NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **171**

HIGHWAY FOG
VISIBILITY MEASURES AND GUIDANCE SYSTEMS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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GREAT NECK, NEW YORK

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AREAS OF INTEREST:

- MAINTENANCE, GENERAL
- HIGHWAY SAFETY
- ROAD USER CHARACTERISTICS
- TRAFFIC CONTROL AND OPERATIONS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1976

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff

Transportation Research Board

This report will be of interest to highway administrators, traffic engineers, maintenance personnel, and safety specialists concerned with alleviating the highway hazards caused in many locations by fog. The report presents a measurable fog visibility index developed through the project research and explores the feasibility of several warning and guidance systems. The index may be employed as a criterion for selecting fog countermeasure actions. Other findings of the study should aid in providing greater understanding about appropriate measures of combatting highway fog problems.

Although the hazards of highway fog have been recognized by highway officials for many years, development of fog abatement techniques and other countermeasures to facilitate safe driving in fog has generally proved a difficult task.

Research in this area was initiated in 1967 by the National Cooperative Highway Research Program. The first project, directed particularly toward fog abatement procedures, resulted in publication of *NCHRP Report 95,* "Highway Fog." Although the project was reasonably successful in meeting its objectives, it was clear that further research would be valuable. Consequently, funds were allocated for studies to determine needed standards of visibility in both day and nighttime fogs and to evaluate the feasibility of fog warning and guidance systems.

The approach taken by the Sperry Systems Management Division of Sperry Rand Corporation in conducting this second project was (a) to consider the factors affecting visibility under fog conditions, then (b) to construct analytic models of visibility and formulate a fog visibility index, and (c) to validate the index by both computer simulations and field testing. In connection with the second part of the project objective, a number of warning and guidance techniques were reviewed, ranging from presently available variable-message signs to the longer-range possibilities offered by automatic highway guidance systems.

Three areas for additional study are identified here by the research agency. These concern driver behavior in fog as revealed by speed and headway distributions, techniques for providing traffic and visibility data inputs to system control algorithms, and the factors affecting driver receptiveness to warning messages and the credibility of warning systems.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was conducted by the Traffic and Transportation Systems Group of the Sperry Systems Management Division, Sperry Rand Corporation, with William H. Heiss serving as principal investigator. James O. Dyal was the principal investigator during the initiation of the program. Dr. Wayne Mount and Richard Brown of the Sperry Rand Research Center made important contributions, particularly in the development of the analytic models and the survey of fog instrumentation.

Appreciation is extended to members of the Traffic Systems staff who served as test personnel at never convenient hours during the on-road fog tests, and to the Federal Aeronautics Administration Maintenance Section at MacArthur Airport and the New York Flight Service Station for their cooperation, particularly during the Videograph calibration tests. Thanks also are due to the Long Island State Park Commission and the New Jersey Turnpike Authority for permission to use their facilities for on-road fog tests.

HIGHWAY FOG

VISIBILITY MEASURES AND GUIDANCE SYSTEMS

SUMMARY

An analytic study of highway fog was undertaken to determine the fog densities that produce significant detrimental effects on highway safety and traffic operations. The study also evaluated the feasibility of a number of active and passive warning and guidance systems to improve safety and efficiency of traffic flow through the area.

A fog visibility index was developed as a means of quantifying fog levels. Three analytic models of visibility through fog, which were based on the detection of a stopped vehicle in a through lane of a freeway under different lighting conditions, were the basis for the development of the index. The fog visibility index, for which "instrument" visibility (or extinction coefficient) and ambient light level were inputs, was calibrated and validated by computer simulation studies and a series of on-road tests in fog.

The analysis, as corroborated by the on-road tests in fog, showed that, although the driver is deprived of some useful visual information at less dense fog levels, driver performance is not seriously degraded until the visibility drops below approximately 600 ft in daylight.

Limited tests on the UCLA closed-circuit television driving simulator demonstrated successful simulation of fog. Based on limited data, the driving simulator tests indicate that the reaction and perception time of a reasonably alert driver in fog is about 1.4 sec, which is less than the time normally used in stopping distance calculations.

A survey was made of available fog-measuring instrumentation. The scatter types of instrument appear to be the most suitable for general highway fog use, although they are not as accurate as transmissometers. All of the instruments currently available measure a more or less limited sample of fog, and therefore single-device installations are subject to gross errors in patchy fog and bank fog.

Tests under realistic highway conditions in the presence of dense fog constituted perhaps the most difficult task of this project. A significant number of runs was made possible through the use of weather prediction advisors, the availability of an instrumented test vehicle, and the cooperation of willing test subjects.

Some potentially useful fog countermeasure techniques are available to the highway designer and traffic engineer. In the near term, variable-message signs can be effective when properly used. Lane-marking "pancake" lights have potential as guidance aids to help keep drivers from becoming disoriented, particularly when unexpectedly entering a dense fog area. However, in order to provide an indication of lane blockage, which is the more serious hazard, lights along the center of the lane are probably also necessary for the detection of the stopped vehicle.

Some of the more advanced active guidance systems appear to be technically feasible, and the simpler block guidance systems are technically feasible at the present time. Such systems may be economically feasible in conjunction with

freeway surveillance and control system installation. In the longer term, passing aids and automatic guidance systems currently being studied may prove to be readily adaptable to guidance systems for highway fog.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

Dense fog is a threat to the safe and efficient operation of motor vehicles. The hazards of dense fog have intensified with the proliferation of freeways, expressways, and other highly improved roadway systems. Attempts have been made to prevent, abate, and disperse fog as well as to improve visibility within and guidance through fog. Completely satisfactory solutions to the problems produced by dense highway fog have not been found.

This is the second highway fog research project sponsored by the National Cooperative Highway Research Program (NCHRP). The first project included the preparation of a state-of-the-art summary of fog abatement procedures; guidance systems; measures of visibility and the effects of fog on traffic operations; exploration of fog abatement and vehicle guidance systems under highway conditions; and the test of selected fog abatement techniques. The results of the first study were published in *NCHRP Report 95* (*1*).

The specific objectives of this second NCHRP highway fog project, as included in the statement of the research problem, have been to:

1. Analyze the highway fog problem and determine the day and night fog levels (standards of visibility) that produce significant detrimental effects on driver performance and traffic operations.
2. Explore the feasibility of active and passive guidance systems (for freeways and expressways) that will inform and warn the motorist of prevailing roadway fog and traffic conditions ahead and that will guide and control traffic more safely and conveniently through the fog area.

RESEARCH APPROACH

In pursuit of the two specific research objectives, the project was divided into four areas:

1. Fog detection and measurement.
2. Driver performance and traffic operation related to visual range.
3. Fog measurement related to highway action.
4. Warning and guidance system feasibility study.

The first three areas were aimed in part at the determination of suitable standards of visibility under day and night conditions. The approach taken was to establish a measurable fog visibility index valid under various illumination levels and to relate this index to the corresponding degradation in driver performance and the various courses of action that can be taken. The fourth study area was related to the feasibility, the second research objective, and it included the study of a limited number of warning and guidance systems.

Drivers are impaired by highway fog in the performance of three groups of tasks. The first is immediate vehicle guidance and control—keeping the vehicle in lane and at the desired speed. The second group can be described as situational—tasks associated with control changes that may be required because of operational conditions such as changing lanes or stopping to avoid other vehicles or obstructions. The third group is "navigation"—choosing the proper road at branch points, leaving at the desired exit, and the like.

In terms of highway safety and in the context of this study, the second group of tasks is considered the most important. On freeways and expressways in particular, fog affects much less a driver's ability to maintain position on the road (because the vehicle guidance function can be accomplished using close-in vision) than it does one's ability to detect a vehicle in the lane ahead. The general tendency, therefore, is for most drivers to overdrive their vision with potentially disastrous consequences. The impairment of a driver's navigational ability through masking of landmarks and impairment in reading signs is more an inconvenience than an immediate direct hazard although it can lead to erratic driver behavior. Attention was therefore directed to the specific situation of a stopped vehicle (or an obstruction) on a through freeway or expressway lane as a focus for project planning and to aid in the execution of the study.

An important consideration is that approximately half of the fog-related accidents occur during daylight in spite of the fact that fog is more likely to occur at night. It has also been noted that large, multivehicle fog-related accidents are most likely to occur during the early morning rush hour, although not necessarily in the direction of maximum volume.

In the investigation of the various fog countermeasures and warning and guidance systems, performance in daylight fog was therefore considered more significant even though the relative frequency of fog occurrences is lower.

CHAPTER TWO

FINDINGS

HIGHWAY FOG ANALYSIS

The purpose of conducting the highway fog analysis was to develop a fog visibility index to relate visibility on the highway to various fog conditions. Development of the fog index was achieved in three steps: (a) consideration of the various factors and parameters that affect visibility under fog conditions, (b) construction of analytic models of visibility in fog for different light conditions, and (c) formulation of the fog visibility index from the analytic models and the associated computer simulations. The index was subsequently calibrated and validated with results of the computer simulations and the on-road tests.

For the fog visibility index to be of practical utility, it was necessary to:

1. Have as inputs only those variables that are easily and reliably measured in the field.
2. Ensure that the input variables apply to all conditions.
3. Use the least possible number of variables.
4. Ensure that the fog visibility index be generally applicable to all highway fog situations.

Visibility Factors and Parameters

The most hazardous driving situations arising in fog include (a) lane blockage from a stopped or slowly moving vehicle, (b) lateral tracking errors that result in a vehicle's leaving the roadway or compromising safety in adjacent lanes, and (c) inability to comprehend highway signs or signals. Of these, the blocked-lane hazard is considered to be the most serious. The analytic models were, therefore, intended to predict at what point a stopped vehicle in a traffic lane first becomes visible.

Fog impairs visibility by means of two major mechanisms. Fog, by absorption and by scattering, attenuates light transmission between the object to be seen and the observer. As a consequence of light scattering from various sources, the fog itself becomes illuminated. The latter phenomenon produces a veiling effect and is a major cause of variable visibility under different lighting conditions.

In general, the visibility of objects is a function of the contrast they present to their background. The visibility of objects in fog under threshold conditions (in which objects are barely visible) does not appear to be affected appreciably by color. The visibility of larger objects is a function of the ratio of the object brightness to the background brightness (contrast ratio). The contrast ratios for threshold visibility are a function of the observer, the conditions to which he is being subjected, the size of the object, the background luminance, the brightness, and the time available.

A quantitative analysis of driver perception in highway fog, therefore, requires consideration of complex interrelationships among object luminance, ambient illumination, light attenuation, and scattering in the medium intervening between object and observer as well as the visual capabilities of the observer.

In order to gain further insight into visibility-impairing effects of highway fog on a driver, and as an aid in the generation of a fog visibility index, analytic models were constructed for three highway-lighting conditions. These models cover the most important situations associated with a stopped vehicle on a freeway or expressway and include:

Case 1. Day, natural ambient illumination—no lights on either the target vehicle or the observer's vehicle.

Case 2. Night, automobile lights on—taillights and/or stoplights illuminated on the target vehicle and headlights illuminated on the observer's vehicle.

Case 3. Day, automobile lights on—taillights and/or stoplights illuminated on the target vehicle and headlights illuminated on the observer's vehicle.

In formulating these analytic models, driver physiology was considered in selecting the visibility thresholds, but such psychophysical effects as driver reaction and perception time were deferred to when the relationship of visibility distance with safe driving speed and possible highway fog countermeasure actions are considered.

Analytic Models

Case 1. Day, natural ambient illumination

The Koschmieder theory of "airlight" is directly applicable to this case, and leads to:

$$V = -\frac{1}{\sigma} \log \frac{\epsilon}{C^*} \quad (1)$$

in which

V = visual range (the maximum distance at which an object can be seen when the intrinsic contrast ratio between the object and the background is C^*), in feet;

σ = atmospheric extinction coefficient (feet^{-1}), which can be derived from a transmissometer reading; and

ϵ = contrast discrimination threshold (the smallest value of contrast ratio that can be perceived by an observer).

The standard (Koschmieder's) approach is to assume a black object is viewed against the horizon sky ($C^* = 1$) with a 2 percent observer's contrast discrimination threshold, giving:

$$V_p = \frac{3.912}{\sigma} \quad (2a)$$

in which V_p is the standard visual range.

Eq. 2a is frequently used in translating transmissometer outputs to visual range. It is a reasonably good approximation, particularly in dense fog wherein objects lose their color and the fog itself becomes the background. In recent practice, the tendency has been to use a large contrast discrimination threshold, such as 0.06. This changes the constant in Eq. 2a, giving:

$$V = \frac{2.813}{\sigma} \qquad \text{Case 1} \qquad (2b)$$

In highway situations, the intrinsic contrast ratio C^* does not necessarily have a magnitude of 1, although it is usually close.

As noted earlier, the contrast discrimination threshold is a function not only of the particular observer but also of object size, background luminance, and observation time. It is also a function of the degree of certainty on the part of the observer that the object is truly present. Contrast discrimination thresholds have been investigated by a number of researchers. The results of much of this work have been summarized by Middleton (*3*) and in the *IES Lighting Handbook* (*4*). The latter gives a series of curves showing the relationship between contrast ratio, object size, background luminance, and exposure duration for threshold seeing. The 2 percent contrast discrimination threshold commonly used is typified by an object of 3.4-milliradians (mrad) arc against a background of 10-footlambert (fL) luminance with an exposure duration of 1 sec. Increasing the exposure duration above 1 sec will result in minimal improvement in contrast discrimination threshold. Increasing the object size will improve the contrast discrimination threshold moderately, up to a subtended angle of about 1°. Decreasing either the object size or exposure duration appreciably will produce a significant degradation (increases in magnitude) in the contrast discrimination threshold. Typically, the back of a car subtends an angle of about 10 mrad at 400 ft.

Case 2. Night, automobile lights on

This case was formulated as the detection of a point source of light (the taillight of a leading vehicle) against a luminous background produced by backscattered light from an observer's vehicle headlights. It has been established empirically that thresholds of illuminance from a point source are a function of background brightness. Results of work in this area performed during and just after World War II are summarized by Middleton (*3*). From his data was derived an approximation for the threshold illuminance as a function of background brightness, valid for brightness levels pertinent to highway conditions (see Appendix A).

The illuminance, E, from the taillight at the driver's eye can be quantified from Allard's law. An equation for the background brightness, B_b, based on a searchlight model has been derived in integral form. Both of these are given in Appendix A. Equating the taillight illuminance, E_T, to the observer's threshold illuminance, E, yields an expression that contains visual range, V:

$$I_T \frac{e^{-\sigma V}}{V^2} = K_1 (1 - K_2 \sqrt{B_b})^2 \qquad (3)$$

in which

I_T = taillight intensity;

K_1 and K_2 = constants used to fit the observer illuminance threshold data.

This expression is not directly solvable for the visual range, V, in a general closed form. However, when appropriate values are substituted for the various parameters, the visual range can be readily determined for different background brightness and taillight intensities by numerical methods, as was done in a computer simulation of the problem described in a later section.

An alternative approach to this case was taken by considering the observer's eye as a radiometer. An alternative expression for the background brightness was concurrently developed and is detailed in Appendix A.

Case 3. Day, automobile lights on

Two possibilities exist for this case. The taillights of the leading vehicle may be seen first (at the lower levels of ambient illumination), or the back of the car may be seen first. The first situation, designated Case 3A, can be treated in the same manner as Case 2 with a new term added to the expression for background luminance, B_b, to account for the fog-scattered ambient illumination. Bennett (*5*) has developed an expression for background brightness due to fog-scattered sunlight in terms of a scattering function (see Appendix A), but because of the lack of tabulated values or a suitable expression for values of the scattering function, Bennett's expression is of little help in computing visual range. Empirically derived and measured values of ambient background brightness are therefore used. The background brightness due to ambient light is added to the background brightness due to headlight backscatter, and the resulting brightness applied to the equations of Case 2, which are treated in the same manner as before.

Case 3B, in which the body of the car is seen first, can be treated as Case 1 (daylight without vehicle lights). The strict approach would be to add the illumination and backscatter from the headlights to that coming from the ambient light. However, at ambient brightness levels high enough to result in the body being seen first, the light contribution from the headlights is negligible, thus rendering the conditions the same as in Case 1. Photometer measurements made during on-road tests substantiate this conclusion, there being no measurable or observable change in background luminance with the headlights on or off in daylight fog.

The analytic models for each of the cases are generally valid except at the extreme ranges of fog density where certain conditions may limit their accuracy. In particular, all the models assume that the fog itself forms the background against which the obstruction or taillight is viewed. This is aways valid for objects viewed against the horizon, and is also valid for dense fogs, but it may not always be true in lighter fogs particularly where the surrounding terrain is not level. In addition, only singly scattered light was considered. Multiple scattering of light becomes more significant in extremely dense fog, and limits the accuracy of the model for background brightness produced by the headlights for extremely dense fogs at night.

Computer Simulation

The analytic models thus formulated relate the fog density in terms of the extinction coefficient, σ, to the visual range, V, in that fog. With appropriately representative values of target intensity (representing taillights or stoplights) and background brightness (representing ambient or illuminated day or night conditions) the models describe the visual range deterioration with increasing fog levels. These relationships, when verified by actual data, basically fulfill the first research objective of this study.

However, while the model for Case 1 is a relatively simple relationship, the models for Cases 2 and 3A do not provide an explicit expression for visual range in terms of the variables involved. In order to analyze the relationships with a view toward achieving a single generalized expression for visual range that could be embodied in a fog index definition, the models were evaluated numerically using a computer. Both treatments of background brightness were considered for Cases 2 and 3A. Numerical quantification also provided a measure of the expected ranges that would be compared to the actual measurements in the on-road tests for model verification.

Another objective of the computer study was to examine the adequacy of a number of the parameters, conditions, approximations, integrations, limits, and so forth used in the models. A discussion of these is included in Appendix A.

A comparison of the searchlight and radiometric versions of the Case 2 model (night with vehicle lights on) was made using early forms of the models. The two versions gave essentially the same results for all but very dense fogs. For very dense fogs the radiometric version gave lower visual ranges than did the searchlight version because the radiometric version predicted greater values of background brightness. Because the searchlight version produced a background brightness closer to typically measured values, it was used in subsequent computer simulations.

Figure 1 shows the results of a computer analysis for a target vehicle having its taillights on [5 candlepower (cp) level] at nightime and at three levels of background brightness in daytime. Also shown in the figure is a curve for the Case 1 situation (daylight without taillights on, using a 0.06 contrast threshold ratio, ϵ, which is more typical of actual conditions. The curve is included in order to show at what levels of daylight fog density an observer sees the rear of a vehicle before he sees its illuminated taillights.

Fog density is represented in the analytic models in terms of the extinction coefficient, σ. This parameter is taken as the independent variable in Figure 1. However, because fog density is most frequently represented in terms of visual range (most fog-measuring instruments are calibrated in terms of visibility distance), the fog density has been converted to visibility range dimensions. The standard relationship of Eq. 2a was used to convert the extinction coefficient to what is termed "photometric visual range" in this and subsequent figures.

Figure 2 shows results for 20-cp taillight intensity, which is typical for stoplights and turn signals. Figures 1 and 2 show that, in daylight conditions of higher ambient light intensities, the body of a vehicle is visible at a longer distance than stoplights or taillights, except in the densest fogs.

Fog Visibility Index

The results of the computer simulation presented in Figures 1 and 2 indicate a reasonably good linear relationship between the fog density extinction coefficient, σ, and the predicted visual range, V, on a log-log display for the daylight-no light condition and night condition. Neglecting, for the moment, the curvature that does exist for the daylight-lights on case, the following can be written:

$$\log_e \sigma = n \log_e V + b \tag{4}$$

in which b and n are parameters to be determined. From this, a general expression for V in terms of b, σ, and n is obtained:

$$V = \frac{b}{\sigma^n} \tag{5}$$

The daylight-lights on case represents a transition between the conditions of the other two cases. The curves for this case show considerable curvature, particularly for the higher levels of ambient background brightness. The high ambient brightness levels, however, are those of full daylight and under these conditions the driver initially detects the body of the vehicle as in Case 1. Also, during daylight fog, not all vehicles will have their lights on, except in the lowest ambient light conditions (early dawn or late dusk) for which the curves are close to linear. Therefore, even for this case the relationship of Eq. 5 is valid with the proper choice of parameters b and n.

