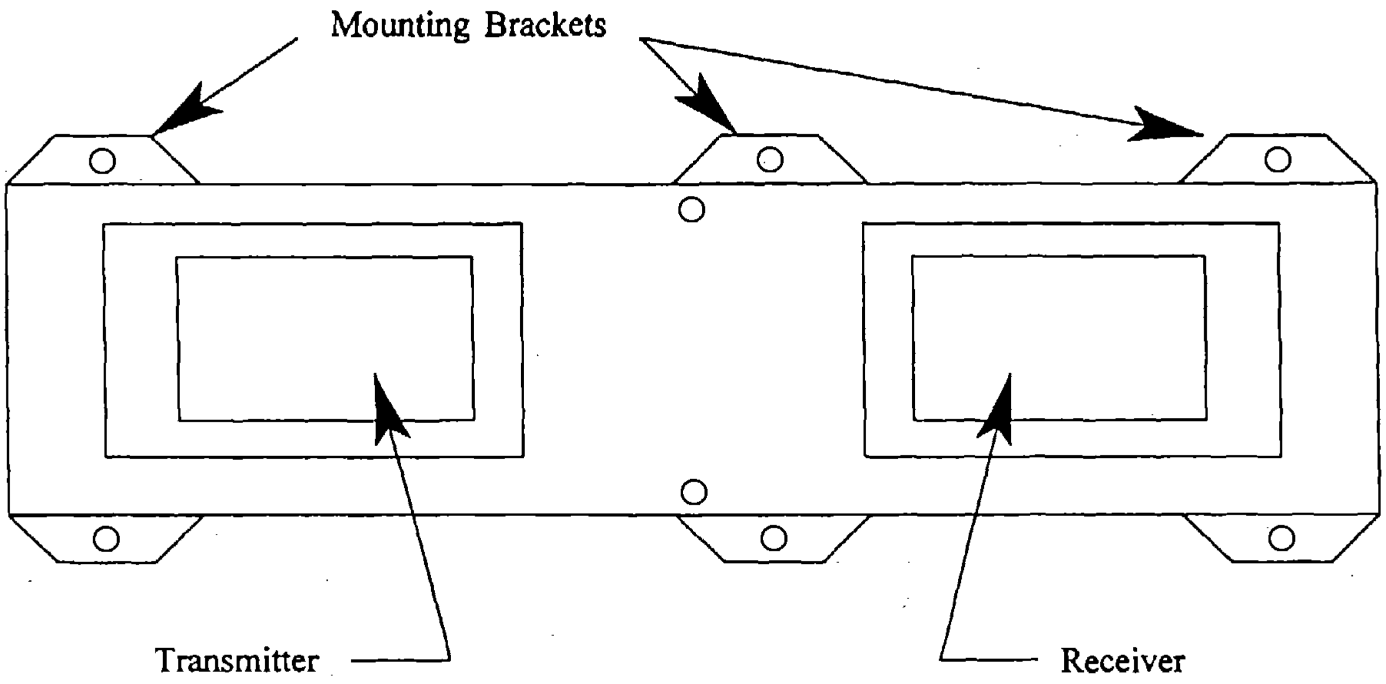
The AVM III sensor is a miniaturized version of an environmental sensor used to examine visibility conditions. It was originally developed for the United States Air Force to be attached to aircraft flying over potential target areas. In this capacity, it would provide pre-strike information such as the percent cloud cover and density, heights of cloud bases and tops, as well as the presence and intensity of any precipitation.

As it has been designed to be mounted under aircraft, the AVM III is extremely small, with total system dimensions of 460 mm by 85 mm by 65 mm (18.5 in by 3.5 in by 2.6 in) and a weight of approximately 1.8 kg (4 lb). A diagram of the system is presented in figure 20.

Like the stationary HSS (301B) sensor being examined in the real-world test, the AVM III utilizes the forward scatter approach for visibility detection. Chapter 9 of this report provides additional information on the forward scatter visibility technique. Since it was developed for use in aircraft, the AVM III was designed for use up to speeds approaching 500 knots. To accommodate such speeds, the sampling interval is approximately 2 s, as opposed to 60 s for many of the stationary sensors participating in the field tests.(45)

Table 19. Mobile sensor functional characteristics

	Operational Performance	Qualitative Performance	Quantitative Performance
Functional Requirements	The sensor should be insensitive to ambient temperatures.	The measurement of visibility should not be affected by external ambient or naturally occurring light sources.	The sensor should measure visibilities of at least 0 to 400 m (0 5- 1,320 ft) with accuracy better than ±20 percent.
	The complete sensor system should have a low power consumption.	The measurement of visibility distance should not be affected by the type of visibility reduction such as rain, snow, or fog.	The visibility measured by any sensor at any instant should closely correlate with the visibility experienced by the vehicle driver.
	The sensor output should be in a useable form.	The information provided by the sensor should not indicate the presence of low visibility in good visibility conditions or vice versa more than once per year in continuous operation.	The system should be able to detect and report visibility changes of 70 m (231 ft) in length at speeds of up to 100 km/h (60 mi/h).
	The sensor should be low maintenance and require minimal calibration.		
	The system should be self-diagnostic and report when it is unable to take accurate readings.		
	The sensor should be unobtrusive when installed on the vehicle.		
	The sensor should be insensitive to normal vehicular vibrations.		
	The sensor should be capable of being installed on any vehicle.		
	The sensor should have the potential to evolve into an extremely low-cost mass-produced item.		



Note: approximate scale 10 mm = 17 mm (1 in = 1.58 in)

Figure 20. HSS AVM III mobile sensor

DATA COLLECTION METHODOLOGY

The HSS AVM III sensor was mounted on the roof of a Mn/DOT vehicle for field testing in the Duluth, Minnesota area. The installation is shown in figure 21. A laptop computer recorded sensor output, and a video camera was positioned on the dashboard, pointed forward, to record a visual observation of conditions. The sensor was installed on the Mn/DOT vehicle to allow for efficient data gathering. The mobile test plan required data to be collected whenever low-visibility conditions were found to be present at the Thomson Hill test site.

In addition to low-visibility detection, the sensor was tested to examine the effects, if any, of normally encountered roadway objects or conditions in close proximity to the vehicle. Examples of such conditions include travel through tunnels, tree-lined streets, and parking garages. Table 20 describes all conditions examined during the test period.

During the data collection process there were 16 periods when the visibility dropped below 500 m (1,650 ft). These 16 events form the basis of the qualitative evaluation. During one of these events, the mobile sensor was located at the test site of the stationary sensors while manual observations were being taken. This event has been used for a quantitative evaluation of the mobile sensor's output.

Table 20. Mobile sensor test conditions

Weather Conditions	Tunnels	Tree-lined roads	Urban Settings		Evening Conditions		Environmental Conditions	
			Downtown Duluth	Heavy pedestrian areas	Headlights	Passing vehicles	Wet roads	Gravel roads
Clear	x	x	x	x	x	x	x	x
Fog	x	x	x	x	x	x	x	
Dust								x

OPERATIONAL PERFORMANCE OF THE MOBILE SENSOR

The evaluation plan submitted in April 1993 outlined nine operational aspects that, as a minimum, a selected mobile visibility sensor should prove capable of performing. The performance of the mobile sensor under each of these nine functional areas is described in the following paragraphs.

