As a base for comparative purposes, with clear conditions, it was found that the average 85% speeds varied from approximately 54 MPH to 49 MPH in the fog zone. These speeds are 5 to 13 MPH lower than prevailing speeds on rural State Highways in Oregon. Part of the difference may be due to the off road test track.

The average mean speed for State Highways based on all stations utilized in monitoring the 55 MPH speed in 1976 was 55.9 MPH. The average minimum mean speed in the fog section with clear conditions was approximately 43 MPH. With no special signing the average minimum mean speeds for vehicles in the fog zone were approximately 19 MPH for 400 foot visibility, 16 MPH for 300 foot visibility, 13 MPH for 200 foot visibility and 9 MPH for 100 foot visibility. Posting the 15%, 50% and 85% speeds at different levels of visibility did not provide conclusive evidence of speed signing alone having significance in improving traffic flow with respect to speed measurements on the test track.

It is anticipated that the final report for this project will be completed early next year and the findings will be discussed in more detail in the report.

VISIBILITY IN BLOWING SNOW AND APPLICATIONS IN TRAFFIC OPERATIONS

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INTRODUCTION

In cooperation with the Wyoming Highway Department, Dr. R. A. Schmidt of the Rocky Mountain Forest and Range Experiment Station developed a visual range monitor as described in a separate paper at this symposium (6). Operational application of this device on Interstate Highway 80 (I-80) since January 1974, has demonstrated the accuracy and reliability of the data; but it has also raised the question of how visibility information should be interpreted and used. This paper presents results of experiments exploring the relationship between wind and visibility, with emphasis on changes accompanying snow cover depletion, and shows how this information is used for traffic operations.

The Visual Range Monitor

As described by Schmidt (6), the visual range monitor (VRM) uses a photoelectric particle counter to measure size and frequency of blowing snow particles. Given certain assumptions, visual range (V) can be calculated from these data using the equation

$$V = \frac{KU}{FX^2} \qquad \text{Eq. [1]}$$

where U is windspeed, F is particle frequency, X is particle diameter and K is a constant. A generating anemometer is used to measure wind speed. Although the particle counter measures a light path only 25 mm long, averages from even a period of minutes appear representative of conditions over the longer but varying sight distance of a motorist.

The Wyoming Highway Department has installed VRM units at two locations (Arlington and Elk Mountain) on I-80 between Laramie and Walcott Junction. Data are telemetered via a combination of radio, microwave, and landline to highway department offices in Laramie, where wind and visibility are continuously recorded on strip charts.

After the first year of operational testing, the need for visibility standards in highway operations became apparent. A corollary observation was that relatively subtle changes in the wind/visibility relationship that existed over the course of a drifting event would have to be taken into account in the development and application of a standardized decision criteria.

For a given windspeed, visibility was poorer when there was ample fresh snow on the ground, but improved near the end of an event when the ground had "bared up" Evident in retrospect, this relationship between visibility and snow availability is difficult to recognize on the charts during an event, and impossible to quantify because wind is seldom steady long enough to allow conclusive comparisons. The relationship between wind and visibility can change rapidly, as during a period of snowfall, but more subtle gradual changes equally relevant to highway safety can extend over many hours or even days.

For these reasons, a computer was utilized to analyze the data real-time and provide the complex interpretations that boggled the mind of radio operator, scientists and engineer alike.

RELATIONSHIP BETWEEN WIND AND VISIBILITY

Snowfall with Light Winds

The relationship between wind and visibility during snowfall with light (< 7 m/s) winds is relatively easy to deduce from Eq. [1]. If size of snow particles remains constant, visibility will vary inversely with precipitation intensity. If particle frequency also was independent of wind, then visibility would improve in direct proportion to wind.

Because visibility attenuation is usually not severe for light winds, the remainder of this paper is directed to the more critical case where snow previously deposited on the ground is relocated by winds > 7 m/s (as measured at 10-m height), with or without concurrent precipitation.

Antarctic Studies

It is not as clear how visibility might vary with wind for the case of relocated snow, because both frequency and mean diameter of particles increase with windspeed.