Because Eq. 5 relates visual range to measurable characteristics of the fog, it is a suitable expression for a fog index. Further, because virtually all fog density measurements (including visual estimates in daylight) are calibrated in terms of a photometric visibility distance, V_p, rather than extinction coefficient, a fog index (FI) can be expressed as follows:

$$V = \mathrm{FI} = B\, V_p n \tag{6}$$

where B is the previous parameter b in modified form. The fog index is thus a single simple expression with only the quantities B and n to be established for any specific class of fog conditions. The values used for B and n must include the many elements involved in the analytic models and should be based on standardized vehicle and driver characteristics. Differences in types of vehicle, for example, can be accommodated in the application of the fog index (e.g., the maximum safe stopping speed as a function of the fog index could be dependent on vehicle type, if required).

The suggested values for the parameters that fit the simulation results for discrete conditions of ambient illumination are given in Table 1. The value of ambient background brightness used in selecting the parameters for early dawn was 1 candle per square foot. At this level, the

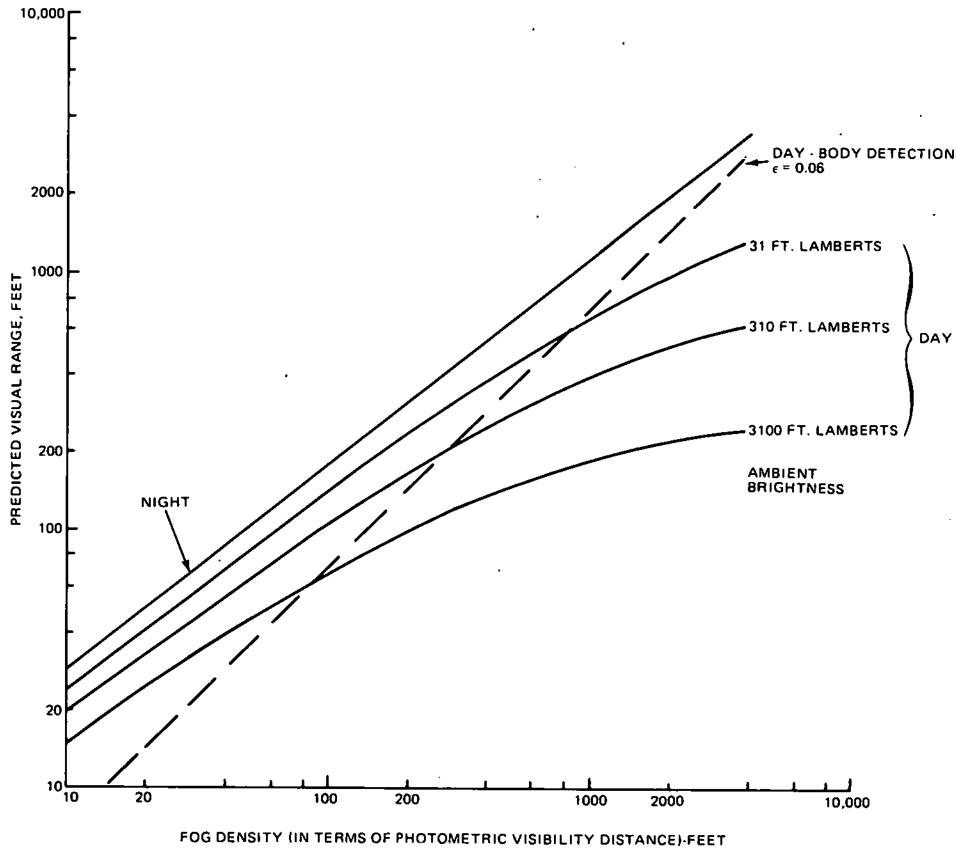

Figure 1. Analytic models for vehicles with taillights (5 candlepower)

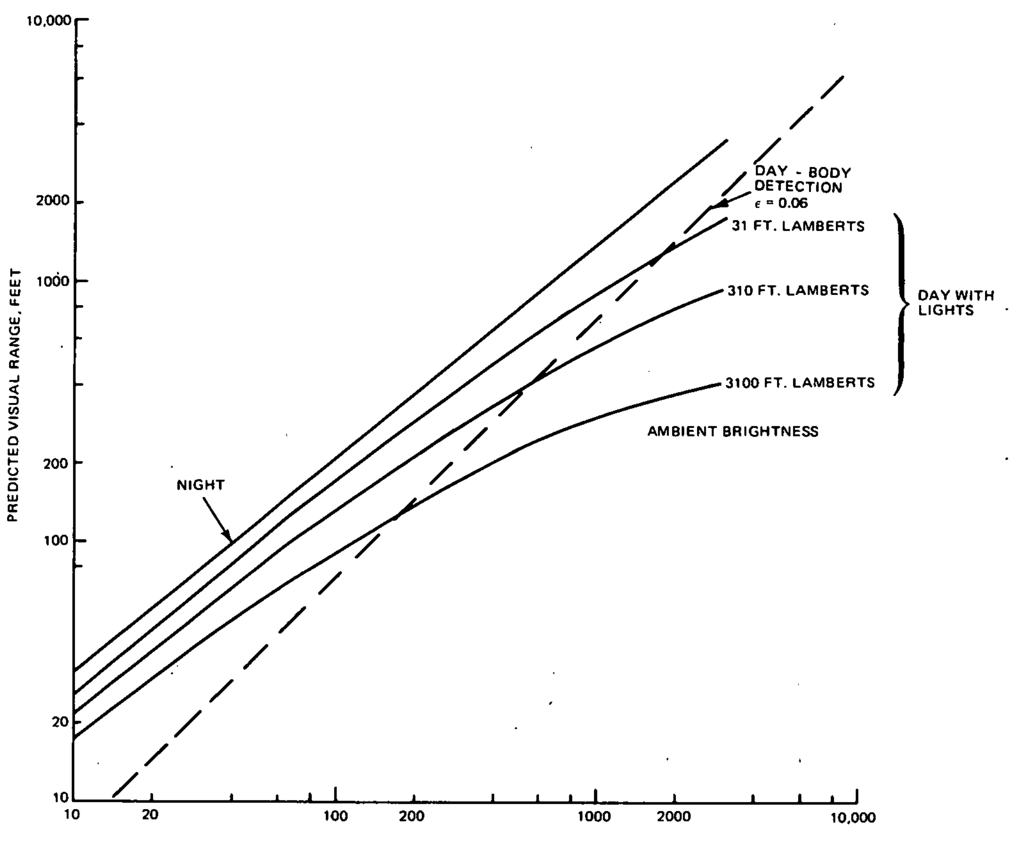

Figure 2. Analytic models for vehicles with stoplights (20 candlepower).

taillights provided appreciable help in detecting vehicles. However, because some vehicles were observed to be driven without their lights on, transition to the daylight parameter should be made at that brightness or preferably lower.

The difference in parameters and fog index values between the night and dawn conditions is very small. The reason for this is that the background brightness produced by the headlights is of the same order as the ambient background brightness in the dawn transition period.

Safe Stopping Speed

For safe operations in a fog environment, it is desirable to be able to establish a maximum speed that will allow a vehicle to be safely stopped within the visibility distance existing at a particular time and place. The need to know the relationship between vehicle speed and stopping distance is not unique to a highway fog study. The subject is discussed in the ITE *Traffic Engineering Handbook* (*9*) and the AASHO *Policy on Geometric Design of Rural Highways* (*10*). The latter makes specific recommendations for use in highway design. The speed-distance relationships adopted for this study are based largely on the AASHO policy recommendations.

The distance within which a vehicle can be stopped is for convenience divided into two parts: the distance traveled during the time a driver perceives and reacts to a hazard, and the distance required for actual braking. The braking distance for a given initial speed is dependent on the roadway condition and on a number of parameters, such as the type and condition of the vehicle brakes, tires, and suspension. AASHO (*10*) tabulates recommended braking distances and average coefficients of friction for initial vehicle speeds from 30 to 70 mph for both wet and dry pavements. The safe stopping speed has been derived from these tabulated values.

Perception reaction time, as used here, includes the time needed for a driver to recognize a hazard once it becomes visible, to decide upon an action, and to initiate braking. AASHO (*10*) recommends 2.5 sec as the total perception reaction time for highway design use. This is for unalerted drivers and includes a 1-sec reaction time, which is adequate to accommodate most slowly reacting drivers. With previously alerted drivers, the perception reaction time drops considerably. Because drivers are presumably somewhat more alert when driving in fog, a perception reaction time of 1.8 sec has been used in this study. There is an interaction between perception reaction time, the degree of loading the driver with other tasks, and the strength of the stimulus. These have been taken into account, in part, in the selection of the perception reaction time but to a larger extent in the selection of the minimum required stimuli (i.e., threshold contrast ratio or threshold illuminance).

The relationship of stopping speed versus visual range for both wet and dry pavements is shown in the curves of Figure 3. Depending on the conditions producing the fog, dense fogs may be associated with either wet or dry pavements, and both conditions were encountered during the on-road tests described in later sections. In special situations there may be some justification for adopting a different set of curves. The curves of Figure 3, for example,

TABLE 1

FOG INDEX PARAMETERS

AMBIENT ILLUMINATION CONDITION	B	n
Night	4.32	0.81
Early dawn	4.28	0.80
Day	0.75	1

are based on level grades, and adjustments are advisable at significantly nonlevel grades. Suitable speed-distance relationships may be derived using the approach outlined in Appendix D and by consulting Refs. (*9*) and (*10*). The choice of curve to be used depends on the type of fog typically encountered and other considerations specific to the location in question.

VISIBILITY MEASUREMENTS AND MODEL VERIFICATION

The visibility measurements were in general addressed to the specific problem of determining the maximum distance at which a stopped vehicle in a traffic lane could be detected. Driver performance in reaction to this hazard can be predicted based on physical principles and the results of physiological and psychological experiments described in the literature. The prediction involves a degree of extrapolation and therefore needs to be validated. The visibility measurements were intended to provide the data for validating the predictions. For maximum usefulness, they included measurements made under driving conditions as realistic as practicable.

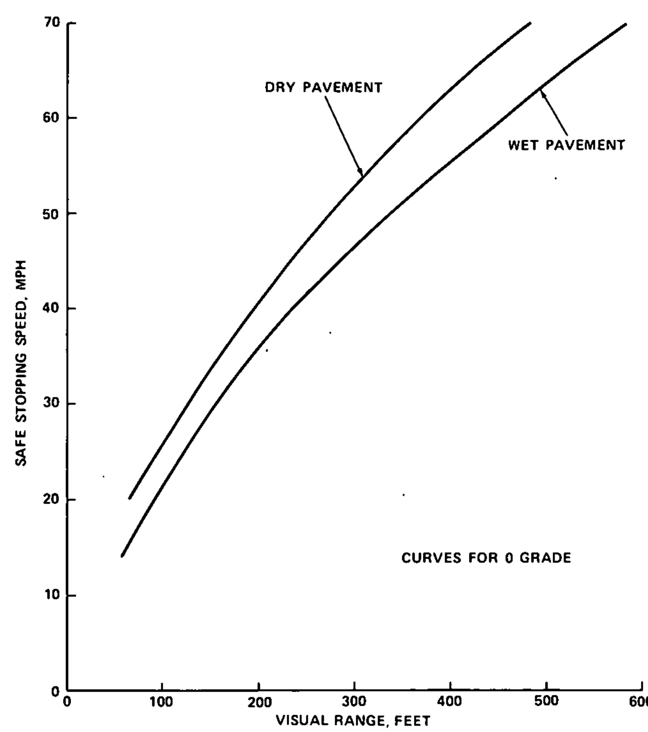

Figure 3. Safe stopping speed.

On-Road Tests

The on-road visibility tests constituted the major part of the visibility measurements. The tests essentially determined the distance at which a driver (and an observer) moving in a test car in fog could first reliably determine the presence of a target car or special test car or special test target located ahead in an adjacent lane of the roadway. The test procedures and instrumentation are described in detail in Appendix B.

The on-road test experiments were initially planned to be performed on the New Jersey Turnpike during periods when the fog was of sufficient density to require closing of the turnpike. Experiments could then be conducted in relative safety under reasonably realistic conditions. The New Jersey Turnpike seemed ideally suited for such tests because (a) the northern end, where dense fog frequently occurred, was within one hour's driving time, and (b) between 1964 and 1969, the road averaged six closings per year due to fog. The occurrence of fog is by no means regular and dependable, and in actuality there were no fog closings on the New Jersey Turnpike during this past year. In recognition of this possibility, arrangements were made to conduct tests on mid and eastern Long Island as well. Dense fog occurs more frequently on eastern Long Island than on the New Jersey Turnpike. However, the fog is most frequently of a different type (sea fog instead of radiation fog), and consequently extremely dense fog is less common. Unfortunately for this study, the incidence of dense fog was considerably lower than normal in both areas, and therefore the amount of data collected was not as great as had been hoped for. Table 2 summarizes the on-road tests for which a test crew was dispatched.

The fog densities in which data were taken varied (in terms of photometric visibility) from 235 ft to about 1,200 ft. The bulk of the data were taken with the visibility between 450 and 800 ft. Fog density measurements were taken before the start of each run, during the latter part of each run, and immediately following each run. Considerable differences between the various fog density readings were frequently encountered. This was particularly noticeable with the start-of-the-run measurements because the location of the target was from ½ mile to more than 1 mile distant from the start of the run. Little weight was given to start-of-the-run readings. The differences between the fog density readings taken when passing the target and those taken immediately following the end of the run were frequently appreciable although normally less. Reduction of the data therefore required considerable care and judgment in order to arrive at a best estimate of the average fog density between the target and the point from which it was first sighted, the factor of prime interest.

The data taken on or immediately following the runs, in addition to the fog density measurements, included various sky and background brightness levels, test vehicle speeds, and distances to the target at the time of initial target sightings by the driver and the observer.

It had been postulated at the beginning of the program that, because of the added burden of driving, the driver would not see the target so soon as the observer. A comparison was therefore made of the initial sighting distances of drivers and observers. All of the test subjects were tested in several runs in both positions. On a fractional basis (the difference between the sighting distances relative to the average of the two) large differences (up to 50 percent) were seen in both directions. The mean difference of 53 runs, however, was not statistically significant, being only about 2½ percent less for the observer with root mean square (rms) variation of about 16¾ percent.

Degradation in performance due to the added burden of driving must therefore be considered negligible compared to the effects of the other variables and uncontrolled factors of the test. Significant differences, however, were detectable between some of the pairs of test subjects. But

TABLE 2

TEST SERIES SUMMARY

TEST SERIES NUMBER	DATE	PLACE	REMARKS
1	June 23, 1971	McArthur Field	Videograph calibration
	September 17, 1971	Montauk Parkway	15 runs
	October 22, 1971	MacArthur Field	Videograph calibration
	October 27, 1971	Mid Long Island	Insufficient fog
2	January 13, 1972	Mid Long Island	6 runs
	April 18, 1972	Mid Long Island	Insufficient fog
3	May 17, 1972	Old Montauk Highway	8 runs
4	May 18, 1972	Mid Long Island	Insufficient fog
5	June 1, 1972	Montauk Parkway	26 runs
	June 7, 1972	Montauk Parkway	Insufficient fog
	June 14, 1972	Mid Long Island	Insufficient fog
6	June 20, 1972	Mid Long Island	Insufficient fog
	June 27, 1972	Mid Long Island	Insufficient fog
7	June 28, 1972	Mid Long Island	Insufficient fog
8	August 25, 1972	Montauk Parkway	21 runs
9	September 14, 1972	Montauk Parkway	Insufficient fog
10	September 26, 1972	Mid Long Island	Insufficient fog

even with the same test subjects in the same position, considerable run-to-run variation was present.

Data from the on-road tests are shown in Figures 4a through 4e. The figures are scatter diagrams in which the initial target sighting distance is plotted against fog density for several sets of conditions. Fog density is presented in terms of photometric visual range to aid in interpreting the data. Also shown are the curves of predicted visual range based on the analytic models.

The parameters used in categorizing the data include (a) the color and condition of the target (whether white or black, with taillight and/or stoplight, or without lights), (b) the background ambient light levels (low, less than 31 fL; intermediate, to 310 fL; and high, over 310 fL), and the headlight condition of the test observer's car (off, low, or high beam). All of the parameters are not necessarily of significance to a particular case. Under intermediate and high ambient light conditions, the light from the headlights is undetectable and is therefore highly unlikely to have affected the results. At higher ambient light levels, the body of the target will be detected at a longer range than the target light, except possibly stoplights at the intermediate ambient light level. Conversely, at very low light levels the target lights (when on) will be detected prior to the target body, so the target body color would not be expected to affect the results.

The shaded areas in Figures 4a and 4c represent the predicted visual range from the analytic models for taillight detection under the ambient light conditions included in the figures. In Figures 4d and 4e, no distinction is made for target lights because detection under daylight conditions is always of the target body. An additional condition for which no analytical model was derived was the condition of night with no target lights. Some data, however, were taken under these conditions and are presented in Figure 5. As was expected, these conditions produced the shortest detection ranges measured relative to the fog density visibility range; the worst case was that of a white target with no lights at low ambient light levels.

Driving Simulator Tests

The on-road tests were conducted under conditions as realistic as possible. The test subjects viewed the target through the windshield with its light loss and glare-producing potential, and a visual search was involved with its associated impairment of visual thresholds. The target was representative in many respects, particularly under conditions where the initial detection was by the taillights or stoplights. When the initial detection was of the body, the target shape did not exactly duplicate the shape of a typical vehicle; however the white and black target surfaces provided the two extremes of vehicle light-scattering characteristics.

On-road tests can not be made completely realistic, and target placement is one example. The placement of a target in the same lane as the test vehicle is out of the question when other vehicles are on the same roadway. And even if the roadway were closed, the placement of an actual vehicle or even a substantial target in the roadway would be unsafe. Another area in which full realism is not possible or is difficult to attain in on-road tests is that of driver expectation. As the tests were actually conducted, both the driver and the observer knew that there was a test target located ahead at the side of the road, although they did not know how far ahead.

The driving simulator tests were undertaken in an attempt to explore areas of driver expectation, to help determine how successfully fog could be simulated, and to what extent driving simulators can be used in studying the highway fog problem. These tests were of necessity limited in scope, thus it was not possible to explore the effect of driver and observer expectation on the on-road test results in depth. However, it has been established that fog can be successfully simulated, and the driving simulator has proved to be a useful tool in the investigation of driving in fog, particularly with respect to behavioral aspects.

Driving simulator tests were conducted within the University of California (Los Angeles) Driving Simulator Laboratory closed-circuit television system by staff members of the UCLA Institute of Traffic and Transportation Engineering. Details of the tests and the equipment used are contained in Appendix D. In brief, the equipment consists of model roadways and a landscape mounted on conveyor-type belts capable of moving forward or backward at varying speeds. The simulator also has a TV camera mounted at the end that is positionable in 2 degrees of freedom to provide a view as seen from a vehicle located on the road which is shown in Figure 6. The scene is viewed by the test subject in a driving "cockpit" consisting of a TV monitor, automobile seat, and controls placed within a small black cubicle together with a speaker and microphone for communication. Fog is simulated by placing a specially constructed filter over a prism in front of the lens of the TV camera. The filter consists of a fine-screen pattern of white dots; the density increases with elevation-angle in order to produce the three-dimensional effect of fog. Density is doubled with each increase in angle corresponding to a doubling of the distance to the landscape. Filters were produced for two density levels—one for approximately a scale 500-ft equivalent distance, and one of very dense fog equivalent to about 30 ft.

The test consisted of taking two sets of data on each of five subjects. The first set consisted of determining the threshold distance of a standard circular disc target both when receding and advancing slowly. The order of presentation of the receding and advancing targets was random. The second series of data consisted of determining the distance at which each of seven obstacles in one of the two roadways was initially detected. The obstacles were presented in random order at scaled closing speeds of 20 and 30 mph.

The threshold series data served to help calibrate the filters and also served as a basis of comparison for the obstacle data. With the low-density filter, the mean scaled threshold distance of four test subjects for the approaching target was 346 ft, for the receding target 485 ft, for an average of 416 ft. With the high-density filter, the mean scaled threshold for the approaching target was 38 ft, and for the receding target 75 ft. The average was 55 ft.