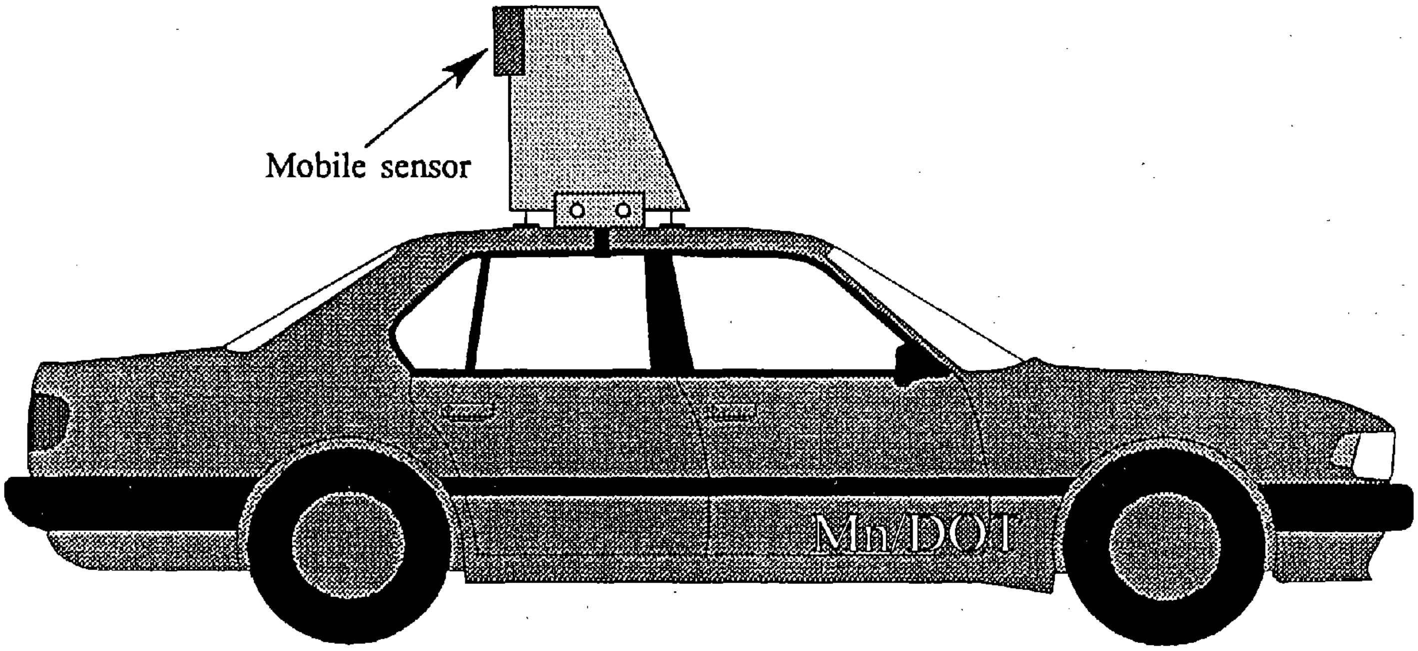


Figure 21. Mobile sensor vehicle installation

1. The sensor shall be insensitive to ambient temperatures.

The mobile sensor test occurred between March 1994 and July 1994. Performance of the sensor was not limited by any ambient temperatures during this period. The HSS AVM III does include an internal heating element and is rated to operate within a temperature range of -40 °C to 30 °C (-40 °F to 86 °F).

2. The complete sensor system should have a low power consumption.

The listed power consumption for the HSS AVM III is 30 watts, with 9.2 watts required for sensor electronics and the remaining 20.8 watts used to power the window heaters. For field testing purposes, the sensor devices were powered via a power inverter connected to the vehicle's cigarette lighter socket. The onboard laptop computer which recorded the sensor output was powered by an internal battery supply. This was done to prevent overloading of the inverter used for the test. Since the sensor itself was powered from the vehicle's accessory outlet, it can be considered to have low enough power consumption for the intended application.

3. The sensor output should be in usable form.

For the duration of the field test, the mobile sensor was connected via an RS232 interface with a laptop computer. The computer program accompanying the sensor reported the data in a format easily transferred into current visibility readings. In addition to the visibility readings, the sensor reported cloud density, precipitation occurrence, precipitation type, and precipitation intensity. The RS232 connection and ASCII text provide a highly usable solution.

4. The sensor should be low maintenance and require minimal calibration.

The sensor had been calibrated prior to shipment. All that was required for operation was an initial verification of the calibration and installation. For the duration of the test, the sensor was mounted on the roof of the car. The only maintenance required was occasional lens wiping. Due to the temporary mounting of the system, cables connecting the sensor to the laptop computer and power source were exposed and required connection prior to each test run.

5. The system should be self-diagnostic and report when it is unable to take accurate readings.

No specifications were identified by the manufacturer regarding this ability. The sensor output also did not identify any such reporting ability.

6. The sensor should be unobtrusive when installed on the vehicle.

Due to specification requirements outlined by HSS, it was necessary to position the sensor approximately 0.5 m (20 in) above the vehicle. This was to ensure "clean" air flow over the device. Based upon testing, it was found that future examinations could be conducted with the sensor incorporated into the vehicle body structure.

7. <u>The sensor should be insensitive to normal vehicular vibrations.</u>

During the field test, the sensor was driven on a variety of roadways including freeways, trunk highways, and gravel roads. Performance of the HSS AVM III did not vary with the change in roadway smoothness. Similarly, readings were taken with the vehicle stopped and in motion, under the same visibility conditions, and the visibility values did not vary.

8. <u>The sensor should be capable of being installed on any vehicle.</u>

As previously indicated, field testing only involved a temporary mounting on the roof. The power was relayed via a standard in-vehicle cigarette lighter. Therefore, the HSS AVM III is compatible with any vehicle as tested. However, special modifications would be required for permanent installation.

9. <u>The sensor should have the potential to evolve into an extremely low-cost mass-produced item.</u>

The HSS AVM III device is still in the prototype phase of development, however, discussions with the vendor indicate that there are no aspects of this sensor that would prevent low-cost mass production.

QUALITATIVE PERFORMANCE

The qualitative evaluation of the mobile sensor primarily focused on the three qualitative functional requirements presented in the environmental sensor evaluation plan. These three requirements are as follows:

1. <u>The measurement of visibility should not be affected by external ambient or naturally occurring light sources.</u>

A series of test cases was developed to test the mobile sensor's reaction to various ambient lighting conditions. Although the majority of tests occurred during daylight hours, one field test was conducted under complete darkness. During this test, the sensor detected periods of low visibility. To evaluate any effects of rapidly-changing ambient light conditions, the test vehicle traveled through a series of tunnels during the field test. The sensor readings showed no change during these instances. The test under darkness was also intended to evaluate the effects of headlights and taillights. During this test, the vehicle faced oncoming headlights and confronted taillights at stoplights and stop signs. The sensor data did not falsely indicate any low-visibility conditions during these tests.

2. The measurement of visibility distance should not be affected by the type of visibility reduction such as rain, snow, or fog.