Data presented by Budd (2) suggest particle diameter increases (approximately) as the square root of windspeed (U). Mellor (5) has shown from other Antarctic data that the mass flux of snow particles tends to increase according to U^7 at heights above 0.5 m, and $U^{5.4}$ at lower levels. Equation [1] suggests that visual range should vary as a negative power of windspeed, so that

$$V = AU^{-B} \qquad \text{Eq. [2]}$$

where V is visibility at observer height, U is windspeed at 10-m height, and A and B are constants for a given snow condition. Moreover, the above relationships indicate an expected value for B of about 5 at 0.5m height. This deduction is substantiated by the visual measurements of target extinction in the Antarctic reported by Liljequist (4) and Budd et al. (3). Liljequist specifically concluded that visibility at observer height (2 m) was related to the -5th power of windspeed over his range of data.

Since both of these experiments were conducted where snow supply on the ground was essentially unlimited, we are left with the problem of how A and B might change as snow cover is depleted. This important question led to the following experiments using the visual range monitor.

Experimental Procedure

Our studies were conducted at two separate locations. The Cooper Cove site (elevation 2,360 m) is a nearly level area covered by short grass vegetation. The Elk Mountain monitor station (elevation 2,220 m), with low-growing brush vegetation averaging about 20 cm in height, served as a second study site.

The electronic data acquisition system used electronic peak detectors to sample the maximum values of wind and visual range signals output from a VRM over a 5-second (s) interval. This method of sampling helped assure matching of visibility and wind values, since the anemometer was installed 10 m above the ground, while the particle counter was at a a height of 0.5 m and located about 15 m upwind from the anemometer. An electronic calculator served as system controller for selecting channels, controlling peak detectors and digital voltmeter, and storing data on magnetic tape. The least-squares value for A and B in Eq. [2] were calculated at 10-min. intervals and output on a printer and X-Y plotter. Visibility and wind were continuously recorded throughout six separate drifting events totalling 234 hours, over a wide range of weather conditions.

Air temperature and humidity at 2-m height were recorded with a hygrothermograph; precipitation was measured with recording gages located in tree-sheltered spots near the study sites. Characteristics of the snow cover were observed and photographed throughout each run.

Results from Wyoming Studies

The power function (Eq. [2]) is an empirical approximation for the complex relationship between wind and visibility. Over the narrow range of windspeeds encountered in a 10-min sampling period, the power B was quite variable and ranged from 2 to 8, with the lower values generally associated with lower visibilities. To provide the widest possible range in the variables, data were grouped into periods having essentially uniform snow conditions and up to several hours in length. Results of this analysis over all snow conditions gave an estimate for B of 4.90 ± 0.20 (.95 confidence interval), determining an integer value of 5 for the mean.

Statistical analysis of individual storms by hourly intervals showed B to remain essentially constant as snow conditions changed.

Conclusions can be summarized as follows:

1. For practical purposes, it can be assumed that the function

$$V = AU^{-5}$$

applies to all winds strong enough to relocate snow, over the entire range of snow conditions, and with or without concurrent precipitation.

2. The A coefficient ranges from 10^8 for conditions of maximum snow availability, to $>10^{10} m^6/s^5$ in the final stages of a drifting event. A therefore provides a responsive index of snow availability.

3. Variance increases as snow supply diminishes, affecting reliability of the estimates for the A coefficient.

4. Visibility values obtained with the VRM are in reasonable agreement with published target observation data.

OPERATIONAL USE OF WIND AND VISIBILITY DATA

Interpretation of the A Coefficient

The preceeding evidence leads to the practical generalization that the power in the visual range Eq. [2] is constant and approximately equal to 5.0, while the A coefficient changes in response to snow availability. Even subtle variations in the character of the snow surface can bring about significant and identifiable changes in A. A striking example is the abrupt decrease in the A value with the onset of snowfall. Precipitation intensities as light as 0.1 mm of water-equivalent per hour have been observed to lower A from 10^9 to $2 \cdot 10^8$ m^6/s^5 over a period of 30 minutes. The reason snowfall is detectable from an analysis of the wind/visibility data output from the VRM is because older snow consists of subangular grains sintered to form a surface relatively resistant to particle dislodgement. Fresh snow, however, is quickly fragmented and easily transported, so particle frequency rapidly increases whenever new precipitation is received, even though the older snow may lie meters deep on the ground. Therefore, the A coefficient will continue to decrease as precipitation continues until, to use Liljequist's description, the air becomes "saturated" in relation to its snow transport capability. Once the input of fresh snowfall ceases, however, the metamorphosis of particles into "older" snow is rapid.