During the obstacle reaction tests with the high-density

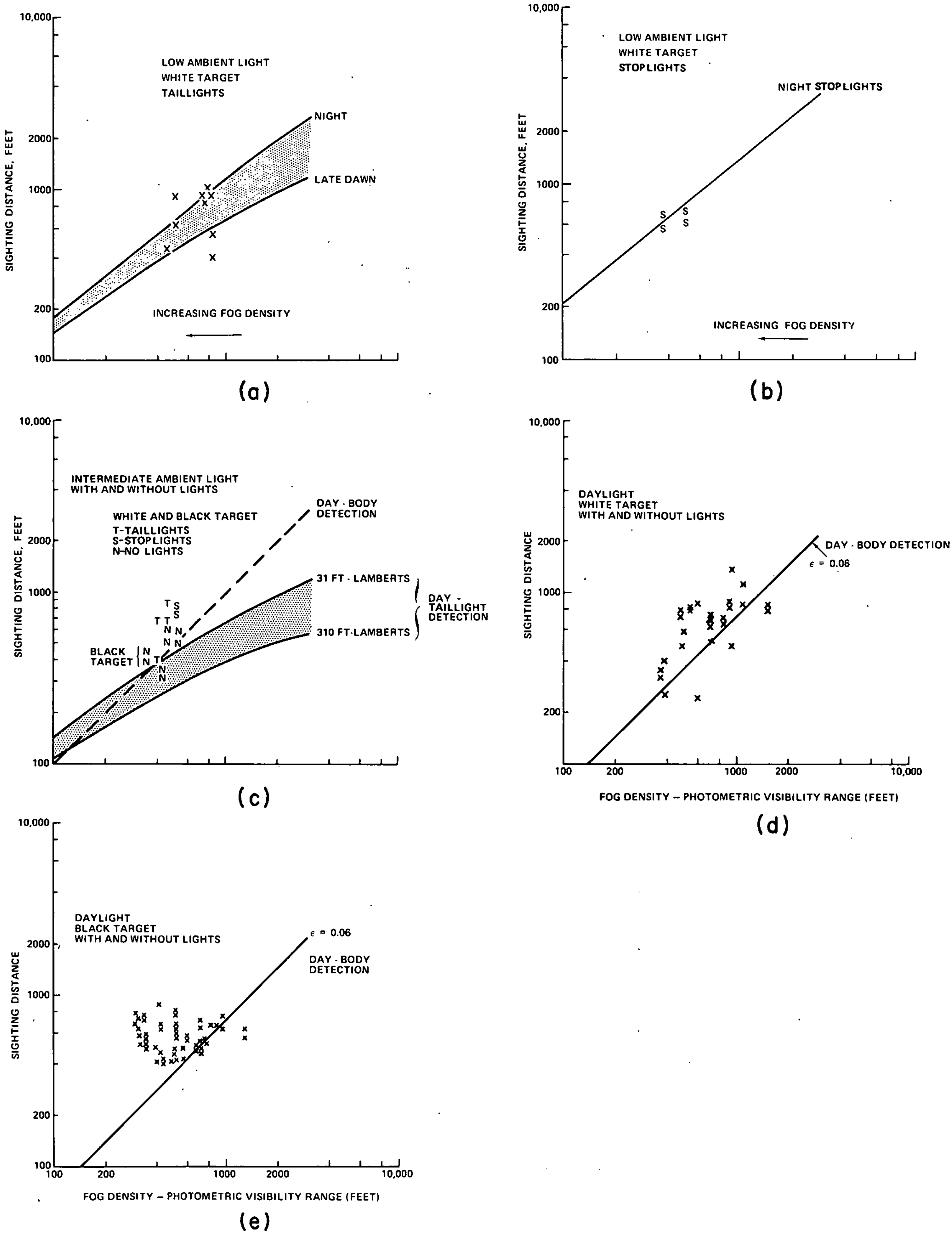

Figure 4. Test results compared to model prediction.

(30 ft) fog filter, only one target, an automobile with lighted headlights, was seen in time for the test subjects to react before the distance closed to zero. The average scaled distance to the target at reaction was only 87 ft. Data were successfully taken from all five test subjects on each of the seven test objects with the low-density (500 ft) fog filter. The mean response distance for the objects varied from an equivalent scaled distance of 3 ft to a maximum of 290 ft.

The relative detectability of the objects varied in much the same manner as would be expected of the scaled-up objects in real daylight fog of comparable density. The most difficult object to detect was a white cylinder and the easiest one to detect was the car with headlights. The easiest to detect of the unlighted objects was a model two-decker bus colored red. For all of the objects, except for the difficult-to-detect white cylinders, the reaction distance at 20 mph is greater than the sighting distance at 30 mph, as was expected. Assuming that the objects become detectable at the same distance for each approach speed, the difference in the reaction distances can be attributed to the difference in the distance traveled during the reaction time. Using the average differences in sighting distance for the seven objects, the mean reaction time calculated to 1.4 seconds.

The perception-reaction time usually assumed under normal driving conditions [AASHO (*10*)] is 2.5 seconds. It has been postulated that under fog conditions the driver is more alert and this time is correspondingly shorter. Accordingly, a value of 1.8 seconds was used in the computation of safe stopping speed in this study. The result of this driving simulator study essentially substantiated the applicability of this lower figure.

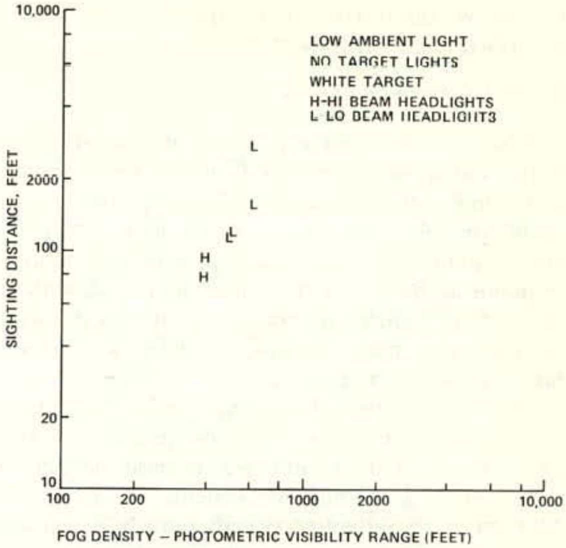

Figure 5. Test sighting distances—night, no target lights.

Figure 6. Simulator and moving landscape.

HIGHWAY FOG COUNTERMEASURES AND WARNING AND GUIDANCE SYSTEMS

General Considerations

Fog has been a hinderance to the safe and efficient flow of traffic and traffic operations from the time motor vehicles first came into general use. Initially, the problem was mostly one of inconvenience, with fog making it more difficult to find the way and contributing perhaps to an increase in minor accidents. As time has progressed, with the large increase of vehicles on the roads, and in particular with the advent of modern high-speed, limited-access and other highly improved roads, the fog problem has become more acute both in terms of snarling traffic operations and increasing travel hazards. Fog countermeasures should increase safety of travel and also increase the efficiency and through-put of the highway system. In case of a conflict between the two, the first priority must be placed on safety, particularly in view of the relative infrequency of fog in most areas.

Fog countermeasures can in general take the form of abating, dispersing, or otherwise eliminating the fog; improving visibility within the fog without necessarily eliminating it; and use of a system that will allow improved and safer operations in spite of the loss of visibility. A fourth category is curtailing or stopping traffic operations with the occurrence of dense fog. This latter course can improve the safety of traffic operations but will adversely affect the efficiency of traffic operations.

Table 3 lists some of the possible types and categories of highway fog countermeasures. They are not all applicable to this study, but have been included as an indication of the types of action that could be taken or have been tried in the past. Also, some may be part of a more comprehensive fog warning and guidance system.

An active highway fog warning or guidance system involves three major elements: (a) a means of detecting the presence of dense fog; (b) a decision element to decide whether to take any action and, if so, what action or degree of action; and (c) a communication device. The system could be as simple as a manually actuated "fog ahead" warning sign or as complex as a fully automatic vehicle guidance system. Because the fog detection element is common to all of the systems, it is discussed first. The other elements are more interrelated with each other and with the specific type of system under consideration.

TABLE 3

POSSIBLE HIGHWAY FOG COUNTERMEASURES

COUNTERMEASURE	POSSIBLE APPLICABILITY NIGHT	DAY
Fog abatement, dispersal, and prevention techniques	X	X
Vehicle design:		
Taillight intensity	X	—
Headlight intensity, beamshape, and aiming	X	—
Other vehicle-mounted devices	X	—
Special lighting techniques	X	—
Activation of warning signs	X	X
Reduced speed limits	X	X
Increased patrol and enforcement activity	X	X
Restricted use and closings	X	X
Special escort (convoys, etc.)	X	X
Radio, audio, or other advisory warning systems	X	X
Guidance aids	X	X
Block guidance systems	X	X

Visibility Determination

Visibility range determination may be performed by human observers or by instrumentation. The use of human observers is undoubtedly the most common method of visibility determination in current use. The human observer has the advantage of automatically taking into account background luminance and, particularly if on a continuous limited-area patrol, can cope with patchy and variable fog conditions. The primary difficulties are in providing consistent accuracy and in assuring continuous round-the-clock coverage of all areas. Also, precise quantification or continuous recording is not feasible. Even under near ideal conditions, considerable variance will occur in the visibility estimates even among trained observers viewing the same scene. This is due in largest part to the variability of the contrast thresholds of the observers, who are influenced by a large number of physiological and psychological factors, including the degree of certainty applied to the estimate (i.e., how many "false alarm" errors in estimate for a given range is the observer willing to tolerate). In order to quantify the measurement when the visibility is to be determined by human observers, it is helpful to set up a standard criterion such as a given number of standard targets uniformly spaced.

Fog measurement instrumentation is described in detail in Appendix E. To summarize, the quantities to be measured or determined include a fairly gross measure of the background luminance B_b, and either the fog extinction coefficient σ or the backscatter coefficient B_π. At night in a few types of fog, both may be desirable for best accuracy. Of the two, extinction coefficient is the most directly pertinent. Transmissometers measure atmospheric transmissibility, which is exactly relatable to extinction coefficient. Transmissometers, however, are cumbersome and expensive to install and use for highway applications. The various types of scatter devices are considerably less expensive, easier to install, and in general require less periodic maintenance. Of these, the backscatter instruments measure the backscatter coefficient directly (but are rarely calibrated in backscatter coefficient), which in relatively clean fog has been shown to be relatable to extinction coefficient with an accuracy of no worse than 20 percent. Somewhat better accuracy in estimating extinction coefficient is possible at particular locations with limited types of fogs by calibrating the instrument in those particular types of fogs. Forward scatter can be similarly related to extinction coefficient with at least as good an accuracy as backscatter. Total scatter instruments in clean fog can, in theory, always be exactly related to extinction coefficient. All of these instruments provide only on-site measurements over a limited-fog sample size. Several of the currently available instruments provide a continuous current or voltage output, whereas others provide only one or more discrete outputs indicating whether the visibility is above or below a limited number of preset threshold levels.

A state-of-the-art technique using lasers holds promise for making a probing measurement of extinction coefficient over distances of up to one mile (in light fog), thus determining the presence of patchy fog and fog banks. Instruments employing this technique, however, are not currently available.

Both human observers and visibility instruments can cope reasonably well with local fog patches where the location is predictable and fog within the patch is reasonably uniform provided, in the case of the human observers, that adequate coverage of the location can be maintained by reliable observers. Area fog, where the fog is uniform or does not change rapidly from place to place, can likewise be handled reasonably well by human observers and visibility instruments because the precise location does not appreciably affect the range determination. A few *in situ* visibility meters spread through the area would suffice, and reports of officers on patrol would be a sufficient example to the observers, so long as a patrol is maintained somewhere in the area at all times.

Fog of the highly variable density type that exists or may exist over an area poses a much more difficult detection problem. Visibility under these conditions can undergo relatively sudden and unpredictable changes, frequently caused by dense floating fog patches. This, for example, has been reported to be frequently the case on I-5 in Oregon where the visibility in the vicinity of one variable-message sign may be considerably different from the visibility at another sign 1½ to 2 miles away. At times a difference in visibility was noted between a frontage road and the Interstate lanes and, occasionally, even between the northbound and southbound lanes.

Similar patchy fog is not uncommon over the New Jersey Turnpike and other areas. The fog detection method that Oregon has used in its project areas is to initiate an intensive continuous patrol over the 6-mile section whenever fog is predicted or when the visibility starts worsening. Visibilities encountered in the various parts of the section are reported by radio for sign energizing and selection of speed limits. Such a method is expensive in terms of required manpower, even over a limited area. Over more extensive areas, particularly where considerably longer patrol sections are normal (on the New York Thruway, for example, 30-mile patrol sections are typical), the effectiveness of the human observer for fog detection must inevitably be lower with respect to variable fog, and particularly with respect to floating fog patches.

For an automatic detection system, a number of fog detectors would be required for variable fog areas. With a variable-message sign type of system, it is probable that at least one detector, perhaps more, would be required per sign. A time history smoothing (probably nonlinear) should prove useful in improving performance in variable patchy fog.

Careful siting of the instruments can also help because fog patches are prone to form at certain locations (e.g., low spots where cold air tends to collect). Even the northern end of the New Jersey Turnpike, for example, where fog is most frequent and where the typical locations for fog formation and occurrence are fairly well known, the predictability of fog locations is far from perfect.

Warning and Advisory

In terms of traffic safety, two of the most crucial situations involving highway fog are those instances when a motorist suddenly and unexpectedly finds himself in dense fog and when his visibility has deceptively lowered to a much greater degree than is apparent. In the first case the motorist may find the visibility insufficient to maintain his position in the lane at the speed he is traveling; in both cases, the motorist will undoubtedly overdrive his safe-stopping limit of visibility. The driver may have just passed through some patches of light fog, and to accurately judge the density of a fog patch from outside the patch is frequently difficult, if not impossible. The unexpectedness of being in dense fog can easily lead to disorientation or panic and loss of control. It is the opinion of some turnpike operating personnel that several of their major multivehicle accidents have been precipitated by motorists abandoning their vehicles in the through lanes of the roadway.

A rather extreme example of the second type of situation is what is sometimes called the "killer fog," which is a rather dense layer of fog about 6 to 8 ft high. The fog is thick enough that passenger cars are completely covered, but the cabs of trucks are above the fog. Truckers have little difficulty following the alignment of the road, particularly after dawn, because they can look down at the road through the shallow fog layer. However, a passenger vehicle some distance ahead and lying beneath the fog layer may be completely obscured from the trucker's vision. This type of situation can also occur when fog density increases gradually and when few roadside objects are available for identification. In either situation, the driver needs to be advised and warned of possible danger ahead.

Warning systems can take a variety of forms. Recalling the basic elements of a warning system (fog detection has been previously discussed), there remain the warning device and the decision and control element. Each of these elements has a number of different alternates such that considering each of the combinations individually is obviously impractical. The circumstances of the individual fog-prone locality will have a great deal of influence on the feasibility and effectiveness of a particular fog warning system. A number of the possible warnings are considered highly feasible when applied to appropriate situations.

A crucial aspect of fog warning systems is the actual communication of the warning to the driver. This must be done in such a manner that credibility of the warning is assured.

Timeliness and accuracy are two essential ingredients in maintaining credibility. A third is the appearance of reasonableness. A lack of credibility is believed responsible for the failure of many present fog warning systems, particularly those incorporating fixed and manually operated signs, which were discussed previously. There are still many questions to be answered about what is necessary and sufficient for effective communication with the driver, both in general and with respect to fog. In this latter context, an FHWA-funded project has recently been initiated by the Oregon State Highway Division to explore this area.

In the immediate future, variable-message signs appear to be the most feasible means of communicating with drivers. Because of the relatively high cost of supporting, installing, and bringing in power and communications to such signs, they are frequently designed to provide other advisory and warning messages as well, such as the presence of ice, snow, or congestion ahead. One of the simplest automatic fog warning systems is a fog detector having a simple threshold level that operates a pair of "SLOW Fog Ahead" (or similar message) warning signs. Such a simple system can be expected to be most effective at a location where fog forms in a well-defined rather limited area, such as a valley or other low area and particularly where road geometry is such that the fog cannot be seen until the vehicles are quite close to it. It would also be best in relatively lightly traveled areas where more elaborate systems and intensive enforcement patrols cannot be justified on a regular basis. It is important that the warning sign is not actuated too far ahead of the fog, perhaps as little as 500 to 600 ft, if possible, depending on the range of speeds normally encountered at times of fog. An indication of the probable distance to and extent of the fog may be desirable, although the content and wording of the messages requires further study.

The advisability of using an advisory or regulatory speed limit with a single-threshold system seems doubtful because of the wide range of conditions to which it would have to apply. The addition of a speed advisory or regulation is desirable, although perhaps less necessary, for a limited-location system. The necessity of selecting a speed adds to the complexity of the fog detection and control elements. Probably the simplest system that would be adequate is a three- or four-threshold detector combined with a single-threshold photocell to distingiush between day and night. The ambient light and the fog density taken together would be used to select the speed advisory; each of the three to four threshold levels would have one set of speeds at night and a different set during the day. There could be a third set for twilight conditions; however, this may not be justified in view of the short period of time required for the transition from night to day. A fine gradation of speed would not be justified for such a relatively unsophisticated control system, particularly with a single warning sign for each direction.

For highways where the probable fog area is somewhat more extensive and the location of the fog less precisely defined, a multiple-sign system is possible. An example is the fog warning system on I-5 in Oregon mentioned earlier. This system extends for just over 6 miles, with three signs in each direction. The signs are spaced from 1 to 2 miles apart. The northbound and the southbound signs are offset; that is, the northernmost of the northbound signs is slightly south of the southernmost southbound sign. This is done to provide advance warning, and also to conform better to the fog accident pattern history. The signs can be individually controlled from either the state police office at the south end of the area or at the sign location. Normally the signs are controlled from the state police office and are based on radio reports from police officers on patrol. A Videograph has been installed near the center of the area about 200 ft from the roadways but is not presently used as a control device. When energized, the signs display "SLOW" and have the option of displaying the words "WRECK" and/or "FOG" and a speed from 10 to 50 mph in steps of 10 mph. No formal criteria have been established for energizing the signs or setting the speeds; the police officers use their best judgment. The policy is, however, to lower the speeds only when definitely required and to restore them as soon as possible. The signs are not normally set to the same speeds. Since the fog detection and the decision and control functions are exercised by humans and the signs are independently controllable, the system is highly flexible, and can be responsive to a wide variety of conditions. The primary disadvantage is the degree of manning required.

Associated with the signs, a series of twenty inductive loop detector speed traps have been installed: one in each lane at each sign in the direction of the sign, and one in each lane at both ends of the fog area. A mini-computer is used with the loop detectors to derive speed and headway data. These were installed as a research tool in order to be able to assess the effect of the signs and the speed setting on traffic behavior in fog.

In addition to being a research tool, the possibility of using the speed and headway data as a control input is also being investigated. The primary objective, in addition to lowering the speed, is to establish a speed setting that will improve traffic stability. It was established in California's reduced visibility study (*2*) that too low a posted speed can grossly affect traffic stability, actually creating a bimodal speed distribution with substantially increased spread of speeds. This has the effect of increasing the possibility of an initial accident. Stevens (*20*) in a recent paper on the use of variable-message signs, reported an extension of the previous California study, stating:

> Where sufficient data exists, the results are practically unequivocal, there is an advisory speed at which maximum stability exists, and that value differs depending on visibility conditions. As visibility decreases, the posted speed at which the relative dispersion is minimal is lowered. . . . In other words, lowering the posted speed a little below the nonsigned "natural speeds" can improve traffic stability; lowering the speed too much will reduce stability. Each visibility distance will have its own optimal value.

Insufficient data have been collected in Oregon to definitely establish whether this will be true there as well. However, there is no reason to suspect that it won't be true; and the use of speed and headway data should prove valuable as a control input where they can be made available, and they definitely should be considered especially in fog problem areas where a freeway surveillance and control system is to be installed.

The warning systems discussed thus far have been considered primarily in terms of spot or small area locations where there is a high probability of the recurrence of fog. These are the types of places where such systems are likely to be most effective, and there is a large number of such locations that could benefit from warning systems. The places where the fog can occur over a considerably larger area present different types of problems. The fog of large area and of generally uniform density is not likely to be as dense as some of the local fog patches, and whether or not it represents a serious fog hazard depends on the reaction of the driver to it. On the Pennsylvania Turnpike, for example, it has been reported that in such fog the drivers all tend to slow down somewhat and the accident experience in larger area fogs has not indicated them to be a serious safety hazard. Such fogs, however, may tend to induce a false sense of security, leading to excessive speed on the part of many of the drivers. This may have been the case in the areas where the California reduced visibility studies were conducted. The area surrounding the Pennsylvania Turnpike is largely rural, with limited amounts of urban and suburban commuter-type traffic, so there may be less immediate urgency felt on the part of the drivers to arrive at their destinations at a specific time. It is therefore reasonable to expect that the behavior of the drivers and their reaction to signs and warning messages might be different. Also, when drivers have previously been driving for a distance in fog on similar types of roads, it can be expected that they will show a greater resistance to change since a driving pattern will have been established. The same is also probably true during periods when fog is encountered on a frequent or regular basis.