The majority of visibility restrictions in this area are due to either rain, fog, dust, or a combination of the three. Of the 16 low-visibility events, there were no conditions caused solely by rain. Three events involved only fog and the remainder were a combination of rain and fog. No differences in the sensor output could be discerned for the different types of conditions.

3. The information provided by the sensor should not indicate the presence of low visibility in good visibility conditions or vice versa more than once per year in continuous operation.

To test for false alarms, the videotapes were observed to determine if the sensor indicated low visibility during good visibility conditions. The sensor indicated visibility below 500 m (1,650 ft) only during the 16 low-visibility events. These 16 events were the only low-visibility events during which the sensor was operational. Therefore, throughout the testing, all detected periods of low visibility were confirmed with visual observation. These analyses are based solely on visual inspection of the video images and no quantitative verification of the visibilities measured can be performed for these events.

QUANTITATIVE PERFORMANCE

The quantitative evaluation's purpose is to assess the performance of the mobile sensor on a numeric basis. The results of this evaluation will indicate to what accuracy this sensor is capable of performing. The following three criteria form the basis for the quantitative evaluation.

1. The sensor should measure visibilities of at least 0 to 400 m (0 to 1,320 ft) with accuracy better than ± 20 percent.

On May 29, 1994 the vehicle-mounted mobile sensor was located at the Thomson Hill test site. For the period in which the vehicle was parked at the test site, several still frame pictures were recorded by the onsite video camera and downloaded to a computer. Visual observation of these images convey the actual visibility at the site. As was noted in the stationary sensor review, a series of visibility targets were positioned at fixed distances from the point of observation. An observer has viewed each still picture and noted the furthest visible target. Because of the target spacing, the visual observation can only reveal a range of visibility to be at least as far as the last visible sign, and not as far as the next sign in the series. On this date, three different visibility measurements were manually recorded. These three values will form the basis for the quantitative evaluation to follow.

- Manual reading #1. At 7:50 am, visual observation noted five signs visible, indicating a maximum visibility range of 67 to 80 m (221 to 264 ft). The mobile sensor recorded 37 readings within the minute bracketing the manual observation time. The average value of these readings was 102 m (337 ft) with a standard deviation of 3.6 m (11.9 ft).

- Manual reading #2. At 7:55 am, visual observation noted seven signs visible, indicating a maximum visibility range of 100 to 150 m (330 to 495 ft). The mobile sensor recorded 38 readings during the test period. The average value of these readings was 133 m (439 ft) with a standard deviation of 7.0 m (23.1 ft).

- Manual reading #3. At 8:00 am, visual observation noted six signs visible, indicating a maximum visibility range of 80 to 100 m (264 to 330 ft). Thirty-seven mobile sensor readings were recorded. The average value of these readings was 213 m (703 ft) with a standard deviation of 19.6 m (64.7 ft).

Figure 22 illustrates the visibility readings taken by the mobile sensor prior to and after arriving at the test site when the above readings were taken. Also shown in figure 22 are the above-referenced manually-recorded visibility ranges at the above-noted times.

A statistical analysis of the mean and standard deviation is capable of estimating a range for the data. By calculating the standard deviation of a data set and applying Chebyshev's theorem, it can be calculated that 75 percent of the data set lies within two standard deviations on either side of the mean. This is illustrated in table 21 which depicts the observed data range and recorded data range (75 percent confidence) for each quantitative event.

Table 21. Comparison of three visual observation results

Reading Number	HSS AVM III visibility (m)			Observed visibility (m) data range	Each match
	Avg. value	Stand. dev.	75% range		
1	102	3.63	94.7-109.3	67-80	N
2	133	7.00	119-147	100-150	Y
3	213	19.6	173.8-252.2	80-100	N

The results of this statistical analysis are limited by the visual observer's level of precision. However, the table above illustrates that 75 percent of the data recorded during one of the three instances lies within the visual observation range.

When asked to review test results, the manufacturer noted the higher visibility readings for the AVM III sensor might be attributed to a fog-shadow effect. This effect occurs because the sample volume of the sensor is in close proximity to the body of the sensor. When the wind direction is such that fog drifts over the sensor body before entering the sample volume, then the fog entering the sample volume is dissipated to a degree. The reduced fog density always leads to a higher than true visibility reading.

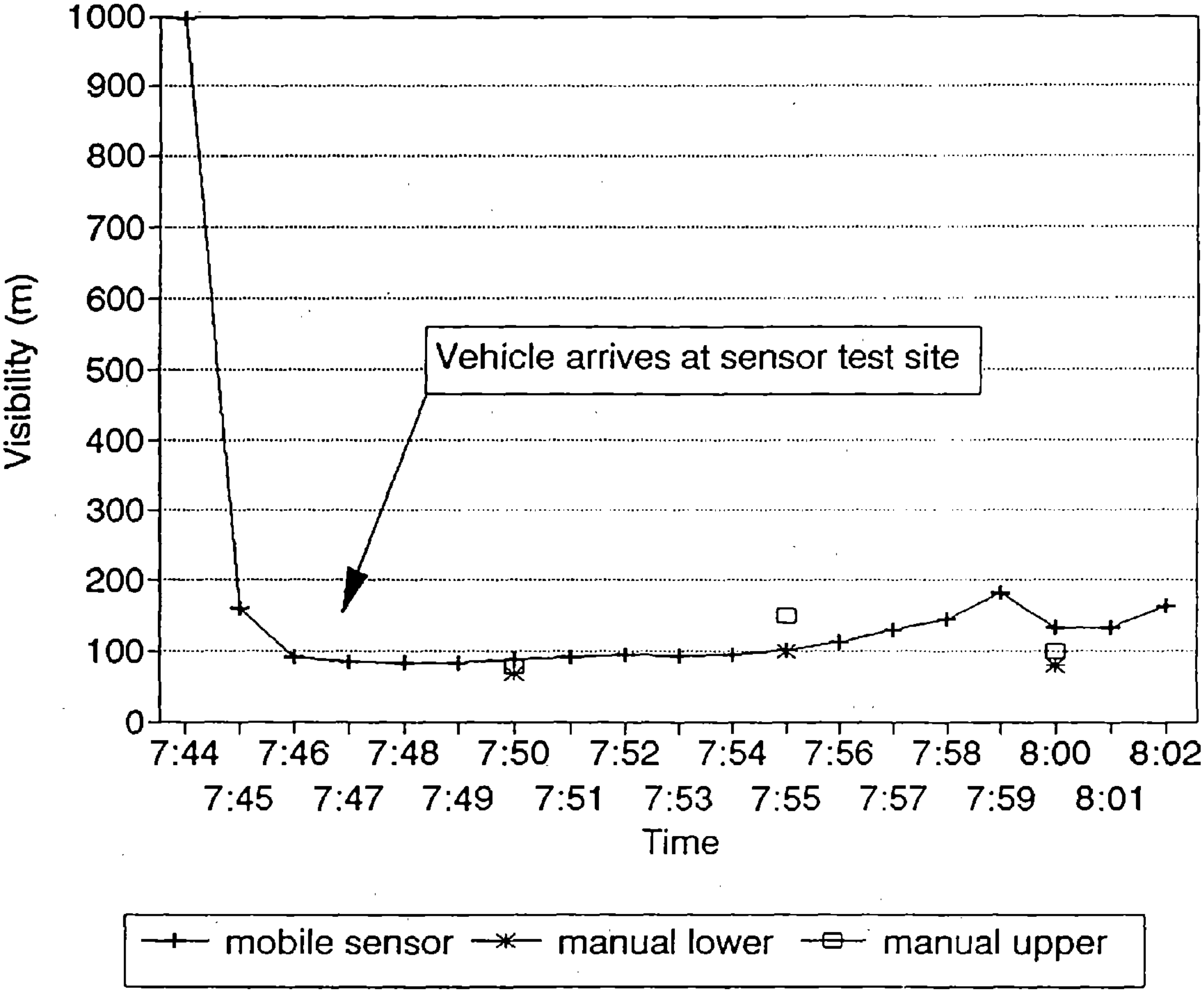


Figure 22. Mobile sensor data vs. manual readings - May 29, 1994

2. The visibility measured by any sensor at any instant should closely correlate with the visibility experienced by the vehicle driver.