In general, an A value $\lesssim 1.2 \cdot 10^8$ m^6/s^5, or an abrupt decrease in this parameter, appear to be reliable indicators of precipitation. On occasion we have also observed smaller decreases in A without precipitation, presumably associated with the disruption of surface crusts at the onset of strong winds. Other changes occur with the arrival of snow from discrete contributing areas upwind, and each location has its unique characteristics that might provide useful information about the progress of a storm.

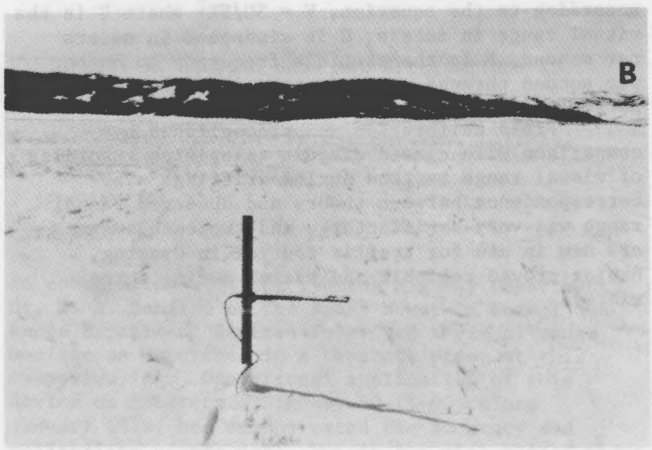
As demonstrated by Figure 1, the A value can be interpreted in terms of snow conditions and potential visibility attenuation. But the change in this parameter over time can provide additional information about trends in snow availability relevant to traffic operations decisions.

Sampling Visibility and Wind Data

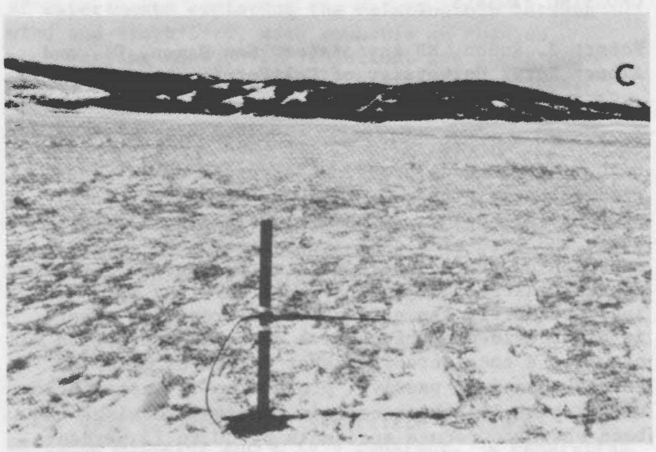
Analog signals of wind and visibility are telemetered from the field monitoring stations at Arlington and Elk Mountain on I-80. Data processing, analysis, and peripheral hardware control are performed by a Hewlett-Packard 9825 calculator with 23k byte memory. The calculator controls the clock, scanner relay, and digital voltmeter used to measure instantaneous values of wind and visibility at the rate of one sample pair from both stations each second. This sampling frequency is sufficient to insure that extremes will be sampled within 5% of their maximum or minimum values.

Figure 1. Snow conditions at Cooper Cove. [Snow particle counter extends horizontally from pipe in foreground. A values (in $m^6 s^5$) refer to the coefficient of Equation 2 assuming B = 5].

15:50 February 21, 1976: A ≐ $7 \cdot 10^8$



13:52 February 22, 1976: A ≐ $1.2 \cdot 10^9$



11:50 February 27, 1976: A ≐ $1.5 \cdot 10^{10}$

Every 8 s, the largest and smallest values of each variable are determined, and only these are retained for analysis. This allows wind values to be matched with their corresponding visibilities--a procedure made necessary by the fact that the anemometer is located about 10 m above the ground, while the snow particle counter (SPC) is typically installed at 0.5 m height. Both maximum and minimum values are used to provide the widest possible range of data for statistical estimation of the A coefficient in Eq. [2].

These paired visibility and wind values are accumulated over approximately 10minutes to provide an adequate sample number for estimating A by least-squares regression analysis, assuming B=5.