The presence of factors that result in an established driving pattern that must be changed adds considerably to the difficulty of designing and operating an effective fog warning system. It is believed that variable-message sign warning systems are feasible under these circumstances. Careful attention will be required as to the number and locations of the signs, the message content of the signs, and the control algorithms used to select the messages and the speeds advised. The use of the speed distribution data should be particularly valuable in such circumstances. Also, the associated and coordinated use of educational programs and broadcast advisory working messages, such as California's Operation Fog Bound, should be of considerable aid.

Probably the most difficult type of fog area to cover with a fog warning system is the more extensive areas where widespread light fog may be present, and the possibility exists for dense fog patches within the area at relatively unpredictable locations. The problem is twofold. First is the problem of detecting the fog and arriving at recommended speed settings at the various locations within the area. Second is the problem of adequately communicating with the drivers. This seems to be the type of fog situation that sometimes prevails in central and southern New Jersey on the New Jersey Turnpike. (Fog is normally more frequent and more predictable at the northern end.) Some of the problems involved, and possible approaches and alternatives will be discussed in the context of the New Jersey Turnpike.

The Turnpike (in 1951) installed a series of variable-message warning signs that included a fog-ahead message. Later (in 1964-1966) variable-speed signs were added. The spacing of the signs is the lesser of 5 miles or within 1 mile of an entrance. All of the signs are operable from the central administration site. Fog detection is performed visually by the state police on patrol. Also, weather forecasts and advisories are received twice daily or more often, as required. These advisories include specific consideration of fog probabilities. A schedule has been worked out for energizing the signs based on the number of delineators visible, ranging from 30 mph for one or two delineators visible to 55 mph for 11 to 14 delineators visible. The road is closed when the visibility is less than one delineator spacing. The problems associated with fog detection have been discussed. One of the possible difficulties associated with the signs is the possibility that a driver may have traveled more than 4 miles from the time he saw a warning and a speed sign before encountering fog, so that by the time the fog is encountered, he may be traveling at a high speed again. A closer sign spacing (1 to 2 miles) would undoubtedly help. However, the minimum spacing that can be economically justified in view of the high cost of procuring, installing, operating, and maintaining the signs is not easily determined. Maintaining the credibility of the signs by lifting the speed restrictions as the visibility improves and turning the signs off when the fog dissipates is not easily accomplished in the more lightly patrolled areas, particularly when the patrolman is otherwise engaged in various enforcement activities and aiding motorists.

The installation of fog detecting instruments could be a help in operating the fog warning system. The presently available devices are not fully satisfactory, and cost may be a deterrent to installing as many of the devices as would be desirable, particularly when a large area must be covered. Nevertheless, the installation of fog detection instrumentation would be a distinct improvement in the fog warning system, particularly when supplemented with visual reports. Computer processing of the instrument outputs would readily allow nonlinear smoothing, which should help give a better indication of the actual visibility. The time pattern of the output of the individual instruments, and comparison of the outputs of the different instruments, can provide an indication of the presence of fog patches.

Other means of communicating with the drivers include the audio and radio techniques mentioned earlier. Strictly audio techniques, such as loudspeakers, do not appear feasible or promising. A possible exception might be at toll plazas. Of the radio techniques, the low-power induction field radio appears the most promising for a localized pinpoint message and is well within the capability of the present technology. One of the advantages of the radio techniques is that an audio tone or a verbal message can have an excellent attention-getting quality, which will reduce the chance of a missed message.

Guidance

Guidance Aids

The simplest guidance aids are the various types of lane and roadside delineators. The previous NCHRP fog study (*1*) included a summary discussion of several studies of the devices in fog, including the use of various types of raised reflective markers and beaded reflectors. In general, the retroreflective types were found to be best at night, but provided little or no help in daylight. The use of edge marking was found to have little effect on vehicle placement in lanes, although edgemarking did give the driver a higher degree of confidence and, therefore, might help to reduce the possibility of driver disorientation.

Guidance aids using artificial lighting have been found to be more effective both by day and night. Finch (*25*) proposed the use of small lights as lane and roadway delineators and later tested the concept in the University of California fog simulator with positive results for both day and night fog (*26*). An installation of lights set into the road was tried on the Pennsylvania extension section of the New Jersey Turnpike. The lights were installed at each end of each lane-marker stripe. The intensity of the lights was adjustable to accommodate varying fog conditions. In terms of its effect on traffic operations, the lights are considered one of the most effective of the many highway fog countermeasures tried on the New Jersey Turnpike. The project was finally abandoned because of severe maintenance difficulties; the lights were made of a cast-iron housing with stainless steel covers. A combination of traffic and corrosion wore the cast iron to the extent that covers were torn off in subsequent snowplowing operations. The maintenance problems are not believed to be insurmountable because lights of this type have been successfully installed in airport runways subject to snowplowing operations for a number of years, although admittedly not subject to the same degree of wear-producing traffic.

When installed as lane delineators, the lights serve two functions. They provide an alternate source of the visual cues that help orient the driver, normally provided by the edge of the road and the painted lane delineators. Second, they provide some indication as to the relative density of the fog ahead. For best results, the intensity of the lights should be made variable and adjustable as a function of ambient light level and fog density (i.e., the Fog Index). This will aid in reducing glare and dazzle at night, particularly in light fog, and help reduce the possibility of a grossly misleading apparent visibility while still providing help in daylight fog. As can be seen from Figure 1, a light is visible for a considerably greater distance at night than during the day. Lamps with peak intensities of 600 cp are available; and such an intensity would be required for good visibility in bright daylight fog, whereas 20 to 30 cp could be more suitable for a 200-ft visibility fog at night.

Quite suitable for this type of guidance system would be an automatic control system having fairly simple logic such as that suggested for automatic control of warning systems. The control here is much less critical than with the warning systems because maintaining credibility is not a major factor. Multiple detectors might still be needed, however, if patchy fog is a possibility.

On the New Jersey Turnpike, the lamps were installed as lane delineators because drivers are conditioned to drive between lines and also in the belief that they would undergo less wear at the lane edges. Some initial thought had been given to installing the lights in the middle of the lanes with the vehicles straddling them. This would have the advantage of providing an indication of a blocked lane since vehicles would block the view of the lights ahead of it for following vehicles. Drivers could then adjust their speed as a function of midlane lights visible. This concept has a great deal of merit; however, matching the conditioning of the drivers with respect to the lane delineator was deemed more important.

An alternative was to install a supplemental series of lights down the center of the lanes. These supplemental lights should be of a different color than the lane delineator lights although they need not be spaced so closely as and need not be quite so bright as the lane delineator lights. One possible refinement to a lane marker light system is to progressively energize the lights at the recommended driving speed, forming a pacer system such that vehicles not synchronized in speed would periodically lose the aid of the guidance lights ahead of them.

A related type of guidance system is installed on the Pennsylvania Turnpike. It consists of a series of strobe lights mounted on the median barrier in a 1-mile section near Carlisle, Pennsylvania. In late fall and early spring this area frequently experiences fog while surrounding areas are clear. Drivers can therefore enter fog quite unexpectedly and, as a result, the location has a poor fog accident record. The installation consists of a string of strobe lights spaced about 100 ft apart interconnected to flash in sequence in the same direction as the traffic flow. Separate strings are used in each direction, the lamps are hooded and mounted so that only drivers traveling in the proper direction can see the direct light. The lights, which were developed by the Air Force for use on temporary landing strips, are line-powered. The initial experimental installation used a Videograph to energize the lights with the occurrence of fog. The experience with the initial experimental system was generally favorable, although the temporary nature of the installation caused considerable difficulty in keeping the system operational. The problems encountered were largely caused by mechanical damage to interconnecting wiring, but the strobe lamps and the Videograph proved to be quite reliable. Because of the favorable performance of the initial system, a permanent system has been installed. The cable between the lights was buried and strobe lamps were attached through a quick-disconnect connector so that if the median guard rail is struck and the strobe light is displaced and damaged, the connection to the lamp will be broken, and the remainder of the system will remain intact and operational. In the permanent installation, the Videograph was replaced with a Fumosen fog detector, primarily on the basis of cost and the fact that the continuous output provided by the Videograph was not required; a presettable threshold switch closure was sufficient.

Because this type of installation provides delineation of only the center median, drivers will not have as much help with respect to lane placement as they would with lamps mounted as lane delineators. Strobes, on the other hand, can be seen farther through the fog and, because of their short duration, cause less difficulty with glare and dazzle for a given brightness. Also, the initial cost of installing the system will probably be lower for the strobe system. The relative over-all effectiveness of the two systems is a little difficult to assess at the present time because the experience with the strobe system to date is insufficient to permit an accurate comparison.

Advanced Guidance Systems

Three categories of advanced guidance systems were considered: automatic guidance systems, anti-collision systems, and block guidance systems. In recent years some work has been done on the fully automatic guidance type primarily as a high-speed ground transportation system and as a means of increasing highway capacity. A completely automatic guidance system would obviate the highway fog problem because nonvisual sensors would be used. The cost of such a system is sufficiently high that it will probably never be justified solely as a highway fog countermeasure.

Anti-collision systems are of another advanced technology area being pursued in a context other than primarily as a highway fog countermeasure (because most rear-end collisions occur during periods of clear visibility). A sensor to detect obstructions in the roadway ahead would be extremely valuable in preventing or minimizing the occurrence of accidents in poor visibility. The sensor would not solve the problem of maintaining lateral control of the vehicle. However, lateral control is generally not the major problem, and some of the guidance aids previously discussed can help considerably in that area. Radars have been primarily considered for this application and for adaptive speed control systems, which in effect are versions of an automatic control system (*13*). Experimental radars having a range of about 300 ft have been built. This would correspond to safe stopping speeds of about 46 and 53 mph for wet and dry pavements, respectively.

These speeds can be increased, or the required detection range reduced, if the radar is used to directly operate the braking system. The radar operation eliminates the perception and reaction time allowances. One of the major problems associated with a straight radar is lack of sufficient discrimination. A highway sign can return a much larger signal than many potentially more dangerous targets. This is especially troublesome because of the difficulty in confining the beam to the roadway, particularly on two-lane roads with curves. There is also a problem of interference and blinding from radars on opposite-direction vehicles. The inclusion of a passive frequency-doubling reflector on the back of vehicles has been proposed as a solution to these problems. The radar would then respond only to reflector-equipped vehicles. It has been estimated that such a radar could be built within five years to sell for between $50 and $100. In view of the U.S. Department of Transportation's interest and pressure for such safety devices, their feasibility appears favorable. They will, however, have to be viewed more as a long-term solution to the highway fog problem.

Lidars (light radars) are another potential collision warning device. They have the advantage in that the beam can be more precisely shaped. Although light is attenuated to a much greater degree than radar waves, experimental lidars used as probing fog detectors have demonstrated that penetration beyond the visibility range is possible. The cost of these devices is much greater than radars at the present time, but the technology is so new that accurate cost forecasting for the future is nearly impossible.

The block guidance system can be considered to be a form of headway control system, which also has potential as a highway fog countermeasure. In essence, a block guidance system divides the roadway into sections or blocks, detects which blocks are occupied, decides whether it is safe for a vehicle to proceed, and then communicates that information to the vehicles and their drivers. Block systems have had their counterparts in the rail industry for many decades. There the problems are somewhat simpler because the vehicles are laterally confined to a particular track, making detection simpler. Also, the traffic volume is much lower, thus allowing larger block size and less equipment. Many of the same techniques are applicable. The problems of higher volumes, shorter headways, and shorter stopping distances leading to small natural block sizes, with an attendant increase in required hardware, can conceivably be eased by operating the system with "coupled" vehicles in platoons or convoys of vehicles.

The key to the successful operation of a block control system is to keep track of which blocks are occupied. In the early railroad systems, this was accomplished by impressing a voltage between the two rails in each block; as a train entered a block, it shorted out the voltage. With motor vehicles, the detection is much more complex because the roadway is not inherently a transmission line, as is a railroad track. Detectors commonly used with motor vehicle traffic include induction loops buried in the pavement, overhead and side-mounted sonic detectors, magnetic detectors and magnetometers buried in the pavement, pressure plates in the pavement, and electromagnetic pulse and other radar detectors. As presently used, all of these detectors are normally limited-area detectors. The loop detectors, sonic detectors, and electromagnetic pulse detectors are normally considered presence detectors, the others are motion detectors, which detect the passage of a vehicle but not its presence. Radar presence detectors could be built, but are not currently available. Of the presently available types, only the loop detector type is capable of detecting the presence of vehicles over a larger area, and it appears to be the most suitable of the commonly used vehicle detectors. The maximum area that could be covered with a single detector is not precisely known, but extrapolation of available data indicates that some of the newer high-sensitivity detectors should be capable of operating successfully with loops 500 ft long with single-lane coverage.

Ideally, the sensor should be able to continuously detect the presence of a vehicle anywhere within a block. An alternative procedure would be to count vehicles in to and out of a block. Potentially this could be accomplished with all of the vehicle detector types mentioned. An alternative is the use of an automatic vehicle identification (AVI) system. An AVI system would have the advantage of providing a tag for each vehicle to reduce the possibility of confusion from count errors. One of the major sources of error with the present detectors arises fom vehicles being between lanes when they cross the detectors and being counted as two vehicles. An AVI system allows the elimination of these duplications. Also, if a vehicle is somehow missed in leaving one section, it could be picked up farther downstream and removed from the block count. There is no assurance that AVI systems will become sufficiently commonplace in the near future so that all or even a large percentage of the vehicles on the road will be equipped with the passive transducer required. In all probability they will be initially installed on buses and trucks for automatic toll collection purposes. The Port of New York Authority is about to undertake an operational evaluation of such a system. When equipped vehicles become sufficiently common, it may be feasible to install a guidance system using AVI detection with access denied to vehicles not properly equipped.

Passing-aid studies funded by the Department of Transportation are also directly pertinent to headway control systems. The requirements are sufficiently close that a successfully operating passing-aid system can be readily modified to serve as a block guidance or headway control system with very little or no additional hardware required; the primary differences are in the control algorithms and logic used. The technical feasibility of a block guidance or headway control system and the passing aid should therefore be comparable.

The use of a cooperative system, either active or passive, may be feasible and possibly could be combined with communications to the vehicle. One passing-aid concept combines the detection and communication functions. In this system, a standard induction loop detector was modified to amplitude modulate the carrier signal. The vehicle then carried a tuned sensing coil that picked up the signal when the vehicle passed over the loop. The presence of modulation was used to transmit the "safe to pass" information. The tuned pickup coil has the incidental effect of making the vehicle somewhat easier to detect.

The control system can have varying degrees of sophistication. The complexity is influenced to a great extent by the characteristics of the detector used. One of the simpler systems, a form of local control, is applicable with a direct presence detector. Entry into a block, or group blocks, immediately before an occupied block is prohibited by signal. The number of blocks in a group is dependent on the size of a block relative to the distance required for stopping the vehicles. A slow warning signal could also be provided in the next preceding block(s).

For the sensors that require a more sophisticated processing to determine the presence of a vehicle within a block, a computer at a central location is more advantageous (as compared to somewhat simpler but duplicated processing equipment distributed in the field). In this case, outputs of the detectors would be transmitted to the central location, and the signal commands would be returned from the central location over some type of data link.

One interesting variation in the control algorithm is the use of speed data derived from the sensors (as by measuring the time required for a vehicle to go between two detectors) to predict when the vehicle should exit the block as an aid to keeping track of the presence of vehicles within the block. A vehicle changing lanes could then probably be identified, for example. The speed information could be used to make the number of blocks for which entry is prohibited a function of speed of the leading vehicle (taking advantage of the fact that a vehicle does not stop instantly), thus increasing the capacity of the road. This would not be feasible unless the block size were smaller than the stopping distance.

Communication with the driver can be made by means of signal lights, by induction radio messages for vehicles so equipped, and conceivably by means of one of the various forms of variable-message signs. Signal lights are the most likely.

Roadside variable-color signals are one form of signal lights. However, they may not be readily seen from the inside lanes of a multi-lane highway, and all lanes would have to be controlled as a single block, instead of each lane individually. If the blocks are of larger size and platoons of vehicles are to be handled, treating all lanes as a single block is probably preferable even though individual detectors may be required for each lane. The signal lights can be mounted overhead, in which case individual lane control is simplified.

Signal heads may be required at multiple locations within a block if the block sizes are large, because a vehicle may not be able to stop within sighting distance of the signal. In this case the vehicle would overshoot, and the driver would not know when it would be safe to proceed, particularly during daylight when lights are least visible. With smaller block sizes where the protected zone is several blocks long, the problem is less serious.

Lights set in the roadway, such as were suggested as a guidance aid, could be used as block control signals. Where individual lane control is desired, they could be set in the center of the lanes. Multiple colors could be used in the conventional manner. Another possibility is using single-color lights spaced sufficiently that, when energized, a light would always be visible ahead. In this latter case, the visibility of the control light ahead would be the criterion for proceeding. This system would tend to be fail-safe, both in terms of a burned-out lamp and when an intervening vehicle blocks visibility.

CHAPTER THREE

INTERPRETATIONS AND CONCLUSIONS

INTERPRETATIONS

Two of the major work areas in this study have been (a) development of analytic models of visibility through fog and (b) on-road tests in which measurements were made of actual sighting distances from a moving vehicle in fog. The analytic models were, in effect, the application and extension of earlier work now widely and generally accepted, particularly Allard's law and Koschmieder's work in daylight visibility. One of the purposes of the on-road testing programs was the evaluation of the models because of the extensions and extrapolations involved in the models, and because there were a large number of parameters for which values needed to be established and validated.

To facilitate the merging of the on-road test data with the analytic models, data from the on-road tests were segregated to correspond approximately with the analytic model cases and were plotted along with the appropriate analytically derived curve in Chapter Two. As can be seen from the figures, there is a good deal of scatter in the data. This scatter is attributable to a number of sources. One is inherent to the vision of human observers, on both a run-to-run basis and from person to person. These variations are clearly evident in the figures. For most of the runs, two data points were taken for each run. The two data points are generally identifiable as two points having exactly the same fog density. There were statistically significant differences when comparing the sighting distances of the test personnel. However, in most cases the run-to-run variations exceeded the person-to-person differences. In addition to the random variations normally experienced in physiological experiments, visual search effects may have contributed. The reason is that the location of the target within the search pattern, at the time it first comes within visible range, is random and therefore may contribute to the randomness in the time before the target enters the foveal region of the eye.

Another contributor to scatter is the uncertainty of fog density determination. The Videograph sampled a small patch of the fog through which the target must be sighted, and the fog, as expected, was not homogeneous during the tests. Although an attempt was made to arrive at the best estimate of fog density averaged over the sighting distance by taking into account the various Videograph readings, it remains just that—a best estimate.

In most of the figures, the test data show a trend similar to the predicted sighting distances, except for daylight with black targets. The predictions are, for the most part, conservative with respect to the data means, being equivalent to approximately an 85-percentile curve. For daylight data with the black target, at the denser fog levels, below 500 ft, the sighting distances were greater than the equivalent sighting distances for the white target as had been expected because the black target normally has a greater contrast against a fog background. With lighter fogs, however, the sighting distances did not increase correspondingly with the prediction, and sighting distances for the white target were as great or greater. A possible explanation is that as the visibility increased the fog itself was no longer the predominant background, and the intrinsic contrast of target against background was progressively smaller as fog density decreased. The background in the absence of fog was typically dark grass and trees and only occasionally was it the sky horizon. An incident that tends to verify this hypothesis occurred on one of the daylight runs. The car used to transport the target (light green in color) had not been removed prior to the test and was identified before the target was detected, even though it was a few feet beyond the target and partially blocked by the target. If this hypothesis is correct, the models can still be used because, from a practical viewpoint, if the fog does not obscure the background, it is not likely to obscure a vehicle either. As can be seen, all sighting distances for light fog were 400 to 500 ft or greater, which is a sufficient stopping distance for automobiles traveling at speeds of up to 50 to 60 mph.