The analysis undertaken for the quantitative evaluation was based on human sight at the test location. Assuming that the visibility experienced by a vehicle driver at least correlates to that experienced by a stationary observer, the preceding analysis shows that the sensor output closely mirrors driver visibility.

3. The system should be able to detect and report visibility changes of 70 m (231 ft) in length at speeds of up to 100 km/h (60 mi/h).

None of the low-visibility events involved were due to patches of low visibility of 70 m (231 ft) in diameter. However, this ability is primarily associated with the sampling rate of the device in question. With a sampling period of 2 s, at least one sample would be measured for a patch of low visibility of 70 m (231 ft) in diameter at 80 km/h (48 mi/h).

CHAPTER 15. VIDEO IMAGE ANALYSIS TO DETECT LOW-VISIBILITY CONDITIONS

INTRODUCTION

During the analysis of technologies available for low-visibility detection, the project team noted that no use of video detection had been made in this field. Video-based sensors are increasingly being utilized in the transportation field for vehicle and incident detection. It may provide a cost-effective solution if the same hardware could also be used for low-visibility detection. Also, since video images were being collected as part of the manual verification of onsite low-visibility conditions, the project team proposed to investigate the use of video images in this application.

TEST METHODOLOGY

Using the Fotomagic software program, the video images were initially examined to determine those conditions, if any, which would greatly hinder or prevent analysis. It was found that owing to software limitations and the nonillumination of targets, night images would be impossible to examine. Also eliminated were those images where rain covered the camera lens, making accurate analysis extremely difficult. Based upon these restrictions, 48 images were identified for detailed analysis. The images were selected from the following days:

- May 30, 1994.
- June 5, 1994.
- June 6, 1994, with heavy fog conditions.
- June 24, 1994, with heavy fog conditions.
- June 27, 1994.

The targets #1 through #6 used for the real-world test formed the primary objects for analysis on the video image. Two additional areas of the video image were identified for analysis: a near portion of the edge of the freeway and a distant portion of the freeway. For the purpose of the video analysis, these video objects are termed targets #1 through #8. The resultant target designations are shown in figure 23.

To conduct the series of detailed analyses, two forms of data were required: visibility and target average intensity. For purposes of this investigation, the visibility observed by the HSS sensor was used. The HSS sensor was selected based upon results discussed previously which indicated that it was the most accurate of all the tested sensors.

Figure 23. Target scheme for video image analysis

The average target intensity was obtained by masking out all picture elements which do not belong to the target. A distribution of the pixel intensity values attributable to each of the eight targets was then obtained via a specific software package which performs a statistical image analysis. An example of this process is depicted in figure 24. The low values indicate the black portion of the target and the high values represent the white numerals. From these distributions, the average intensity value is calculated by summing the pixel intensity and dividing by the number of pixels.

To determine if there were any video image attributes which correspond to low-visibility conditions, the analysis process was separated into three elements. The initial investigation sought to summarize the average intensity data for each target across time to detect any possible trends. The intensity of each target was then analyzed against visibility conditions to determine if a relationship existed between target intensity and visibility. The third and last test sought to analyze a standardized subset of each target set, including both bright and dark pixel sets, against visibility conditions to determine a relationship of target contrast to visibility.

TEST ANALYSIS AND RESULTS

As stated previously, initial investigations were focused on the targets to examine if any trends or patterns were present. Results of this analysis are presented in figure 25 and appendix I. Examination of the results illustrates that the intensity of the target increases with distance under any conditions. For example, in figure 25 the intensity of target #2 is higher than that of target #1, target #3 is higher than target #2, and so on for all six targets. This effect was found to be uniform over time. It would appear that this phenomenon was caused by the fact that, as distance increased, contrast was reduced and the target in question began to appear uniformly gray.

Additional review of the analysis revealed that the average intensity of a target was greater during fog conditions than clear conditions. When fog was present, the average intensity of target #6 was in the range of 95 to160 m (313.5 to 528 ft). During clear conditions, the range of average intensities fell to 50 to 140 m (165 to 462 ft).

It could be anticipated that factors other than visibility could influence the intensity of the targets in the video image. Assuming that such effects are uniform over a limited area, it may be possible to normalize the intensity readings to remove such effects. This was tested by normalizing the intensity of the six targets. Targets #1, #2, and #3 were normalized by target #7, the intensity of the near portion of the roadway edge. Targets #4 - #6 were normalized by target #8, the distant roadway edge. The results of this analysis are shown in figure 26, plotted over time. Upon review, it was determined that this type of normalization indicated no environmental effects on target average intensity.