The Critical Visibility Statistic

In using visibility data for traffic operations decisions, one is faced with selecting the critical statistic. Should traffic operations be based on an average visibility? And if so, over what period of time? If minimum visibility is considered the limiting factor, over what time period? To the author's knowledge, this problem has not been resolved for the case of blowing snow where visibilities exhibit such a complexity of frequencies and amplitudes.

It can be shown that "stopping sight distance" (SSD) cannot exceed the minimum visibility if a safe vehicle speed is to be maintained. Since amplitude varies with time, a logical course is to base traffic operations on an average of several minimum visibility values measured over a specified time period. To reduce the weight given to anomalous or extreme gusts while providing a statistic representative of minimum visibilities, we have defined the hourly minimum visibility as the geometric mean (i.e., calculated from the logarithms) of the six 10-minute minimum values. This procedure simplifies programming for hourly reports and recommendations, and has given reasonable results in preliminary tests and operational trials.

In summary, although the statistical analysis to determine the A coefficient uses all the wind and visibility data (150 paired values) over each 10-minute period, only the lowest visibility value (and the strongest wind gust) are retained for traffic operations decisions. Although these 10-minute extremes are used to warn the computer operator of dangerous conditions, traffic operations are based on the hourly minimum visibility as defined above.

Use of Visibility Data for Traffic Operations

Traffic operations routines are included in the same program used for measurement and analysis of the wind and visibility data telemetered from the two field monitor stations on I-80. Warnings and notices are printed after each 10-minute sampling period as required. Summaries of visibility and wind conditions are output hourly, along with recommended regulations and warnings when minimum standards are exceeded.

Recommended speed limits are determined by equating SSD to the hourly minimum visibility, and solving for vehicle speed. The effect of grade can be ignored in view of the arbitrary definition of $\overline{V}_{min}$. Taking 2.5 s as the usual approximation for T, then

$$U_V = -88.35 f + 127.12 [0.48 f^2 + 0.016 f \overline{V}_{min}]^{0.5} \quad \text{Eq. [3]}$$

Application of Eq. [3] requires that information on road surface conditions be kept current in the calculator's information file, and that appropriate friction factors are known for various road conditions.

Visibility information is used for road closure or opening decisions and consideration is given to snow availability as indexed by the A coefficient.

Forecast visibilities are calculated from the current A value and the latest wind forecast issued by the National Weather Service. This is a most important application of the wind-visibility relationship because it allows potential visibility hazard to be expressed in meaningful quantitative terms. As a hypothetical example, current winds speeds gusting to only 13 m/s with an A value of $3 \cdot 10^8 m^6/s^5$, would imply present visibilities to be more than 800 m. But a wind forecast for gusts reaching 25 m/s would mean visibilities as low as 30 m.

As described previously, visibility data are used to detect snowfall, and this information is also used in the decision logic. This feature is important when reports are not available from the field; in addition, it is often difficult for an observer to tell whether or not it is snowing during a heavy drifting event.

A final application of the wind/visibility analysis is for estimating the time required for visibilities to reach the prescribed standard for opening a road previously closed due to poor visibility. This is accomplished by extrapolating the current rate of change in the A value to determine the time required for the standard to be attained.

These examples show how on-line computer analysis of wind and visibility data can provide the engineer or foreman with essential information not otherwise available to him for making timely and sound decisions. Analysis of the relationship between these variables can provide the basis for objective traffic operations standards that are technically sound, unambiguous, and legally tenable.

ACKNOWLEDGMENT

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Abstract
MEASURING VISIBILITY IN BLOWING SNOW

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An electronic system that monitors visibility in blowing snow has been developed by the USDA Forest Service in cooperation with the Wyoming Highway Department. The sensor for blowing snow is a photoelectric particle counter that produces a voltage pulse for each snow particle which passes through a 3 by 25 mm area normal to the wind. The sensor's pulse train is electronically processed to give voltages proportional to five-second averages of particle frequency and diameter. These voltages are combined with the signal from an anemometer in an analog computer which simulates visual range according to the equation, $V = 5U/FX^2$ where V is the visual range in meters, U is windspeed in meters per second, F is the particle frequency in number per second through a 1 cm^2 area, and X is the particle diameter in centimeters.