In terms of the absolute accuracy of the data points, the fog density determination is undoubtedly the measurement most subject to error. The major uncertainty is associated with the nonhomogeneity of the fog. That source, however, can be expected to be essentially random with little bias. There is an uncertainty associated with the calibration of the Videograph. Based on the results of visual calibrations and the comparison of on-road test data with the curves derived from the analytic models, the calibration curve used was probably slightly low. The effect of this bias is in the direction of raising the probability that the target will be seen by the given sighting distance and should be small. Also, for any system using an instrument fog measurement, calibration of the instrument in actual fog will tend to take out the effects of the bias, and the magnitude of the bias is not large compared to the fluctuation from nonhomogeneous fog commonly encountered in practical systems.

CONCLUSIONS

1. Visual range in fog can be quantified as a function of the fog level (expressed in terms of the extinction coefficient), but ambient background brightness and target characteristics must be taken into account.

2. The relationship between visual range and fog density may be summarized in terms of a fog visibility index which can be expressed in terms of an instrument measurement of fog density together with ambient background brightness as a parameter. The light conditions can be simplified to

day, dawn, and night conditions, and accounted for by modification of two parameter constants in the expression.

3. Several different types of fog measuring instruments are available. Most of the types suited to highway fog use measure some form of fog scattering function or coefficient rather than extinction coefficient, and are consequently limited in accuracy for all types of fog. They can be calibrated, however, to better accuracy in a limited number of fog types as generally encountered at a given location.

4. Currently available instruments are not entirely satisfactory because they are *in situ* instruments that sample a limited volume and can therefore be grossly inaccurate in the presence of patchy fog and fog banks. Multiple-instrument installation can improve the situation, however. Such instruments are not mass produced in large quantities, and prices are therefore relatively high.

5. Driver behavior in fog can be successfully simulated in a driving simulator. This simulator can be a useful tool in investigating highway fog problems. It should be particularly valuable in some of the human behavior and driver reaction aspects, particularly those situations that would be too hazardous to test directly.

6. To be effective, each highway fog countermeasure must be tailored to a specific locality to account for the characteristics of the fog normally encountered, the type of highway, and the character of its use during periods of fog.

7. For the near term, variable-message warning and speed signs show the most promise for fog warning systems. The operation of the signs must be prompt, conservative, and realistic to maintain credibility and effectiveness.

8. The use of "pancake" lights, in the roadway, or median lights may prove effective as guidance aids. Care should be exercised, however, that their use does not encourage overdriving the visibility.

9. In difficult fog problem locations and conditions, an effective fog countermeasures program should make use of multiple efforts, including coordinated comprehensive educational and publicity programs.

10. The simpler forms of the advanced guidance systems, such as the block guidance systems, are technically feasible at the present time. Although their costs appear to be significant, their implementation as a part of multipurpose systems (e.g., surveillance and control, incident detection, fog) may make them entirely practicable.

CHAPTER FOUR

APPLICATIONS

The fog index is defined and associated parameters in the form of analytic expressions are given in Chapter Two. The fog index will find its greatest use in relating instrument visibility readings to sighting distances or safe stopping speeds and in the use of it as a criterion for fog countermeasures actions. It is defined in terms of photometric visibility, such as defined in Eq. 2, and ambient background brightness. Visibility is used because that is how most fog instruments are calibrated.

The parameter values selected for the fog index are conservative and should result in sighting distances greater than predicted by the fog index for more than 85 percent of the sightings. A similar conservativeness exists in the relationship between safe stopping speeds and sighting distances. The safe stopping speeds may consequently be on the slow side of what some drivers consider reasonable; it may therefore be necessary to use somewhat greater speeds when setting limits for warning systems to maintain credibility and minimize speed dispersion.

The fog index can be used in computer-operated warning and guidance systems in its analytic form, either as it is or in some alternate or approximate form that simplifies or speeds computation. For warning and guidance systems or other applications not making use of a digital computer, the fog index can be used in setting the various decision threshold levels of the analog or logic circuits used for control. When decision and control is manual, or if manual override is to be exercised, curves or tables are probably the most convenient forms in which to use the fog index.

An alternate formulation of the fog index, shown in Figures 7 and 8, directly relates the safe stopping speed to the instrument visibility. This relationship may be more useful with manually controlled systems. These figures, as well as Figures 1, 2, 4, and 5 are plotted with the "photometric visibility" or instrument-measured fog density as the independent variable and the characteristics of the human driver accounted for in the predicted visual range. If fog density is measured by a subjective human observation, care should be taken in the use of the figures so as not to account for the human observer effects more than once.

When using the fog visibility index, it should be noted that, although the fog index and safe stopping speeds appear as unique functions of fog density and ambient background brightness, the actual sighting distance is a prob-

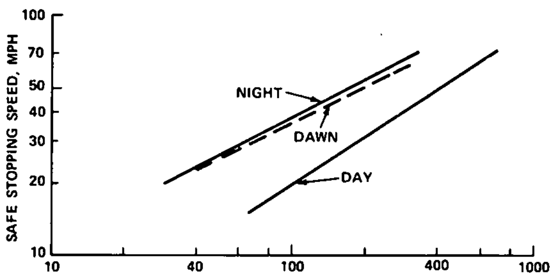

Figure 7. Safe stopping speed—dry pavement, level ground.

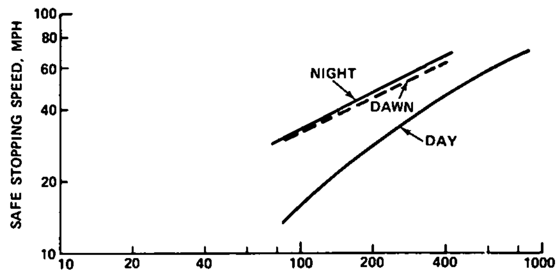

Figure 8. Safe stopping speed—wet pavement, level ground.

ability function due to the randomness associated with human vision and fog characteristics. The curves may be considered as representative of 80 to 90 percentile and therefore individual sighting distances may be in excess of, or occasionally less than, that predicted by the fog index.

A number of different highway fog countermeasures were mentioned as possibilities in Chapter Two and are summarized in Appendix E, which is included for general reference. The primary emphasis of the study concerned warning and guidance techniques. The fog problems, particularly safety problems, are most severe on the higher speed freeways and expressways, which is where the major countermeasures emphasis was placed. The character and the nature of the problems, however, has wide variability due to differences in the types of fogs, their typical durations, time of occurrence, size of the fog area, and its uniformity, as well as differences in the type and use of the highway, the typical traffic volumes and densities during fog periods, and whether it is a long-distance rural highway where many drivers are typically unfamiliar with the roadway, or a suburban highway where the same drivers frequently traverse it. Wide variability compounds the problem. At the present time, there is no completely satisfactory solution to the highway fog problem and much remains to be learned. There are, however, a number of potentially effective measures that can be instituted. In the selection and application of these measures, the needs and characteristics of the specific problem area should be carefully analyzed. The various fog countermeasures and warning and guidance systems discussed can then be reviewed with specific requirements and characteristics of the particular location in mind.

CHAPTER FIVE

SUGGESTED RESEARCH

In the design and application of highway fog warning systems, several areas have been identified where further studies, many of which deal with driver behavior, will be of potential benefit.

Comparatively little is known of driver behavior in fog in terms of speed distribution and headways other than at a few locations and taken over a limited time period. The primary sources of data are the California Reduced Visibility Study (*2*) and the previous NCHRP study (*1*). The Oregon fog project (*12*) is in the process of collecting such data, but little has been obtained to date. The cost of establishing test areas to monitor traffic over an extended time period specifically for a highway fog study is considerable. However, the incremental cost of accumulating such data on a freeway in conjunction with an existing surveillance and control system would be much less. The surveillance and control system being installed on the northern end of the New Jersey Turnpike is an ideal example. The system is instrumented to make direct speed measurements and vehicle classifications at a number of locations and can provide mean speed estimates approximately each ½ mile. The additional equipment required to accumulate driver behavior data in fog is the installation of fog-measuring and data-recording devices at several strategic locations.

Another area that should be pursued in conjunction with such a project is consideration of how speed and fog instrument data should best be combined for use in warning or guidance system control algorithms. The study should also include (a) consideration of how the instrument data can best be smoothed (linear or nonlinear, decay rates) and (b) correlations made with observer estimates of the visibility and fog density.

Further study is also needed to determine the factors required to ensure the unambiguous reception of a warning message by the driver and the factors required to maintain warning-message credibility. This latter area is being considered in part, particularly with respect to signs, in a study just initiated by the Oregon State Highway Division under FHWA sponsorship.

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APPENDIX A

ANALYTIC MODEL DEVELOPMENT AND FOG MODEL PARAMETERS

CASE 1, DAY; NATURAL AMBIENT ILLUMINATION

This set of conditions will be treated using the well known Koschmieder theory of the air light which, for the purpose of continuity, will be briefly summarized here. Middleton (3) has discussed the theory in some depth.

According to Koschmieder, if an object having intrinsic luminance B_0^* is viewed by an observer a distance r removed, the apparent object brightness B_0 is

$$B_0 = B_0^* e^{-\sigma r} + B_h (1 - e^{-\sigma r}) \qquad \text{(A-1)}$$

where B_h is the brightness of the horizon sky and σ is the extinction coefficient of the attenuating medium. The first term is the attenuation of the intrinsic brightness by the intervening medium. The second term is added luminance contributed by scattered, ambient illumination; the so called air light of the intervening medium.

In order to see an object, the observer must be able to distinguish it from its background. A similar expression can be written for a naturally illuminated background having intrinsic brightness B_b^* (at the location of the object). The apparent background luminance is

$$B_b = B_b^* e^{-\sigma r} + B_h (1 - e^{-\sigma r}) \qquad \text{(A-2)}$$

The factor determining the object visibility is called the contrast ratio, defined by

$$C = \left| \frac{B_0 - B_b}{B_b} \right| = \left| \frac{B_0^* - B_b^*}{B_b^* + B_h (e^{\sigma r} - 1)} \right| \qquad \text{(A-3)}$$

In the case of a very dense fog, the background becomes the fog itself, i.e.

$$B_b^* = B_h$$

A-2

Therefore,

$$\left| \frac{B_0 - B_b}{B_b} \right| = \left| \frac{B_0^* - B_h}{B_h} \right| e^{-\sigma r} \qquad \text{(A-4)}$$

or

$$C = C^* e^{-\sigma r}$$

If the observer's threshold of contrast discrimination is ϵ, then the visual range is

$$V = -\frac{1}{\sigma} \log_e \frac{\epsilon}{C^*} \qquad \text{(A-5)}$$

For the classic case of a black object against the "horizon sky" and $\epsilon = 0.02$, the visibility is expressed by

$$V = \frac{3.912}{\sigma} \qquad \text{(A-6)}$$

CASE 2, NIGHT; AUTOMOBILE LIGHTS ON

For this set of conditions it is assumed that the object is the rear lighting of an automobile. The observer is the driver of a following car with its headlights on and oriented parallel to the road surface. Both automobiles are traveling through a uniform fog. No additional ambient illumination is considered. The geometry of the problem is represented in Figure A-1. The points D, H, and T represent driver, headlight, and taillight respectively. In reality, point D is several feet behind point H, but this distance is quite small with respect to the separation between cars and is neglected. The driver's eye level is a distance h above his headlights and he is a distance r behind the preceding car. It is assumed that both headlights and taillights are the same height above the road bed. It is further assumed that the taillights are the only visible evidence of the preceding vehicle; thus the driver's line of vision is at an angle ϕ below the horizontal. The angular spread of the headlights will be represented by α, and the beam pattern is assumed symmetrical about the optical axis.

Beginning the development of the model in its simplest form, consider the illumination from the taillight to the driver and assume that it subtends an angle such that it may be

A-3

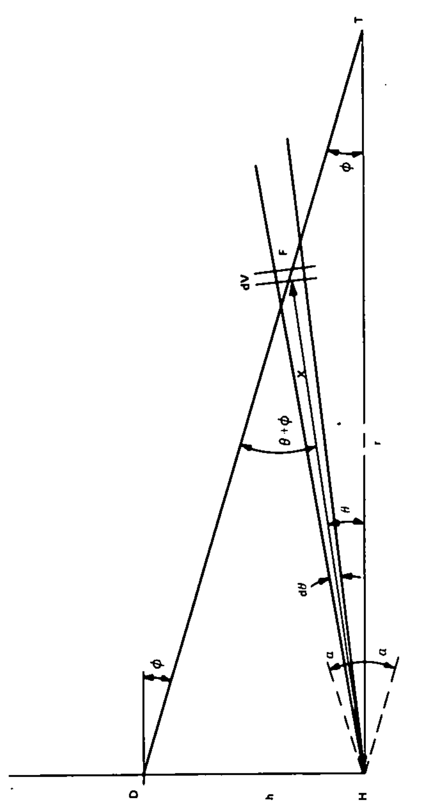


Figure A-1. Target and Observer with Headlight Backscatter.

A-4

considered as a point source of light. The apparent intensity of the taillight as viewed through the fog by the driver is expressed by Bouguer's law as

$$L_{T_r} = L_T e^{-\sigma r} \qquad \text{(A-7)}$$

where L_T is the actual taillight intensity, r is the separation distance, and σ is the extinction coefficient of the fog. According to Allard's law, the illumination at the driver's eye is

$$E = L_{T_r} r^{-2} = L_T r^{-2} e^{-\sigma r} \qquad \text{(A-8)}$$

As in the previous case, consider the condition of a dense fog such that the background against which the taillight is observed is the fog itself, as illuminated by the automobile headlights. A similar problem, that of a searchlight beam, has been treated in the literature by Hampton (14) and by Chesterman and Stiles (15). The approach of Hampton is followed herein since it is more readily available.

Considering the automobile headlight and Bouguer's law, the intensity at range r is

$$I_H = I_\theta e^{-\sigma r} \qquad \text{(A-9)}$$

Consider now the illumination of a differential volume of fog at point F, a distance x from the headlight. This volume is illuminated by a differential beam of light $d\theta$ wide and located an angle θ from the horizontal. The angular intensity distribution of the headlight will be represented by

$$I_\theta = I_{H0} e^{-K(\theta - \delta)^n} \qquad \text{(A-10)}$$

where I_{H0} is the central axis intensity, K and n are constants, and δ is the angle the axis of the lamp subtends with the horizontal. (Preliminary measurements indicate this to be a reasonable approximation to the distribution.) Thus, by Allard's law, the illumination of this volume is

$$E_F = \frac{I_\theta e^{-\sigma x}}{x^2} \qquad \text{(A-11)}$$

A-5

Introducing a volume scattering function $\beta'(\theta)$ and using the notation of Middleton (3), the apparent intensity of the light scattered from the differential volume at D is

$$dI = E_F \quad \beta'(\pi - \phi - \theta)\, e^{-\sigma y}\, dV \qquad \text{(A-12)}$$

where y is the distance from point F to the driver at D. The apparent brightness of the differential volume is

$$dB = \frac{dI}{dA}$$

where dA is the cross-sectional area of the differential volume as viewed from D.

$$dV = y\, d\phi\, dy\, dz \qquad \text{(A-14)}$$

and

$$dA = y\, d\phi\, dz \qquad \text{(A-15)}$$

where z is the dimension normal to the plane of Figure A-1. Combining the preceding equations,

$$dB = I_\theta \frac{e^{-\sigma x}\, e^{-\sigma y}}{x^2} \quad \beta'(\pi - \phi - \theta) \quad dy \qquad \text{(A-16)}$$

The background brightness is the summation of the brightness from each of the differential volumes along the line of sight, therefore,

$$B_b = \int_{y_{min}}^{\infty} I_\theta \quad \frac{e^{-\sigma(x+y)}}{x^2} \quad \beta'(\pi - \phi - \theta)\; dy \qquad \text{(A-17)}$$

where y_{min} is the distance from D to the intersection of the upper edge of the headlight pattern with the line of sight. Making a change of variable and introducing the headlight model of equation (A-10),

$$B_b = I_{HO} \int_{-\phi}^{\alpha+\delta} \frac{\beta'(\pi - \phi - \theta)\; e^{-k(\theta-\delta)^n}\, e^{\left[-h\sigma \cdot \frac{(\cos\phi + \cos\theta)}{\sec(\phi+\theta)}\right]}}{h\cos^2\theta} \cos\phi\, d\theta \qquad \text{(A-18)}$$

The threshold intensity at which the taillight becomes visible against the illuminated fog background is taken to be of the form

A-6

$$E_T = K_1 \; (1 + K_2 \sqrt{B_b})^2 \qquad \text{(A-19)}$$

The basis for this, and the values of the two constants K_1 and K_2 will be discussed later in this appendix when the fog model parameters are considered. Equating the threshold intensity to the taillight intensity at the driver's eye of equation (A-8), and replacing the distance (r) with visual range (V), yields an expression containing the visual range

$$I_T \; \frac{e^{-\sigma V}}{V^2} = K_1 \; (1 - K_2\sqrt{B_b})^2 \qquad \text{(A-20)}$$

This is the equation that was solved by numerical methods as a part of the computer simulation using equation (A-18) for the background brightness. It should be noted that equation (A-18) for the background brightness (implicitly through the angle θ) contains the visual range since $\tan\phi = \frac{h}{V}$.

CASE 3A, DAY; AUTOMOBILE LIGHTS ON, LOW-LEVEL AMBIENT

For this set of conditions, the model of Case 2 will be used with the addition of ambient illumination on the fog. As shown by Bennett (5), the background brightness contributed by fog-scattered sunlight can be expressed by

$$B_s = \int_0^d E_s \quad \gamma\, e^{-Ksx} dx = \frac{E_s\, \gamma\, (e^{-Ksd} - 1)}{-Ks} \qquad \text{(A-21)}$$

where E_s is the insolation impinging on the fog and γ is a scattering distribution function per unit depth of fog. The function γ depends on the fog particle size distribution and density, the angular scattering distribution, the distribution of insolation, and the zenith angle of the sun. The upper limit of integration d depends on the line of sight. The major problem in this model is the evaluation of γ.

Since no tabulated values of this function seem to be available and the complexity of the function which is dependent, as are so many other variables, empirically derived values will be used instead. In actual practice, only the lower levels of ambient light need be

A-7

considered, since with the higher ambient levels the backscatter contribution of the headlamps is negligible and the body of a vehicle is detectable at considerably greater distance than the taillight with the taillight intensities presently used.

INSTRUMENT VISIBILITY ALTERNATE

An alternate to the model developed for Case 2 and Case 3A has been developed from a radiometric viewpoint. This will be referred to as radiometer visibility. In Figure A-2, I_T, I_H, and Obs. represent the taillight, headlight, and observer respectively. Since r (the separation distance) is so much greater than the observer's elevation above the headlight, it is assumed that the observer views along a path coincident with the headlight beam. This is probably most applicable to a high-beam situation. Again, from Allard's law, the flux density at Obs. from the taillight is

$$E_T = I_T\, r^{-2}\, e^{-\sigma r}$$

where σ is the extinction coefficient including both scattering and absorption losses. A radiometer is a flux detector, therefore it sees

$$F_T = A_r\, I_T\, r^{-2}\, e^{-\sigma r} \qquad \text{(A-22)}$$

where A_r is the effective radiometer aperture. Considering the elementary scattering volume dsdr where ds is the cross-section area, the impinging flux is

$$dF(\theta, r) = I_H(\theta, 0)\, r^{-2} e^{-\sigma r}\, ds \qquad \text{(A-23)}$$

The intensity of the backscattered radiation at the scattering volume is

$$dI_B(\phi, r) = I_H(\phi, 0)\, r^{-2} e^{-\sigma r} ds \cdot \beta_\pi\, dr \qquad \text{(A-24)}$$

where β_π is a backscattering distribution function. The flux received by Obs. from volume dsdr is

$$dF_B(\phi, r) = I_H(\phi, 0)\, r^{-2} e^{-\sigma r} ds \cdot \beta_\pi\, e^{-\sigma r} \frac{A_R}{r^2}\, dr \qquad \text{(A-25)}$$

A-8

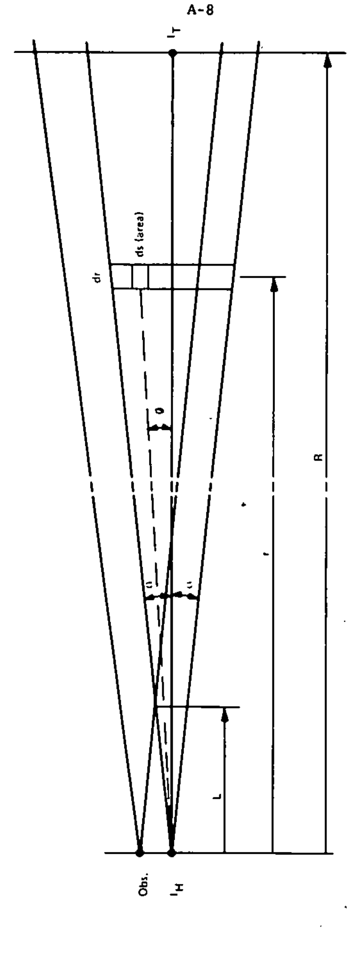


Figure A-2. Radiometric Model with Headlight Backscatter.