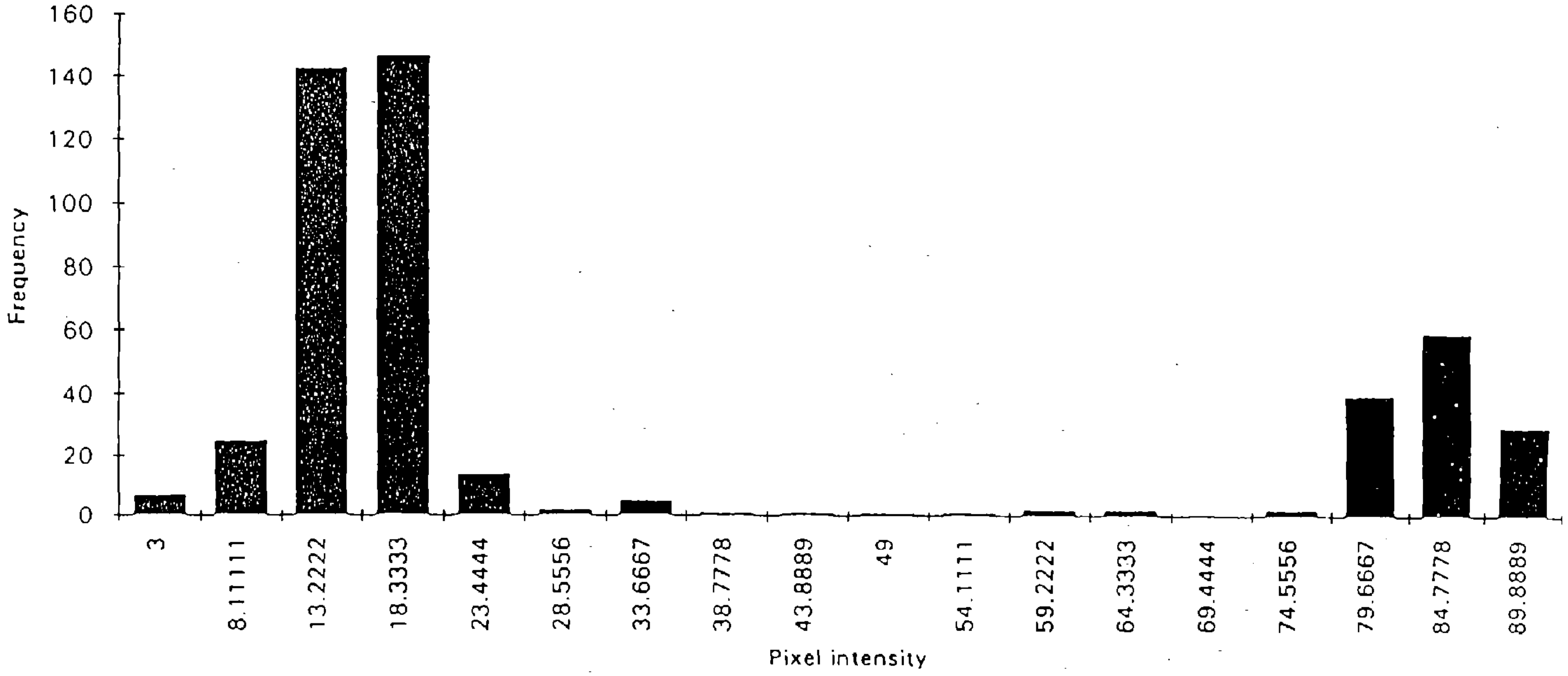


Figure 24. Distribution of the pixel intensity values for target #2 during a clear time constant