Field calibration was accomplished by comparison with closed circuit television recording of visual range targets during drifting. The correspondence between theory and observed visual range was very satisfactory, and two such systems are now in use for traffic control in Wyoming, having proved reliable and useful during three winters.

IMPROVING THE CONSPICUITY OF HIGHWAY-RAIL GRADE CROSSING SIGNALS

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Highway-rail grade crossing "protection" is classified as being either "active" or "passive". Active protection includes swinging or flashing lights, bells and gate arms that are activated by an approaching train, while passive protection refers to stationary signs and pavement markings that indicate merely the presence of a crossing. There is clear evidence that active crossing protection provides a considerably higher degree of motorist safety than does passive "protection". Installation of flashing lights at certain passive crossings has been shown to reduce accidents by 60 to 70 percent, and flashing lights plus automatic gates have reduced accidents by as much as 95 percent.

Despite their obvious safety advantage, active crossings, which constitute approximately 20-25 percent of the nation's public crossings, are

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DRIVER VISIBILITY UNDER VARYING ADVERSE WEATHER CONDITIONS

subject areas
51 highway safety
52 road user characteristics
53 traffic control and operations

FOREWORD

Continuing its long standing interest in the ability of drivers to see, the Committee on Visibility decided in early 1977 that the subject of driving under adverse visibility conditions deserved attention. The committee planned and held a symposium August 16-18, 1977 and this circular contains abridged versions of several of the presentations. Portland, Oregon was chosen as the site in order to afford attendees the opportunity to see the nearby Oregon DOT Fog Research Facility, and the contributions by Oregon and its employees is gratefully acknowledged.

SAFE DRIVING IN FOG

Nathaniel H. Pulling, Liberty Mutual Insurance Company, Hopkinton, Massachusetts

Although highway engineers probably think of the word fog with reference mostly to a ground-level suspension of fine water particles (1) in more general usage the word refers to any thick or murky condition of the atmosphere wherein there is reduced visibility due to a variety of particulates (2). These include not only condensed water vapor, but also rain, snow, dust and smoke. The word fog is believed to have its origins in related Scandanavian words descriptive of all these physical causes of diminished visibility.

Fog of various kinds has often made traveling hazardous for many centuries. Nomads went astray in the dust storms on steppes and deserts (3), and in northern latitudes fog has terrified mariners until very recently. Even with radar, ship handling in close quarters can be dangerous when fog is thick. During the past several decades fog has become much less treacherous for many travelers because our railroads are protected by improved automatic control systems, the larger airports have electronic landing systems, and at sea, Loran and radar are safeguarding ships when visibility is restricted.

But it is another matter with the menace of fog on the highway. Limited-access roads have brought about faster speeds by more and more vehicles, and fog-prone areas are only rarely serviced by automatic signing, vehicle guidance systems, or convoying operations (4, 5, 6). As a consequence, it is likely that a greater number of people experience the terrors of fog today than ever before, and possibly with more injuries and deaths than in years gone by. We don't know for sure, because recent and reliable data on the overall frequency of fog accidents in the United States are unavailable (5, 6, 7, 8).

In the absence of countermeasures for reduced visibility on the highway, how should you or I drive in fog so as to best protect our own lives and those around us? Unfortunately, I have discovered no unequivocal answers. Most of my driving years have been spent along the foggy New England coast line, and today my home is close to the Atlantic Ocean. With this background, I am of the opinion that safe driving in fog seems to be a matter of common sense, alertness and good guesswork. The guesswork is necessary because driver behavior in highway fog is largely unpredictable (8, 9, 10). Unless fog is very dense, drivers slow down very little on the open highway (7, 11), and even under the worst conditions only to about 60 km/h (37 mph). Studies have shown that most drivers overrun their sight distance in fog, and thus become unable to stop their vehicles within the distance on the highway ahead wherein stationary hazards can be identified (5, 12). Because of personality differences and diversity in locale, highway configuration and fog severity, the speeds which drivers choose in fog are substantially different (7). In my own experience, one cannot afford to assume that other operators will drive in fog at predictable speeds. In the absence of guiding data and protocol, therefore, it is my own technique in fog driving to rely on hunches based on long experience as to what other drivers may be doing, on the practices which I am now about to describe, and upon what might be termed, "a little bit of luck".