A-9

The total background flux detector by Obs. is then

$$F_B(\phi) = \int_L^\infty I_H(\phi, 0)\,\beta_\pi \frac{A_R}{r^4} e^{-2\sigma r}\, ds\,dr$$

Assume that the headlight beam shape characteristics are in the form

$$I_H(\phi, 0)\,ds = I_H(0,0)\,e^{-a\phi^n}\,ds, \text{ and } I_H(0,0)\int e^{-a\phi^n}\,ds = \overline{I_H(\phi, 0)\,s}$$

where $s = \pi r^2 \alpha^2$

then

$$F_B = \overline{I_{H(\phi,0)}}\,\beta_\pi\, A_R\,\alpha^2 \int_L^\infty e^{-2\sigma r}\, r^{-2}\, dr \qquad \text{(A-26)}$$

The usual criterion for radiometric discrimination between signal and noise is based on the difference between signal power and noise power. Stated in words, a signal is just detectable when the difference between the noise power and signal power is equal to the root mean square of the noise power, or

$$F_T - F_B = \text{RMS}\,(F_B)$$

The RMS is often taken as 1/6; and

$$F_T - F_B = \frac{1}{6} F_B$$

will be used as our radiometer direction criterion. From equations (A-21) and (A-25) we obtain

$$A_R I_T R^{-2} e^{-\sigma R} = \frac{7}{6}\frac{4\pi}{I_H(\phi, 0)}\beta_\pi \quad A_R\,\alpha^2 \int_L^\infty e^{-2\sigma r}\, r^{-2}\, dr$$

or

$$\frac{24}{7}\frac{I_T}{\overline{I_H(\phi, 0)}\;\beta_\pi\;\alpha\, 24\pi} = R^2 e^{\sigma r}\int_L^\infty e^{-2\sigma r}\, r^{-2}\, dr \qquad \text{(A-27)}$$

where r is the distance to the taillight when it is just visible.

A-10

If Obs. is not a radiometer but instead a human observer, we must use an appropriate criterion, e.g., equation (A-19).

Setting the intensity at the observer's eye to the visual threshold level, produces

$$E_T = I_T R^{-2} e^{-\sigma R}$$

It remains to find an expression for B_B based on this model. Assuming that

$$\sum_{-a}^{+a} \frac{I_B(\emptyset)}{\Delta s} = \frac{\overline{I_B(\emptyset)}}{r^2\,\alpha^2}$$

the brightness of an elementary layer at range r is

$$dB = \left(\overline{I_H(\emptyset)}\; r^{-2} e^{-\sigma r}\right)\left(\beta_\pi dr\right) \qquad \text{(A-28)}$$

where $\overline{I_H(\emptyset)}$ is an appropriately weighted mean beam intensity. The apparent brightness to the observer is

$$dB = \overline{I_H(\emptyset)}\, r^{-2} e^{-\sigma r}.\ \beta_\pi e^{-\sigma r}\, dr$$

and the total background brightness is

$$B_B = \int_L^\infty \overline{I_H(\emptyset)}\;\beta_\pi \frac{e^{-2\sigma r}}{r^2}\, dr \qquad \text{(A-29)}$$

By our criterion for detection,

$$I_T R^{-2} e^{-\sigma R} = K_1\left(1 - K_2\sqrt{\overline{I_H(\emptyset)}\,\beta_\pi \int_L^\infty \frac{e^{-2\sigma r}}{r^2}\, dr}\right)^2 \qquad \text{(A-30)}$$

when the taillight is just visible by a human observer. After appropriate values for the variables and parameters are inserted, the expression can be solved for the threshold range R.

A-11

MULTIPLE-HEADLIGHT CONSIDERATIONS

The highway fog models, in all explicit appearances, seem to take into consideration only one headlight and the figures used in the development indicate a coplaner configuration; i.e., the target, headlight, and observer all lie in the same initial place. Naturally, we all know that automotive vehicles have at least two headlights. The headlight intensity is used in the computation of background luminance which, in physical terms, is luminous power per unit solid angle per unit area. This is specified by the angular intensity distribution of the illuminating source. Since the headlights are displaced horizontally, the effect of the additional headlights is to increase the horizontal coverage without increasing the intensity of the previously illuminated volume except at the greater distances where beams start to overlap. For our purposes, we have assumed that the primary effect of the multiple headlights is to reduce the variations in beam intensity horizontally in front of the car. Thus, there appears no doubling of on-axis intensity or accounting for overlap effects in the models. Expansion of the model to three dimensions and accounting for the horizontal beam shape of each beam and the overlapping of the beams along the line of light between the observer and the target would be the correct approach. The result would be an increase in background luminance contribution from the overlap region. The horizontal displacement of the driver from the headlight will tend to reduce the background luminance contribution from closer in. The magnitude of these effects does not, at this time, appear to warrant a change to the more complex model; we would expect to see the most noticeable changes for low-extinction coefficients (good visibility). Under poor visibility conditions, the major backscatter contributions are the beams from close in, and overlapping does not appear to appreciably affect the background brightness from headlights.

THRESHOLD ILLUMINANCE AND CONTRAST RATIOS

One of the most important factors affecting the validity of the analytic models is the choice of proper threshold criteria. The initial trial computer runs for Case 2 used

A-12

$$E_t = T_n (B_b)^m$$

with constants of $T_n = 1.07\ (10^{-7})$ and $m = 1/2$. These constants are based on a criterion attributed to Langmuir and Westendorp. Hampton (4) had found this criterion sufficient for foveal vision when the background exceeded 10^{-3} candle/ft^2, and used it successfully in modeling searchlight-aided acquisition. The Langmuir and Westendorp criteria, developed with respect to astronomical observations, is supported by data collected by Blackwell (6) and by Knoll, et al. (7). The low background level portion of the curves, presented by Middleton (3), are closely approximated by $E_t = 1.08 \times 10^{-7}\sqrt{B_b}$. These data, however, deviate from this law at higher background levels. Trial runs of the highway fog simulation models, using this criterion, produced results that were quite low with respect to Cornell Aeronautical Laboratory (1) data. Background luminances computed were on the order of 10 candles/m^2. Lindae (11) suggests using a value of 2 candles/m^2 for all fog conditions. Since the background luminance produced by backscattered headlight illumination is a function of the fog density, Lindae's value cannot possibly hold for all conditions, but is indicative of the magnitude of the background. For the models, it was assumed that background luminances produced by backscattered headlight illumination in fog are on the order of 0.1 to 100 candles/m^2 depending on the prevailing fog density. In order to get a better fit in the background brightness range of Case 2, a threshold constant of $T_h = 5.41\ (10^{-8})$ was subsequently adapted based on the data of Knoll, et al. (7).

When the computer program was expanded to include Case 3A, the form of the threshold criterion was changed since the brightness of the levels of interest was greater. The form of the criterion, (due to Hecht (16)) is

$$E_t = K_1 (1. + K_2\sqrt{B_b})^2$$

The constants K_1 and K_2 were selected to give a good fit to the Tiffany data as reported by Blackwell (6). However, since the Tiffany data are based on a 50 percent probability of

A-13

detection, the threshold levels were first increased by a factor of 2 (or about 0.3 log units) to raise the detection probability to a more practicable level for our purposes. Values of $K_1 = 0.235 \times 10^{-8}$ and $K_2 = 5.4$ provide a good fit to the adjusted data.

The contrast ratio threshold for Case 1 and 3B models is analogous to the threshold illuminance in the Case 2 and 3 models and they are closely related. The Tiffany data, upon which the final form of the illuminance threshold criterion was based, were actually taken and reported by Blackwell in terms of contrast ratio thresholds and converted by Middleton (3) to the equivalent illumination threshold for use in his Figure 5-7. The contrast ratio threshold is a function of a number of variables, the more important of which include the background brightness and the size of the object being viewed. The time available for viewing is also a factor. For the larger subtended object angles, the contrast ratio sensitivity is relatively independent of the size of the viewed object, particularly for bright background levels. For subtended angles less than what Blackwell calls the critical visual angle, the threshold contrast ratio falls off in a manner that the product of the contrast and the solid angle included by the object being viewed remains constant. This relation was discovered by Ricco and is frequently referred to as the Ricco region. The contrast ratio thresholds in this region are directly convertible into illuminance thresholds. The "critical visual angle" which denotes transition region is a function of background brightness. The angle is on the order of 1 minute of arc for the brighter background, increasing (for background levels below 10 candles/ft^2) to the order of ten minutes of arc at very low background levels. Similarly, particularly above the Ricco region, the contrast ratio threshold is not strongly dependent on the background brightness for brightness levels greater than about 10 candles/ft^2 or for large objects (greater than about 50 minutes of arc) for brightness greater than about 1 candle/ft^2.

The dependence of the contrast ratio threshold on viewing time is not great for times greater than about 1/2 second, although some lowering of threshold level does occur

A-14

with long viewing time with large background brightness. Shorter viewing time increases the required contrast ratio approximately inversely proportional to the viewing time.

The standard contrast ratio threshold of 0.02 corresponds approximately to the data reported by Blackwell (6) for a background of about 10 candles/ft^2 with a 55-minute target viewed for a few seconds after applying a factor of 2 to increase the probability of detection to a near certainty of seeing.

For use in a practical highway fog context, a further increase to 0.05 or 0.06 seems advisable to account for attention, search, and distraction factors, and also since a degree of recognition is required in addition to simple detection. The larger value also helps to account for the intrinsic contrast ratio being less than unity.

BACKSCATTERING FUNCTION

The backscattering function $\beta'(\theta)$ of equation (A-18) relates the apparent intensity of the light scattered in the direction of the observer to the light illuminating the fog patch. Although, as implied by the notation, the amount of light scattered in a given direction is a function of the angle between the line from the source to scatterer and the direction from which it is observed, the function is relatively independent of the angle in the region of interest in our Case 2 and 3A models; i.e., in the backscatter direction. Consequently, the backscattering function $\beta'(\theta)$ can be replaced by the backscattering coefficient $B\pi$ independent of angle, and removed from under the integral with little loss in accuracy.

In the choice of appropriate values of the backscatter coefficient factor, several alternatives exist. The backscatter coefficient is related to the extinction coefficient, which is a measure of the total light scattered from a fog patch (assuming negligible absorption). One of the questions considered during the initial computer runs was whether the fog effects could be accounted for by the use of the extinction coefficient σ, or must the backscattering coefficient β_π be measured as well? A value of the backscattering coefficient can be

A-15

supplied for each extinction coefficient σ to be considered, or an approximation to the backscattering coefficient may be formed as a function of the extinction coefficient. Supplying an actual value for the backscattering coefficient on an analytical basis is not possible without completely specifying the physical properties of the scattering medium being considered. This was avoided since it was felt that it would detract from the generality of the models. Instead, the approach was to form the best approximation to the backscattering coefficient as a function of the extinction coefficient, letting the end results justify the means. The alternatives considered during the computer simulation runs were

$$\beta_\pi = \frac{P(180)}{4\pi} \quad \left(\text{obtaining a value of } 10^{-3} \text{ for } P(180)/4\pi\right)$$

from Rensch (17), $\beta_\pi = \frac{\sigma}{4\pi}$ (after Hamptons' original approach), and $B_\pi = 5.7 \times 10^{-2}\sigma$ (the mean value of β_π/σ) for various cloud models given to Carrier, Cato, and von Essen (18). The latter two, being quite close in value, yielded the best results. The latter, $\beta_\pi = 5.7 \times 10^{-2}$, was finally selected as being best supported by existing evidence. A maximum error of two per cent, with respect to the cloud models above, is suffered when using the mean value of β_π/σ rather than the actual value. It is the opinion of meteorologists that the physical structure of most fogs resembles that of stratus or low-level cumulus clouds (two of the major cloud models considered by Carrier, et al.). Furthermore, researchers have shown (for example, Fenn (19)) that a maximum error of 20 to 25 percent is suffered in visibility work when assuming that β_π/σ is a constant. Such errors should be tolerable in the final application of this current work; that of defining fog levels of significance with respect to driver visibility.

From a practical viewpoint, it is noted that, except for transmissometers, all of the fog measuring instruments currently in operational use measure some portion of the backscattering functions, and that the backscatter instruments determine the backscatter coefficient (even though they may be calibrated in terms of "visibility").

A-16

HEADLIGHTS

According to the Illuminating Engineering Society Handbook, SAE specifications for automobile headlamps direct that the maximum beam intensity shall not exceed 75,000 candles. Measurements of a purchased sealed beam headlamp (single unit type) produced an on-axis intensity of 48,000 candles at 12 VDC with an angular intensity distribution measured in the horizontal plane as in Figure A-3. Thus, for the Searchlight Model, the on axis intensity I_{HO} was taken as 5×10^4 candles (10^5 candles considering two beams). The Radiometer Model requires a mean value considering the entire angular distribution. A weighted mean value of 10^4 candles was computed from Figure A-3 as indicated thereon.

The Searchlight Model assumes a headlight beam intensity distribution of the form

$$I_\theta = I_{HO} \exp(-K\theta^n)$$

where I_θ is the intensity θ radians off the beam axis where the intensity is I_{HO}. The constants K and n used in the analysis were K = 4.94 and n = 1/2. These values were determined by fitting a straight line to beam intensity distributions plotted on three bases: $\log_e(I_\theta)$ vs θ, $\log_e(I_\theta)$ vs θ^2 and $\log_e(I_\theta)$ vs $\theta^{1/2}$. The latter produced the best fit. The distribution through a vertical plane was considered most representative in consideration of the searchlight model derivation as originally presented by Hampton.

TAILLIGHTS

According to SAE specifications printed in the IES Lighting Handbook, 12-volt bulbs for taillight use can be obtained with 3, 4, or 6 candlepower ratings. A photometer reading of 2 candles was obtained from the test taillight. (We assume that 1 candle was lost in transmission through the red lens.) It is obvious that vehicle taillights come in many sizes and shapes, and often have multiple bulb light sources. To further complicate matters, many taillight arrangements are much too large to be considered as point sources as assumed in the models. This can be compensated for if the specific taillight area under consideration is known, but quite out of the question with regards to a general model. Multiple taillights

A-17

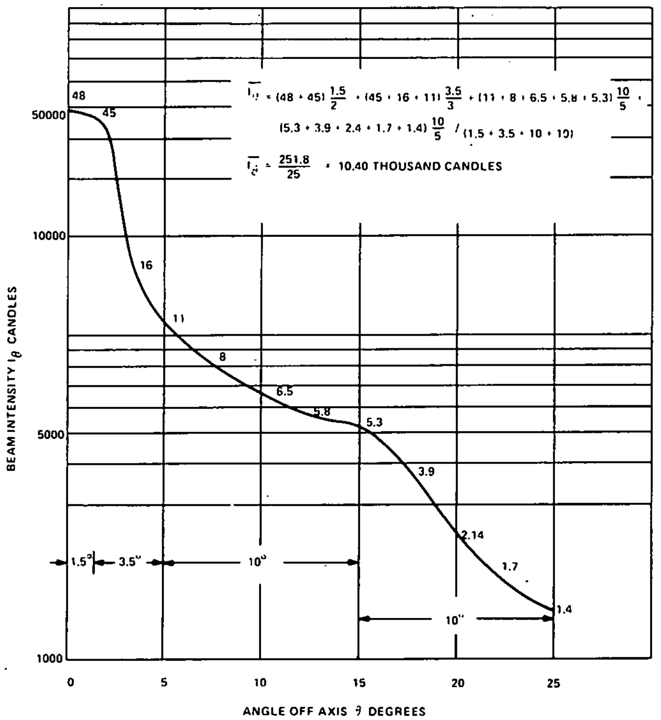


Figure A-3. Headlight Beam Pattern.

A-18

and multibulb taillights can increase the detectability of a vehicle however, so that for the purposes of modeling, assumption of a single 5-candlepower taillight appears to be reasonable. The two taillights on most cars will normally be separated sufficiently so that they can be considered as separate detections, and the effect may be more to help recognition than detection.

MISCELLANEOUS CONSTANTS

Various constants pertaining to the automobile-driver-headlight geometry must be supplied to the physical models for computation. The Searchlight Model requires a value for h, the height of the driver's eye level above his headlight beam. A value of 1.5 feet, given in Figure 9-3 of M. J. Allen (27) is considered to be a representative dimension and was used in the simulation. The height of the driver's eye level in the on-road test observer vehicle was slightly greater, being as much as two feet depending on the driver.

From the same illustration, a value of 1 foot was estimated as being representative of the lower integration limit L of the Radiometer Model. This parameter is the approximate point at which the driver's eyes begin to receive significant backscatter from his headlight beam. The integration limits $\pm\alpha$ for the Searchlight Model were determined from Figure A-3. The value 25 degrees (0.437 radian) was decided as being reasonable. At this point, the photometer readings, used to construct Figure A-3, changed very little with further increases in θ. This was interpreted as meaning that the direct beam was no longer being intercepted; i.e., the photometer was receiving light scattered in that direction by the curved sealed beam lens. The intensity level at this angle is significantly below the level of the main portion of the beam and well out of the driver's field of direct vision. The angle in the Searchlight Model is the angle below the horizontal which the driver's line of sight centers on the taillight of the preceding vehicle. This can be expressed in terms of h and the distance R to the taillight. The expression used is:

$$\phi = \sin^{-1}\frac{h}{R}$$

A-19

HEADLIGHT BACKSCATTER

In order to gain an insight into the magnitude of the backscattered light to help validate the headlight parameters and models, a computer printout was made of the backscatter brightness as a function of the cumulative distance from the headlamp and the observer. Part of the results of the printout are shown in Figure A-4. Of particular interest is the fact that the bulk of the light is returned from quite close in, even for the lighter fogs. This illustrates the importance of the upward scattered light in fog headlamp designs for use in fog.

A-20

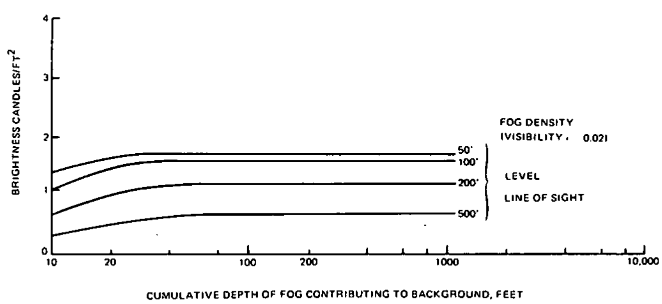


Figure A-4. Backscatter Brightness as a Function of Cumulative Distance.

APPENDIX B

ON-ROAD TEST OPERATIONS AND INSTRUMENTATION

INTRODUCTION AND GENERAL CONSIDERATIONS

The objective of the on-road tests was to acquire data in a realistic driving environment in order to aid in quantifying the driving hazard caused by reduced visibility. The primary emphasis was on the freeway blocked lane hazard, whereby the blocking vehicle is stationary in one lane. The critical question addressed was: under given visibility conditions, at what distance would an approaching driver see the obstruction? This datum allows a safe driving speed to be inferred.

A totally realistic experiment to determine sighting distance under these conditions obvi usly involves unacceptable hazards for both the experimental vehicles and other traffic on the roadway. Consequently, in order to provide a safe but reasonably realistic experimental tableau, the tests were conducted with the lane-blocking stopped vehicle replaced by a portable target placed on the road shoulder just off the traveled lane. Ideally, from a safety standpoint, no other traffic should be present during the experiments, and if a sufficiently dense fog to close the northern end of the New Jersey Turnpike had occurred it would have been exploited. In the absence of such closings, however, the tests were conducted on the less heavily traveled roads, primarily on the eastern end of Long Island near Montauk Point.

Fog of a sufficient density to have a significant impact on highway traffic operations is a comparatively rare and unpredictable event, and generally of short duration, particularly the densest fogs. Also, although a few fogs cover a large area, the widespread fogs are rarely of sufficient density to significantly affect traffic except in localized areas, i.e., denser fog patches which may be drifting around.