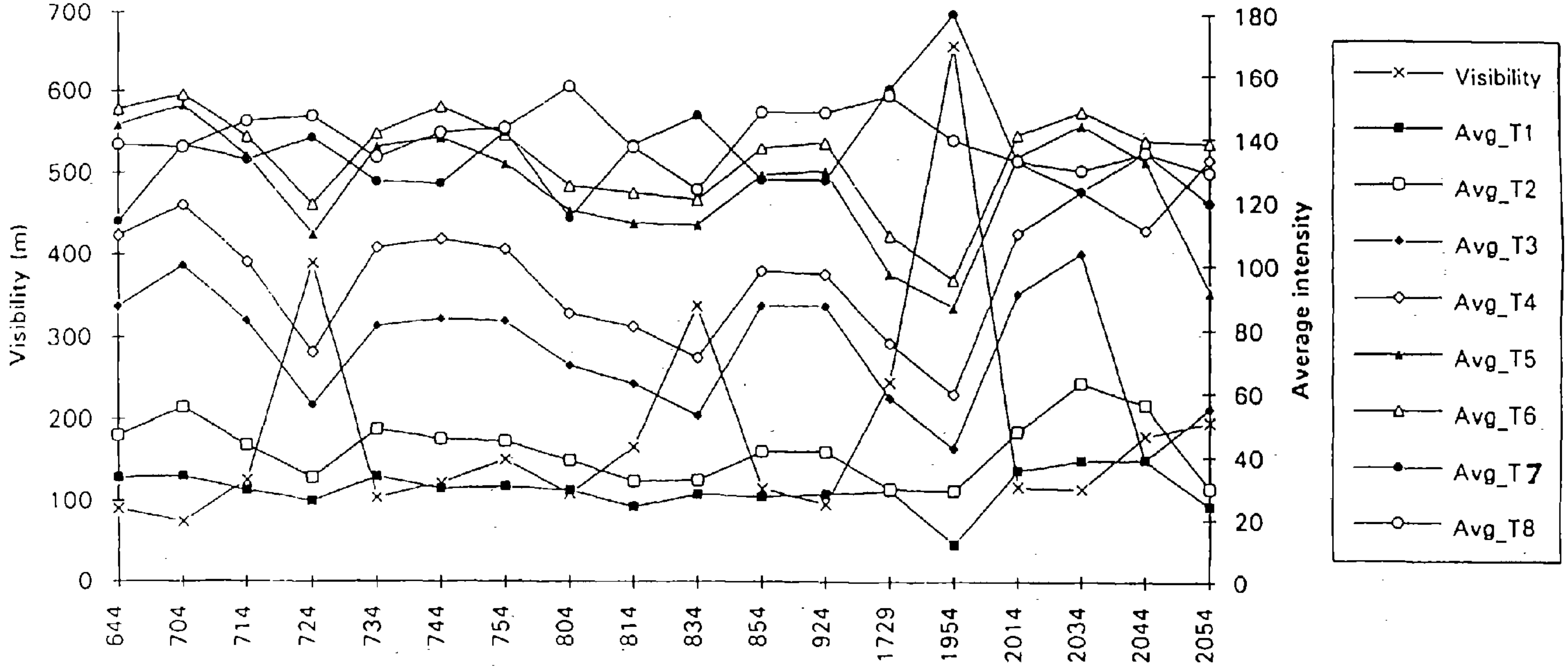


Figure 25. Average intensity and visibility vs. time - June 6, 1994

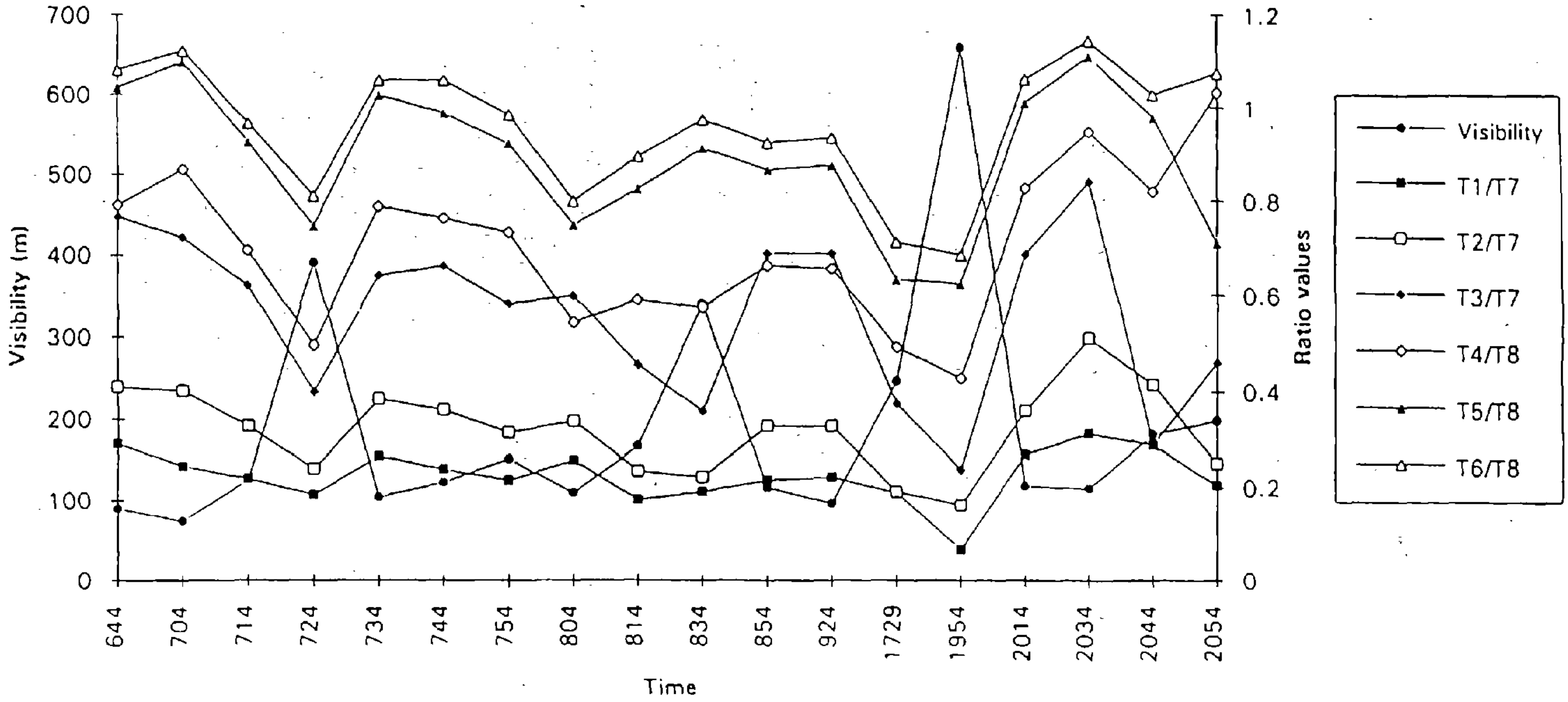


Figure 26. Normalized intensity and visibility vs. time - June 6, 1994

For the second phase of the analysis, an investigation of the average intensity as it relates to visibility was conducted to determine whether a functional relationship exists. When the two factors were plotted against each other in figure 27, it was found that, in fog, average target intensity decreases with increasing visibility. This would indicate that as fog increases and begins to cover the entire picture with a bright cloud, the intensity increases for all targets. This effect can only be observed at very low visibilities which would be expected given the proximity of the targets to the camera.

The effect appears to have the most influence upon those targets further away such as target #6. Very close targets have high contrast which remains relatively unchanged through changing visibilities in fog. Conversely, the contrast at the distant targets was much lower and therefore, easily affected.

Since the human eye is affected by reduction in contrast due to fog, the next phase of the analysis sought to examine contrast.

This analysis was performed by selecting a small number of pixels from those making up each target. The selections included pixels from both the white and dark regions of the target as would be seen on a clear day. A software tool was used to mask out picture information and retrieve only the subset of pixels, or "pixet," desired from each target.

The contrast of a pixet was then quantified by subtracting the average intensity of the dark area from that of the bright area. Three representative targets, #1, #3, and #5, were selected for this analysis process. For each day of available data, the contrasts of targets #5 and #3 were normalized with that of target #1 to eliminate environmental effects other than visibility changes. The contrast ratio of the roadway segments, targets #7 and #8, were included as a control for comparison purposes.

Figure 28 illustrates the results of this analysis. It can be seen that the 5:1 and 3:1 contrast ratios increase with visibility during fog conditions. The ratio begins at zero during extremely low visibility conditions, below 50 to 100 m (165 to 330 ft), and increases as visibility rises. This value approaches, but does not exceed one. In clear conditions, when visibility values exceed 700 m (2,310 ft), the ratio assumes a near-steady value around one, as illustrated in figure 29. Further graphs illustrating this relationship are included in appendix J.

These analyses identify the potential for this ratio to be utilized for developing thresholds for low-visibility detection. The data from this experiment indicate that for target #5, a normalized contrast 5:1 ratio below 0.2 could indicate that visibility is below 300 m (990 ft). With the addition of further data, a series of threshold values could be developed with appropriate warning messages to advise travelers of visibility conditions ahead.

This analysis has demonstrated that the ratio of contrasts between distant and close targets is related to visibility. The ratio increases with increasing visibility. For target #5 placed at 67 m (221 ft) from the camera, the ratio starts at zero for very low visibilities of 50 to 100 m (165 to 330 ft) and climbs to one for visibilities greater than 700 m (2,310 ft).

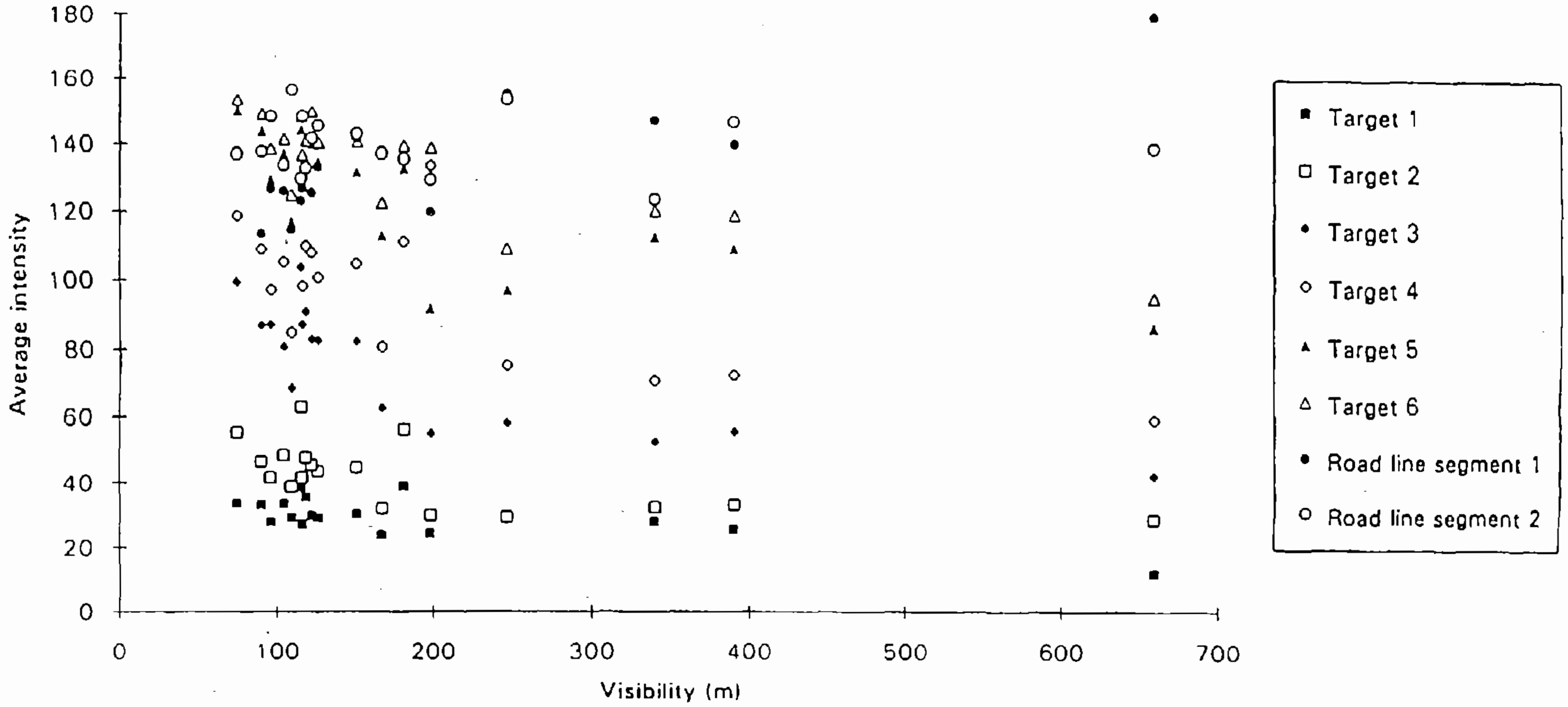


Figure 27. Average intensity vs. visibility - June 6, 1994

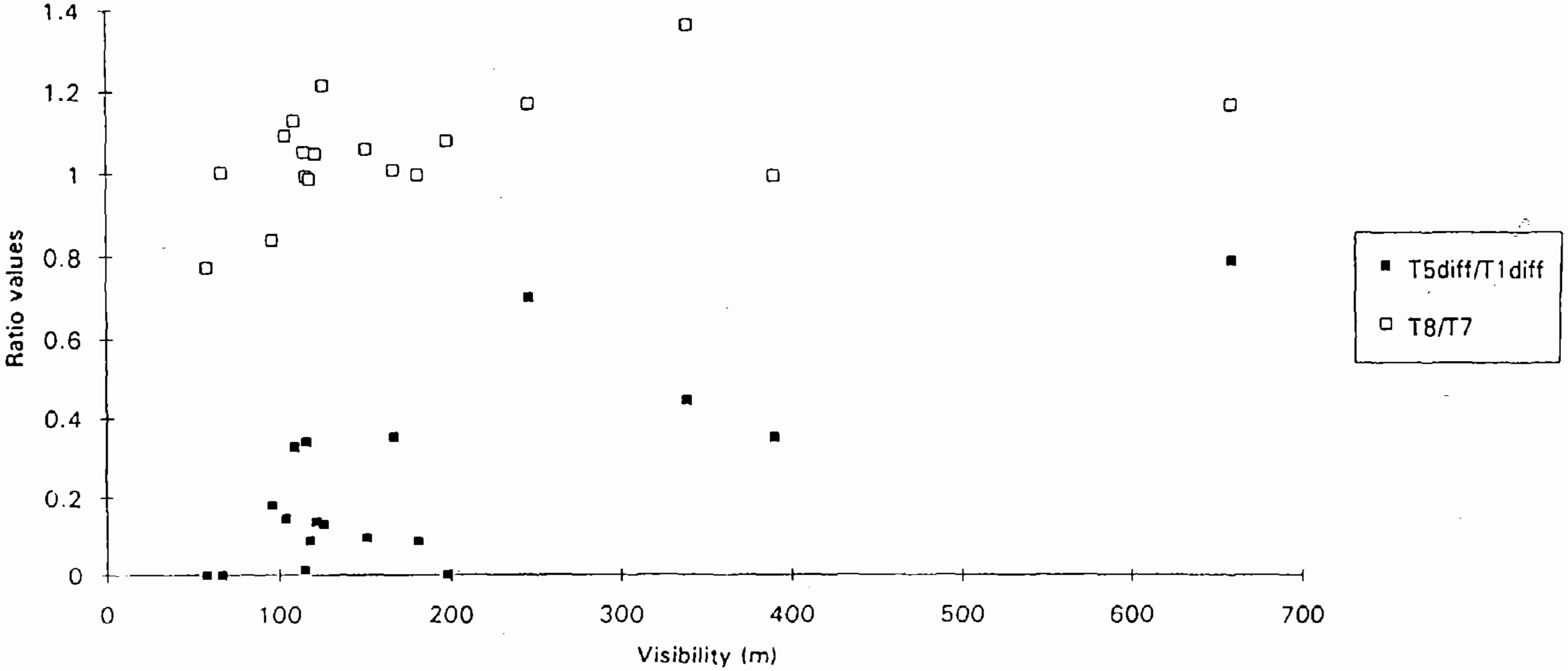


Figure 28. Normalized contrast for targets #5 and #1 vs. visibility

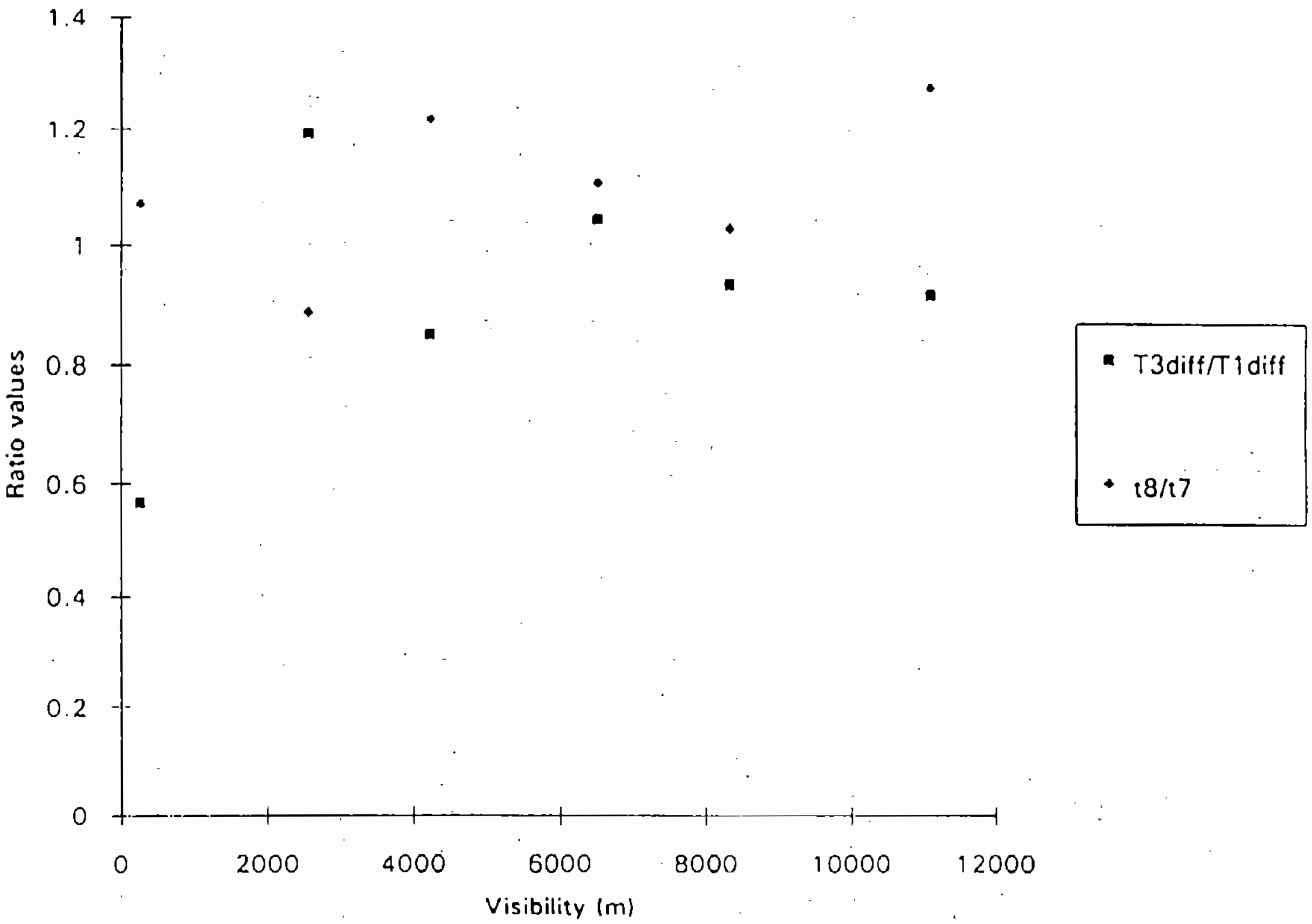


Figure 29. Normalized contrast for targets #3 and #1 vs. visibility

CHAPTER 16. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

States are increasingly using environmental sensor technology to assist with winter maintenance operations. The extent of sensor deployment, however, is patchy, with few States operating fully-integrated road-weather information systems. The main reasons for this situation are relatively high system costs, reliance on general meteorological forecasts rather than obtaining highway-specific information, the need to interpret environmental data, lack of meteorological skills among maintenance supervisors, incompatibility between manufacturers' systems, performance and coverage restrictions with current sensor technology, lack of coordination between State and municipal agencies and weather forecasting services, no desire to automate existing procedures, lack of knowledge of state-of-the-art systems, and a low occurrence of adverse weather conditions, particularly in the southern States.

In the field of IVHS, there are considerable technological developments which will directly impact environmental sensor systems. Significant benefits can be realized by integrating environmental sensor systems into IVHS system designs. Utilization of common communication systems and protocols will reduce costs and allow greater exchange of data. A key requirement is therefore to ensure compatibility not only between different manufacturers' systems, but with other traffic monitoring and control devices, such as loop detectors, weigh-in-motion systems, and variable message signs, and emerging IVHS technologies such as in-vehicle displays and automatic speed control devices.

During the evaluation process, each of the sensors demonstrated the ability to measure low visibility with an accuracy suitable for the highway environment. Over the length of the test some problems were encountered with each of the sensors, except that provided by HSS, which caused the sensors to stop reporting visibility data or to report inaccurate data.

A lightning strike on April 27, 1994 caused a failure in the power board of the Belfort sensor. However, the Belfort sensor had the highest mounting and longest serial connection at the test site. The sensor is therefore more likely to be affected by lightning strikes. The same strike also caused a failure of the data logging computer serial card and the modem.

On five occasions the Vaisala sensor optics were fouled by ice and/or snow. During these occurrences the sensor stopped reporting visibilities but did report a lens fouling alarm condition. This sensor was mounted closest to the ground of the sensors tested, which led to the sensor being the most sensitive to adverse winter weather.

The Sten Löfving sensor was clearly a prototype sensor. The housing was the least environmentally sound and no diagnostic capabilities were provided. No internal power conditioning was provided by this sensor. The failure periods during the test were primarily due to physical manufacturing problems. This sensor was the least expensive provided for the test. With the addition of power supply and diagnostic capabilities, the potential exists for this sensor to provide a suitable low-cost alternative.

The Sten Löfving sensor provided the worst accuracy rate over the test period. Adjustment of the linear calibration factor did not improve the accuracy. However, this sensor provided a good match with the manual observations without calibration. From analysis of the plotted visibilities it appears that the sensor had a greater dynamic range. This may indicate that a nonlinear calibration factor is most applicable.

For visibility reduction due to fog the Belfort, HSS, and Vaisala sensors provided overall accuracy rates which were within the 20-percent accuracy detailed in the functional requirements. During blowing snow the sensors indicated reduced visibility but did not match the very low visibilities being experienced by the manual observers. This may have been due to surface effects causing a greater reduction in visibility near the surface of laying snow. However, the Belfort sensor, which was the highest-mounted sensor, provided readings that were closest to those manually observed.

The HSS and Belfort sensors were marginally more accurate than the Vaisala sensor and were not subject to lens fouling during the test period.