Meteorologically, dense fogs are generally defined as those producing visibilities of 1/4 mile or less and the visibility ranges are generally quantized in 1/8 or occasionally 1/16 mile increments; therefore, visibilities of less than 1/16 mile are recorded as zero. In the highway context, however, a fog density of 1/4 mile is of minimal hinderance to traffic operations, and at most, slightly reduces the ability of those unfamiliar with the roadway. Even a 1/8-mile visibility range is normally sufficient for drivers to perceive an obstruction in time to stop safely. Consequently, it is fog of less than 1/8-mile visibility that is of major interest. Meteorological data of direct use in highway fog studies are quite scarce, and weather forecasts are not normally aimed specifically toward the prediction of fog densities of prime interest to highway fog study.

The lack of much data on very dense fogs, the fact that most weather forecasts are not generally directed toward the prediction of such fogs, and the relative scarcity, unpredictability, and lack of knowledge of the precise time and place of the likely occurrence of dense fogs makes the taking of on-road test data more difficult than had been initially anticipated.

The general types of conditions required for the generation of fog are known, so that the possibility of fog can be predicted, or perhaps as important, the possibility of fog can be ruled out. However, prediction of the precise place, and whether it will be of sufficient density is of much greater difficulty. Since dense fogs are of limited duration, some advance notice of the probable time and location of dense fog is required to allow time to assemble a test crew, load the equipment and instrumentation in the test vehicle(s) and travel to the test site. For tests on the New Jersey Turnpike, predictions from the turnpike's weather advisory service were available. For operation on eastern Long Island, in addition to the National Weather Service advisories giving general weather information for the area, information as to the present visibilities, air temperature, and wind velocities were available from several U.S. Coast Guard Stations, an Air Force Radar installation at

Montauk Point, and during the day, from the East Hampton Town Airport tower. Arrangements were also made with the security guards at the Sperry Rand facilities on Long Island for twenty-four-hour notification of fog approaching 1/2 to 1/4 mile visibility level, particularly when prospects looked good for continuing fog conditions. These notifications proved particularly valuable at the facility near MacArthur Airfield in East Islip where the Videograph calibrations were checked against the airport transmissometer. The New York Flight Service Station located at MacArthur Field was also helpful in providing weather conditions at MacArthur and the other airfields in the New York area. None of these supplemental sources, however, has a weather forecasting capability nor can most of them provide a dew point or wet bulb temperature. (An air temperature approaching the dew point with little or no wind is highly suggestive of fog.) Because of the above mentioned limitations, the services of Northeast Weather Service, Inc., were secured, to provide a better prediction of possible upcoming fog, and to allow for the possibility of conducting the tests over a wider geographic area. They provided a daily forecast of the probability, time, and place of fog within a radius of about 100 to 200 miles. They also provided specific notification of the probability of the occurrence of dense fog and were available for consultation at all times. These services proved very helpful, and it is recommended that similar services be secured if any similar study is undertaken in the future.

One of the major problems in conducting in-field tests in fog, such as this, lies in knowing when to assemble a test crew and dispatch it to the field. Because of the infrequency of dense fog, it is impossible to maintain a crew continuously on duty specifically for these tests, yet at most, only a few hours of advance notice is available. The costs associated with dispatching a test crew when no fog is present is nearly as great as when dense fog is encountered, so false starts are undesirable. On the other hand, dense fog is sufficiently rare that few missed dense fog occurrences can be afforded. The cost of the weather advisory service can therefore be easily justified on the basis of reduced false

starts and reduced missed fog occurrences. Even with the help of the weather advisory service, a significant number of false starts occurred (10 of 17).

TEST CONDITIONS

The variations in test conditions under which data were taken included the fog density (extinction coefficient), ambient light levels, target lighting (taillights, stop lights, or none), and observer vehicle headlights (high-beams, low-beams, or off). Of these, variations in the fog density and ambient light level occur naturally, and little control is available over them. The remaining variables are under the experimenters control. Test data, however, are not equally necessary nor desirable for all combinations of variables. Driving at night without headlights for example, is unrealistic and illegal. Similarly, during daylight, the state of the headlights on the observer vehicle makes little or no difference with respect to target detectability (although it can affect the detectability of the vehicle as a target). A priority was therefore established for the various test conditions. These priorities were established on the basis of their practical importance as a realistic highway fog problem condition, upon the degree of extrapolation required of established work, and ease of simulation on a fog range or elsewhere. The first order priority was: twilight (dawn), no target lights, with headlights on and off. The second order priority conditions were: night with target lights off, headlights on, and during daylight with neither headlights nor target lights on. The lowest priority conditions were night with headlights off and day with headlights on. The former was lowest because it represents an illegal condition as well as a hazardous test condition. In practice, daylight data from all headlight conditions were combined because there was no discernable effect from the headlights. The driver had to check the position of the controls to be able to determine the headlight condition.

RUN SCHEDULE

A run schedule was set up on the basis of completing a run and recording the required data in ten minutes, yielding six runs per hour. (In practice, the average run took closer to 15 minutes, although during some of the later test series, after some streamlining of the data-taking procedures, run times of ten minutes were achieved.) A complete test run series consisted of 24 runs spread over four hours. From consideration of the test condition priorities, it was desired to include twilight (dawn) data in each test series. The daylight conditions were also assigned somewhat higher priority than night, so that the run sequence unit was based on two hours of daylight, one hour of night, and one transition hour (provided that the fog lasts as long as four hours).

For each test run sequence, three distinct target light conditions and three distinct observer car headlight conditions were employed. The 24 runs over each four-hour run sequence unit were distributed over nine lighting configurations, as presented in Table B-1. A mirror image of the night to morning schedule would have been used if afternoon to night fog had been encountered. For the purpose of scheduling the run conditions, dawn was considered to last from a half-hour before sunrise to a half-hour after sunrise. When it was necessary, runs were skipped or added to keep the schedule aligned with the ambient light conditions.

TABLE B-1. MORNING RUN SCHEDULE

Lighting Conditions				Ambient Illumination			
Target Vehicle Tail-Lights		Observer Vehicle Head-Lights		Night	Dawn	Day	Day
Running	Brake	Low	High				
On		On		1	7		
On			On	2			
On							
	On	On		3	8	13	19
	On		On	4	9	14	20
	On					15	21
		On		5	10	16	22
			On	6	11	17	23
					12	18	24

Table B-2 shows the distribution of conditions for which data runs were taken during the performance of the on-road tests.

TABLE B-2. DISTRIBUTION OF DATA RUNS

	TARGET					LIGHT CONDITIONS			VEHICLE LIGHTS		
	BODY		LIGHTS								
	White	Black	None	Tail	Stop	Night	Dawn	Day	Off	Low	High
Test #1	9	0	3	4	2	1	3	5	1	3	5
Test #2	5	1	3	0	3	0	0	6	2	1	3
Test #5	9	13	12	4	6	0	2	20	7	7	8
Test #8	3	15	9	4	5	2	1	15	12	6	0
Total	26	29	27	12	16	3	6	46	22	17	16

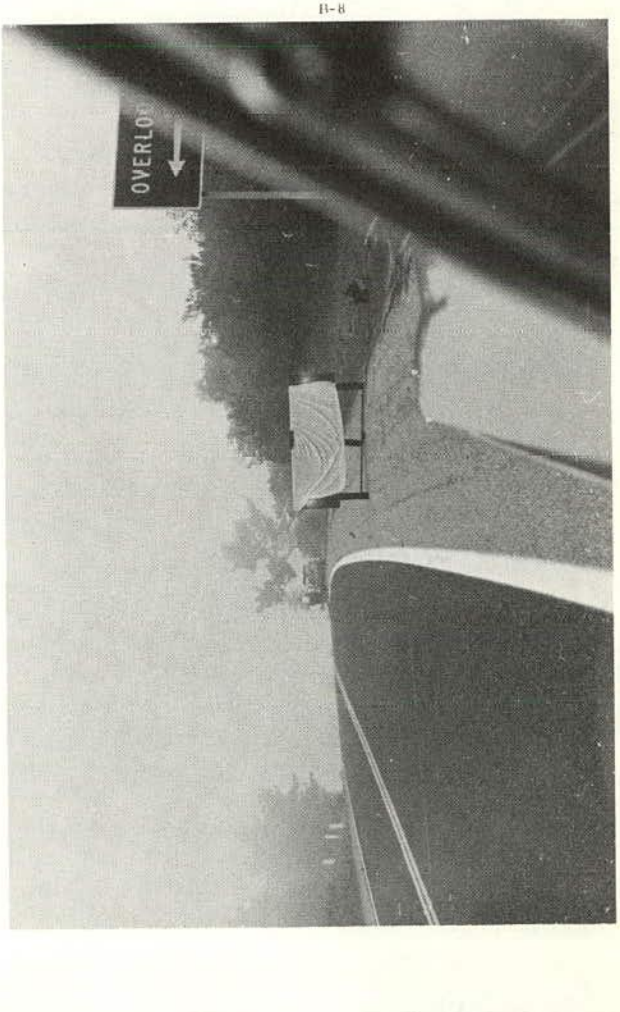
TEST INSTRUMENTATION

Two vehicles were used in the road test experiments. One called the target car and the other called the observer car. The observer car was a 1969 Ford Country Squire station wagon, and incorporated a standard four-headlight system. Other test equipment included:

- Portable target, to simulate vehicle rear end
- Videograph, to measure fog density
- Photometer, to measure target and background brightness
- Data recorder, carried in the observer car.

Portable Target

The portable target was set up just off the roadway and normally about 100 feet upstream from the target car. The target carried two taillight assemblies and simulated in appearance the rear end of a conventional passenger sedan. Figure B-1 is a photograph of the target set up on Montauk Parkway immediately following the conclusion of one of the test series. Although the test target did not have precisely the same appearance as the back of a car, its visibility aspects were representative of many vehicles and considerably more repeatable. The bumper, for example with its generally complex shape, can introduce a considerable amount of variability from run to run and vehicle to vehicle since with favorable geometry specular reflection can momentarily add another apparent light at the target. The effect would be to randomly increase the detection range for some cars under some essentially random condition. Also, there is considerable difference in the visibility characteristics of different makes and models of cars which also adds to the dispersion of the measured data. Since the total number of data points was limited by the availability of suitable fog, reducing the number of dispersion-producing variables was considered desirable, wherever feasible.



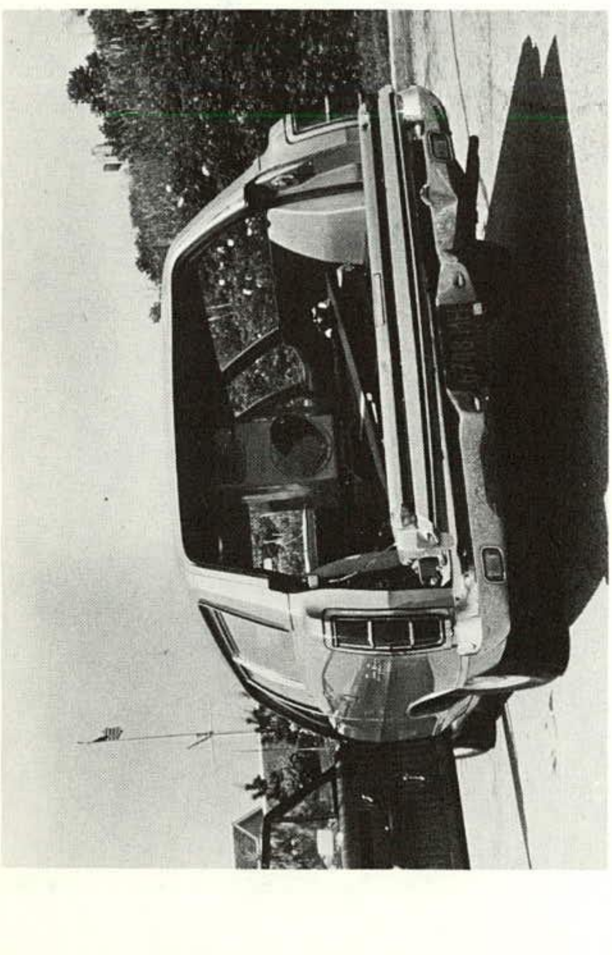
B-9

Both a black target and a white target were made available for presentation since, generally speaking, a white vehicle is more visible in good visibility; but in dense fog, particularly in daylight where the fog forms the background, the black will be seen first. The basic target was black, a white cover being used for white. The target was essentially diffuse, with the flat black paint scattering about 2 to 3 percent of the incident light, and the white cover scattering about 90 percent. Two standard taillight assemblies incorporating 1157-type bulbs and SAE-STPI-65 lenses were mounted on the target. The nominal intensities of a type 1157 bulb are stop - 32 candle power @ 12.8 volts and tail - 4 candle power @ 14.0 volts. Both taillights were energized simultaneously with switching permitting either the taillight filaments, the stoplight filaments, or both to be energized.

Videograph

A Videograph was selected as the basic visibility instrument for the highway fog test. The reasons for its selection are as follows. First, the published and unpublished test results are sufficiently favorable. Second, acceptance of the device for operational purposes appears to be more extensive than any of the other devices offered (U.S. Coast Guard, Canadian D.O.T., and various European Agencies). Third, the device adapts well to field test use, requiring no installation, and is quite portable. Finally is the fact that two of the devices were acquired on loan at minimum cost from Sperry Gyroscope, Ltd. (Ottawa), which manufactures the device in Canada on license from Impulsphysik. Although it is difficult to relate Videograph measurements under patchy and variable fog conditions, the constant human interfacing typical in experimental programs of this nature tends to minimize the risks involved. The choice of the Videograph for the test program, however, is not intended to imply that the Videograph is necessarily the best instrument for use in implementing a highway fog countermeasures system. The instrument, however, proved to be rugged and dependable, and is self-contained in a single unit except for a 12-volt power source.

B-11



B-10

A Videograph was mounted in the rear of the observer vehicle facing aft as shown in Figure B-2. For most of the tests, the Videograph was remounted slightly from the position shown in the figure to point slightly to the left side in order to sample less disturbed air when the vehicle is in motion, and to sample the air over the roadway when stopped at the side of the road.

The Videograph is normally calibrated for a range from 0.1 to 10 nautical miles. Since for this study, the fog intensities of primary interest extend to meteorological visibilities of 200 feet or less, the unit was modified to bring the point of intersection of the receive and transmit beams closer to the Videograph. This reduced the backscattering volume sampled and also reduced the setting of the graduated front panel sensitivity control. The basic operation and stability of the unit remained unchanged, but recalibration was necessary. The initial plans were to check the calibration against a transmissometer at the Air Force Cambridge Research Laboratory. Due to the lack of natural fog conditions at the location during the spring, this was not possible. Since the Videograph was needed in the Long Island area for use in conducting the on-road tests, the Videograph was calibrated against an FAA transmissometer at MacArthur Airport, Islip, New York. The transmissometer is a model N-1, has a 500-foot baseline, and is located on the north side of the instrument runway 06-24 at the southwest end.

The calibration was limited in that the transmissometer with its 500-foot baseline does not provide accurate reading for visibility ranges less than about 300 feet. Also the fog present during the calibration was not perfectly homogeneous so that the output of both instruments fluctuated considerably. Consequently, no attempt was made to arrive at an entirely new calibration curve. Instead the curve was simply lowered to provide the best mean agreement between the two instruments. The magnitude of the adjustment to the curve agreed well with the magnitude of the adjustments made to the Videograph. The calibration was also cross-checked against visual estimates of visibility in daylight fog.

B-12

Because of the frequently fluctuating nature of fog, the Videograph is designed with a restricted rate of response to changes in fog density, requiring about 3 minutes to traverse the entire scale (2 decades). Changes in visibility level encountered over a test run were apparent from the Videograph output. However, care was required in interpreting the data to account for the response lags of the instrument. Care was also taken at the end of run readings to allow the instrument to stabilize.

Photometer

The photometer is used to measure background and overhead ambient brightness, and to check the intensity of the target tail and stoplights.

Background brightness, as presented to driver and passenger in the observer car, can vary widely, especially with less dense fog in the daytime. Fortunately, this is the least hazardous condition for a blocked-lane encounter. In the much more hazardous case of very dense fog, background brightness should be much more uniform. Accordingly, a simple set of photometric measurements was taken: illumination at the driver's eye (through the windshield with headlights on) straight ahead, 45^{o} right, and 45^{o} left, then from outside of the car. Sky brightness was measured overhead, fore and aft.

An S&M Model A-3 Sensitive Photometer was used. This photometer, which uses a cadmium sulfide cell is more sensitive than the normal photographic type of photometers and much more portable than the more precise laboratory photometers. It is lightweight, easily used, self-contained, requiring no external power, and has a built-in dial illumination for use in low-ambient light levels. The light acceptance angle is about 40 degrees. Since the photometer was originally intended for special photographic use, it is not directly calibrated in photometric units. The unit was, therefore, calibrated against a Spectra Pritchard Photometer for reflected light (luminance) with incandescent, fluorescent, and red taillight sources. It was also spot checked at a few points for incident light against a Weston Model 703 light meter using incandescent light.

A more sophisticated and accurate spot photometer could have been used, which would have allowed more localized background brightness to be taken in the immediate vicinity of the targets. The immediately available instruments, however, were more awkward and cumbersome to use, and therefore would have added appreciably to the time required for data taking, and thus would have reduced the number of test runs that could be taken.

Data Recorder

The data recorder took the form of a phototheater, a black-painted box about three feet long. The box was equipped at one end with a Super-8 movie camera and at the other end with an instrumentation panel.

Self-contained lights provided illumination for the instrumentation panel. The camera was capable of being remotely-controlled, and operated at film speeds of 12, 18, or 24 frames per second. Most of the data were taken at 18 frames per second.

The instrument panel, depicted in Figure B-3, contained a survey speedometer and odometer, a meter indicating the Videograph output current, a stop watch, four indicator lights, and a run identification card allowing the test sequence, data, and run numbers to be recorded. One of the indicator lights was connected to the brake-stop lights of the test vehicle. The other three were individually energized by the observer through a small control box in the front seat. The camera was started whenever the observer light was activated, and continued to run until stopped by the activation of a reset switch on the control box. While operating, the camera made sufficient noise to be heard by the driver and the observer, so the camera was started during the early part of a test run, and stopped after passing the target at the end of the run.

The survey speedometer-odometer provided direct mileage readings to 1/100 of a statute mile, and could be interpolated to between 0.001 and 0.002 statute mile. The speedometer was easily readable to the nearest mile per hour.

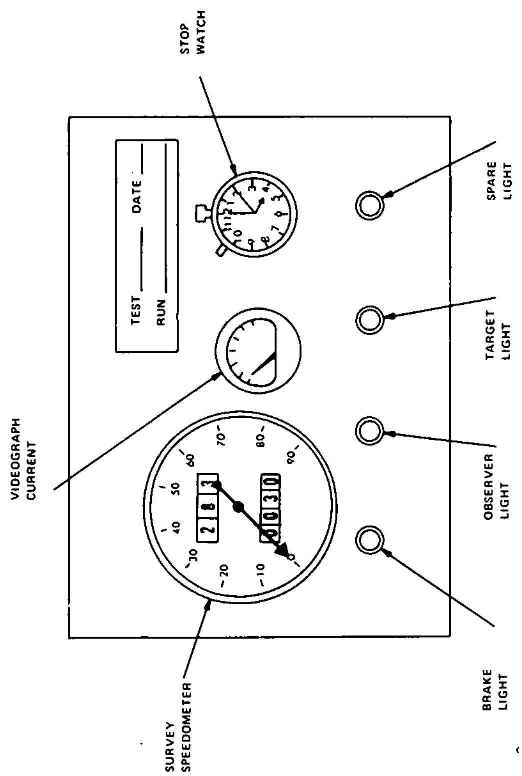


Figure B-3. Phototheater Instrument Panel.

During the run, when the observer first saw the target, he pushed the button energizing the OBSERVER light, and when the driver first saw the target, he lightly depressed the brake pedal. (It was not necessary to detectably slow the vehicle.) When the front of the test vehicle was even with the front of the target, the observer energized the TARGET lamp. The difference between the odometer readings at the BRAKE light and TARGET light indications provided a measure of the driver sighting distance, and similarly the difference in readings at the initiation of the OBSERVER and TARGET lights for the observer sighting distance.

The switches on the control box produced a noticeable noise when activated, so during the run the observer was instructed to periodically depress the SPARE lamp switch to reduce the possibility of the observer influencing the driver when the observer saw the target first.