None of the sensors provided for test were specifically designed to measure visibilities in the ranges that are of interest to highway safety. However, the sensors did demonstrate adequate performance in these ranges. Some manufacturers have indicated that new designs are being made available specifically for the highway market.

It must also be noted that the sensors, as presently tested, have a limited visibility range. This would necessitate the use of numerous visibility devices along the roadway to provide continuous coverage. However, due to the relatively high costs of the sensors, coverage would have to be initially restricted to well-known areas of low visibility and high-volume roads.

Siting of the sensors is critical since information from the sensors provides a guide to conditions over the highway network. If they are incorrectly sited, inappropriate maintenance actions may result.

The HSS AMV III mobile visibility sensor demonstrated the ability to be used either in conjunction with, or in place of the stationary sensors. It was found to be a low-maintenance device, requiring only regular cleaning of the lenses to remove dirt accumulation caused by regular driving during winter conditions. The sensor did not react to vehicular vibrations caused by normal driving operations. Opposing headlights and taillights also did not cause any unusual sensor reaction or malfunction. However, the sensor was restricted as to where it could be mounted due to the need for "clean" air flow over the device.

The mobile sensor is still in the prototype phase, and thus costly, but discussions with the vendor note that no element of the device would prevent low-cost mass production from occurring.

The analysis of video images identified that the ratio of contrast between distant and close objects is related to visibility. There is potential for video images to be used to trigger low-visibility warning devices. However, a significant amount of work with large data sets would be needed to identify the accuracy of such a sensor. The analysis identified that uniform targets with a good mix of dark and light areas may provide more accurate data for a video-based algorithm. A checkerboard pattern may provide a suitable image. Further work is also needed to investigate the potential for nighttime video-based visibility measurements using lighted targets.

The data collection process illustrated that the manual estimation of visibilities is prone to significant error. Thus, even where a driver is adjusting speed to match what they believe is their sight distance, significant inaccuracies are present.

The analysis of vehicle speeds at the test site indicated that drivers do slow down when visibilities drop below 200 m (660 ft). However, the effect is not as significant as has been reported in other studies for this nature.

RECOMMENDATIONS

1. Environmental sensors should be designed to readily communicate with other traffic control and monitoring devices. This requires the adoption of open interfaces and use of standard communication protocols. Compatibility between manufacturers' systems would greatly benefit users.

2. Systems integration is recommended if the full benefits of environmental sensors are to be achieved. Data from the sensors on pavement conditions and visibility need to be combined with general meteorological information to allow short-term forecasts to be made.

3. Lower-cost sensors should be developed. This would enable greater coverage of the road network and the opportunity to include lower-volume roads in remote locations.

4. Research into mobile sensors should be continued. Potential opportunities exist for increasing network coverage by installing sensors on either selected vehicles, such as maintenance vehicles, or ultimately on every vehicle under various IVHS scenarios. The most promising areas relate to visibility, pavement condition, pavement temperature, and road friction.

5. Additional research into the use of video imaging should be conducted. Although limited work was conducted in this area as part of this study, this technology has the potential to provide a low-cost alternative to existing visibility detectors. This system would also be easily adaptable to IVHS products.

6. Better use needs to be made of the information available from the environmental sensor systems and meteorological forecasts. Training of system users is therefore a key requirement. Although beyond the scope of this study, it is recommended that a comprehensive training program be developed.

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