DATA REDUCTION

After completion of a test series and return of the processed film, the film was searched for the frames on which the observer, brake, and target indicator lights were first activated. Of these, the frames corresponding to initial target sighting by the observer and the driver and the time of passing the target were identified. Vehicle speed, Videograph current, and the odometer reading were then recorded for each of these times. The stopwatch readings were not normally used.

The odometer is directly readable to 1/100 mile and the readings were interpolated to the nearest 1/1000 mile. In most cases, the interpolation was performed by counting the frames on both sides of the event to the even 1/100 mile point, taking into account any changes in speed. The speed changes over the 0.01 mile interval were negligible for the target sightings, but frequently were appreciable when passing the target. The general procedure of counting frames for interpolation was found to be easier and more repeatable than trying to interpolate directly.

The photometer readings were converted into luminance values (ft. Lamberts), and the Videograph currents converted into equivalent visibility. In addition to the above three Videograph readings per run, Videograph readings were recorded at the beginning of the run, following the end of the run, and at the initial data frame of the run. The Videograph visibility adopted for a particular run was a weighted estimate of visibility over the distance that the sighting took place. The readings taken when passing the target and immediately following the run were given the greatest weight; the relative weighting of the readings being adjusted as a function of the magnitude and direction of any changes occurring during the run to help compensate for the known lag characteristics of the Videograph.

The major error contributors in the sighting distance determination occurred in the interpolation of the odometer readings and as a result of the sampling effects associated with the camera frame rate. The calibration of the odometer itself was better than 0.1 percent error when checked over measured distances. The odometer reading was interpolated to the nearest 0.001 mile, and the reading error is believed to be at most 0.002 miles, or about 10 feet. Most of the data were recorded at a film speed of 18 frames/second, or 55 milliseconds/per frame. At 50 mph (close to maximum at which data were taken) this amounts to about 4 feet/frame. Treating these errors as uniform random distributions, the resultant root mean square (rms) error for the sighting distance is 8.8 feet.

One final adjustment made in the sighting distances prior to plotting them in Figures 4 and 5 was to increase the distances by an amount equal to the distance traveled by the test vehicle during an assumed one half second reaction time. This was done to avoid duplicating the reaction time which was included in the safe stopping speed.

APPENDIX C

SAFE STOPPING SPEED

For the highway fog study, it was necessary to calculate the maximum safe stopping speed (with the visibility distance as the independent variable). Mathematically, the derivation of the relationship is much more tractable when the stopping speed is treated as the independent variable, and the stopping distance as the dependent variable. The standard equation for the approximate stopping distance of a vehicle is

$$d = 1.47\ Vt + \frac{V^2}{30\ (f + g)} \qquad \text{(C-1)}$$

where d is the stopping distance in feet, V is the initial speed in mph, t is the perception and reaction time in seconds, f is the average coefficient of friction between the tires and the roadway, and g is the grade.

Table III-1 in AASHO "Geometric Design" (10) tabulates values of coefficient of friction, braking distance, and total stopping distance (for a 2.5-second perception and reaction time) on level ground for initial vehicle speeds of 30 to 80 mph and for both wet and dry pavements. The values for braking distance may be used directly if the conditions are appropriate. It should be noted that the coefficient of friction is a function of the initial speed. The tabulated values from AASHO "Geometric Design" were fit to the equation

$$f = k_1/V^{k_2} \qquad \text{(C-2)}$$

where k_1 = 1.032 and K_2 = 0.15 for dry pavement, and k_1 = 1.04 and k_2 = 0.31 for wet pavement, with V in miles per hour. The fit to the tabulated values is excellent for dry pavements and a little less accurate for wet pavement.

Combining the two previous equations

$$d = 1.47\ Vt + \frac{V^2}{30\ (k_1/V^{k_2} + g)} \qquad \text{(C-3)}$$

For level ground this becomes

$$d = 1.47\ Vt + \frac{V^{k_2 + 2}}{30\ k_1} \qquad \text{(C-4)}$$

APPENDIX D

DRIVING SIMULATOR STUDY

This portion of the Highway Fog study was performed at the Institute of Transportation and Traffic Engineering using the UCLA Driving Simulation Laboratory Closed Circuit Television System (DSL-TV). The task included conducting a simulator study and a brief investigation of some of the behavioral aspects of driving in fog. Particular attention was given to the influence of driver expectation on the detectability of other objects, e.g., vehicles, obstructions, etc. This task included the collection of driver response data under two low-visibility conditions using the DSL-TV.

Of particular interest was the relationship between driver performance and visibility conditions under various speeds when the driver had no warning, but some expectation of encountering a hazard.

BACKGROUND

The task of driving during foggy weather is a special case of the total driving task which has been described by Hulbert(21) as involving two major aspects. One aspect is lane keeping (tracking) and the other is avoidance of obstacles in the roadway. While driving, the motorist is continuously transmitting information to his "computer center," the brain, primarily through his sense of sight. In clear daylight this information includes events or conditions existing as far as two or three thousand feet ahead. Much of this information is either discarded as not pertinent to the driving task or is stored for later reference if other events or conditions develop to the point that a decision must be made to change the driving pattern. Many such decisions that require little or no physical response by the driver are, of course, continuously made as he drives. Since the range of vision ahead is usually large, ample time is available for making these many decisions.

D-2

Only a very few decisions must be made comparatively quickly and driving speeds are accordingly higher when visibility is great and traffic is light.

When driving in fog, even with a visibility of six or seven hundred feet, all roadway events and conditions must be appraised, decided upon, and acted upon in less than eight seconds if the vehicle is moving at 65 mph. Therefore drivers tend to reduce speed in fog (2). However, they do not always reduce speed sufficiently to be able to stop when they encounter a slower moving vehicle or stationary obstacle.

There are two pertinent facts concerning fog that drivers apparently are guided by. The first is that visibility distances of more than six or seven hundred feet at ground level are not considered a limiting condition to drivers on highways where travel is at 65 or 70 mph (2). The second fact is that fog which limits driving visibility below 600 feet occurs relatively infrequently. There are very few days of fog sufficiently dense at test sites to reduce visibility below the 500 foot level. Therefore, drivers are not well prepared to drive safely when visibility is 500 feet or less.

It was the intent of this study to determine if simulated driving in a fog situation could be created that would make it possible to collect data on driver's reactions when they unexpectedly encounter obstacles in their path and visibility is 500 feet or less. This goal was achieved and data collected from five drivers at two closing speeds: 20 mph and 30 mph. Seven different obstacles were studied including approaching vehicles with headlights operating.

DESCRIPTION OF TV APPARATUS

The study was performed using an unprogrammed TV display system developed for the UCLA Driving Simulation Laboratory. A special display and procedure was developed for this study. The TV camera had to be equipped with a specially designed filter. The TV display (monitor) was placed in a driving cockpit in order to provide an immediate environment similar to that in an automobile.

D-3

The TV camera is a black and white GPL Model 1000 with up to 1000 lines horizontal resolution, 15 mHz bandwidth, and a scan rate of 525 lines per frame. The camera lens is an f2.0 Schneider Xenon with 16mm focal length, operating through two 1.5-inch silvered prisms to lower the optical axis to 0.75 inches (equivalent to a full scale eye height of 48 inches).

The TV monitor, a Conrac model CVA23/C, is a self-contained 23-inch display monitor designed to give optimum pictures in high ambient light areas from a video line carrying composite video and sync signals.

The filters developed for this study for use in conjunction with the TV camera to simulate three-dimensional fog were composed of several layers of cellulose acetate sandwiched between distortion-free glass slides. The cellulose acetate has a fine screen pattern - small white dots, to disperse light, on clear acetate obtained from the screen side of a Xerox Document Carrier - which proved ideal for our purposes.

A mounting device was attached to the top of the silvered prism and the prism was carefully measured to obtain the precise lengths of cellulose acetate necessary to simulate an exact distance covered by fog on the landscape. The filter had to be cut and placed on the prism so that the fog density doubled with each doubling of distance from the TV camera. The filter was thus relatively clear at the bottom of the scene and grew progressively denser toward the top.

Precision steel blocks were machined for the cutting of the cellulose acetate. A set of blocks was made for each length of acetate to be cut and was so designed that the cellulose acetate could be fitted into it, clamped down, and then cut to the specified measurement with a tolerance of ±.0005 inches. The ends of the cellulose acetate strips were forged together with a soldering iron prior to the precise bonding of them to the distortion-free glass slides with a strong liquid adhesive.

D-4

Two density (visibility) levels were produced: one at approximately 500 feet scale equivalent distance, and the other to provide only enough visibility to see the roadway immediately in front of the vehicle. In this way the visibility range of interest was bracketed.

DESCRIPTION OF DRIVING "COCKPIT"

The test chamber consisted of a small (5 x 8 foot) black cubicle located within a compartment only slightly larger. The larger compartment allowed ambient light to filter from the laboratory area into the test chamber to avoid complete darkness.

The television monitor, automobile seat, and controls were placed within the small black cubicle. In addition, a microphone and speaker were placed within this chamber for purposes of two-way communication between the driver and the researchers.

Attached to the brake pedal was a microswitch which allowed the subject to stop the driving scene depicted by the roadway and landscape belts; however, the subject could not restart the driving scene belts.

Within three milliseconds from the closing of the microswitch, all power to the monitor and camera was cut off, thus stopping the belts and blanking out the image to the subject so that a measurement could be taken on the model landscape of the distance remaining between the obstacle and the TV camera prism lens. After a measurement was taken the power was restored manually by the experimenters and the foggy driving scene was once again displayed to the driver.

DESCRIPTION OF THE MODEL LANDSCAPE

The model roadway and landscape consisted of a 16-foot long and 5-foot wide table equipped with conveyer type belts capable of moving forward or in reverse at varied speeds. The roadway consisted of two belts capable of moving in the same or in opposite directions (each being controlled independently of the landscape belt). These two narrow belts were directly on top of a wider belt which represented the surrounding landscape. This wide belt could also be manipulated in terms of speed.

D-5

The two narrow belts were painted black with white striping in the middle of the two lanes to represent traffic lanes, the wide belt was covered with felt and miniature foam rubber objects such as trees and rocks to represent the adjacent landscape.

This model was designed on a scale of 72 to 1. The TV camera was mounted on a cantilever bridge at the end of one side of the table so that it could be positioned to represent the location of a vehicle on the roadway. Scale model vehicles and other obstacles were magnetically attached to the roadway belts and thus appeared to be moving whenever the belts were moved.

DESCRIPTION OF OBSTACLES

Threshold Target

In order to calibrate the fog filters it was necessary to collect driver detection distance data in terms of how far away they could detect a "standard target". The target was based on information from a 1965 ITTE report (22) as follows: Appendix A, page 2:

DEFINITION OF VISUAL RANGE

"There are several possible ways in which visual range can be defined. We propose to use the Meteorological Visibility as established by the U.S. Weather Bureau as a basis for defining visual range. This system uses subjective observations of specified objects at various distances. Meterological Visibility is defined as the distance at which a black target can be seen against a uniform sky background in the daytime. For the daytime conditions we used circular black discs of approximately one-half degree of total visual angle as targets. At varying distances the physical size of the target will change so that the circular discs will always subtend a total angle of one-half degree in angular subtense at the observer's eye. Given this example, at 100 feet the disc will have a diameter of 0.87 feet; at 300 feet the disc will have a diameter of 2.62 feet; at 900 feet the disc will have a diameter of 7.87 feet; at intermediate distances the size will be scaled proportionately."

D-6

Calibration Target

For the 72:1 scale model the target was a matte black disc 1.57 inches diameter which subtended 1/2° of visual arc when placed 15 feet away from the TV camera lens.

Obstacle Targets

No. 1. A model automobile, colored red, 2-7/8-inches long (bumper to bumper), 1-1/8-inches wide, and 13/16-inch high (scale 1:96) fitted with two low voltage subminiature lamps as headlights (activated).

No. 2. A cylindrical shaped object, colored red, relatively small in size: 5/8-inch in diameter and standing 15/32-inch high.

No. 3. A model automobile, colored gold, the same dimensions as 1, but without headlights.

No. 4. A cylindrical shaped object, colored black, relatively large in size: 2-1/2-inches in diameter and standing 1-5/8-inches high.

No. 5. A cylindrical shaped object the same as 2 except colored white.

No. 6. A model two-decker bus, colored red (with advertising panels, etc.), 4-1/2-inches long, 1-5/16-inches wide and 2-1/2-inches high (scale 1:96).

No. 7. A cylindrical shaped object the same as 4 except colored white.

SUBJECTS

Five licensed drivers (employees of ITTE) were asked to participate as subjects. Four males and one female ranging in age from 19 to 51 participated.

Name	Age	Years Driving	Miles/ Year	How Often Drive	Glasses
C. Wojcik	51	23	8,000	daily	Yes (nearsighted)
B. Zabot	22	6	2,000	1-2/mo.	No
K. Seidner	19	1½	7,000	4/wk.	No
E. McGahan	48	25	2,500	daily	Yes (nearsighted)
R. Sandes	30	13	5,000	daily	No

D-7

PROCEDURE

Driver subjects were escorted into the laboratory area containing the test chamber and seated behind the wheel of the driving "cockpit". With their hands on the steering wheel they were shown the brake pedal and told to keep their right foot on the floorboard unless they were applying the brakes. A white cross marked the place on the floorboard where they were to place their right foot. This assured that the distance they moved their foot was standardized and thus not a source of variance in braking response to the unexpected obstacles. The intercom system was explained and demonstrated.

Two sets of data were collected: a set of "threshold" reactions, and their reactions to the seven different obstacles. Prior to a test series the test subjects were given the same instructions stating the nature of what would be seen on the screen, and what was expected of them. They were also given an opportunity to ask questions. The intercom system was used to provide supplementary instructions, and the tests subjects were told that any comments they wished to make could be heard.

Ten "threshold" reaction data points (reaction distances) were collected at each of the two density levels. Half of each set of trials had the threshold target approaching and the other half were receding. A random order was selected for presenting the approaching or receding targets. Thresholds were determined by averaging across the ten trials.

A rest was given after the completion of the threshold series and then a second set of instructions were given over the intercom for the detection of the seven obstacles. The seven different obstacles were presented (approaching only) to each of the five drivers. Each one encountered these in a different order at two different closing speeds and reaction distances were recorded for each.

D-8

RESULTS

Calibration Study

Only four of the five sets of data were available for analysis of calibration threshold data (one set was misplaced). The mean values for each of these four drivers is shown in Table D-1 for Approaching Target, Receding Target, and Average of Both; for Density Level I and II.

TABLE D-1

RESPONSE DISTANCES FOR STANDARD TARGET (INCHES)

DRIVER	FOG DENSITY I (approx. 500' visibility)			FOG DENSITY II (approx. 30' visibility)		
	APPROACHING TARGET	RECEDING TARGET	AVERAGE	APPROACHING TARGET	RECEDING TARGET	AVERAGE
1	26.30	60.10	43.20	1.60	6.70	4.15
3	44.18	39.15	41.67	3.73	11.24	7.48
4	37.04	55.43	46.23	14.22	16.19	15.20
5	122.76	168.85	145.81	4.30	5.99	5.15
AVERAGE	57.57	80.89	69.23	5.96	10.03	9.25

Obstacle Detection Study

In density level II fog, the only obstacle target that was responded to was the automobile with headlights on. Table D-2 shows the response distances for this obstacle at both fog densities.

Table D-3 presents response data for each of the five drivers for each of the seven obstacles in fog density level I at closing rates of 20 and 30 mph.

D-9

TABLE D-2

RESPONSE DISTANCES TO APPROACHING CAR WITH HEADLIGHTS ON (INCHES)

DRIVER NUMBER	FOG DENSITY LEVEL I APPROX. 500'		FOG DENSITY LEVEL II APPROX. 30'	
	CLOSING SPEED 20 mph	CLOSING SPEED 30 mph	CLOSING SPEED 20 mph	CLOSING SPEED 30 mph
1	50.50	27.75	16.25	12.25
2	28.75	48.75	12.00	13.00
3	60.75	54.50	16.75	18.75
4	53.25	59.75	10.00	14.38
5	48.75	40.00	14.75	15.87
AVERAGE	48.40	46.15	13.95	14.85

TABLE D-3

AVERAGES OF FIVE DRIVERS' RESPONSE DISTANCE TO SEVEN OBSTACLE TARGETS

OBSTACLE TARGETS	FOG DENSITY LEVEL I AVERAGE RESPONSE DISTANCE (Inches)	
	20 mph Closing Rate	30 mph Closing Rate
No. 1 Red car with headlights on	48.40	46.15
No. 2 Small red cylinder	10.43	8.23
No. 3 Gold car	11.58	6.60
No. 4 Large black cylinder	24.17	14.85
No. 5 Small white cylinder	5.04	1.83
No. 6 Two decker bus	20.45	17.50
No. 7 Large white cylinder	0.46	1.08

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4. The response distances to the seven obstacles were taken only as the obstacles approached the driver because of time constraints and also because the approaching obstacle represents the critical transition from the uncoupled to the coupled state. These data were collected at two differential speeds, 20 and 30 mph, as shown in Table D-3. These closing rates are representative of a wide variety of highway speeds because they can occur at any absolute speeds. The data indicate the wide range of response distances associated with the various obstacles as seen with the density level I filter. It is important to note that when coming relatively unexpectedly upon targets of unknown size, shape, and color even the most noticeable target (car with headlights on) was not seen until it was on the average 48.40 inches or 290 feet away at 20 mph and 46.15 inches or 277 feet at 30 mph closing rate. In fog density level II, only the car with headlights on could be seen and then not until it was 87 feet away at either closing rate.

5. Five of the seven obstacles were responded to sooner (at greater distance) at 20 mph than at 30 mph closing rate which is in the expected direction. Response times can be inferred from the the differential distances. The average difference in response distance for the two speeds is 3.47 inches, which scales to 20.82 feet. If it is assumed that the target becomes visible at the same distance for the two speeds, then the reaction time can be readily shown to be equal to the ratio of the difference in the reaction distance to the difference in speeds. The difference in speed was 10 mph or 14-2/3 feet/second. Therefore the inferred reaction time averaged over the seven objects is 1.4 seconds.

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CONCLUSIONS

1. The UCLA TV driving simulator is capable of modification to present a fog-like roadway scene which produced differential driver responses as a function of two levels of reduced visibility.

2. The data in Table D-1 show differences that were expected; the calibration targets were detected further away when the "fog" density was less and the targets were receding. The approaching targets simulated transitioning from "uncoupled" to "coupled" as described in the UCLA Rear Lighting Study (23). The receding targets on the other hand are more representative of driver behavior during car following (coupled). Therefore, these calibration threshold data should be considered in two separate categories:

a) Target approaching at 15 mph closing rate, density level I produced an average response distance of 57.69 feet, which when multiplied by 72 (the scale used) and converted to feet, gives a 346-foot visibility distance.

b) Target receding at 15 mph rate, density level I produced an average response distance of 80.89 feet; scale equivalent is 485 ft.

The standard psychophysical technique for establishing threshold data is to average the ascending (approaching) and descending (receding) values. This would yield a threshold of (485 + 346) ÷ 2 = 415 feet visibility distance for the density level I filter which was designed to achieve approximately 500-foot visibility.

3. The calibration threshold data for the density level II filter shown in Table D-1 indicates that the approaching target was responded to at an average distance of 5.96 inches, which is equivalent to 36 feet. The receding target was visible until it was (on average) 12.53 inches, or 75 feet, away. The average visibility threshold is thus (36 + 75) ÷ 2 = 55 feet, which is almost twice the anticipated visibility distance.

APPENDIX E
FOG MEASUREMENT TECHNIQUES

PARAMETERS TO BE MEASURED

The analysis leading to the analytic models disclosed that fog extinction coefficient σ, backscatter coefficient β_π, and natural illumination backscatter brightness are the most important of the environmental parameters that need to be determined or estimated in order to allow a reasonable prediction of the visibility through highway fog. Since a high degree of precision is not required, a photometer to measure the natural illumination levels poses no major difficulties. The most likely candidate is a photometer using a cadmium sulfide or related cell. These are reliable and relatively inexpensive devices. Other candidates would include the iron selenium cells, silicon (p-n junction) solar cells, photosensitive transistors, etc. For the simpler systems, simply knowing whether it is daylight may suffice.

Considering the fog parameters and their influence on visibility, the extinction coefficient describes the attenuating properties of the fog, while the backscatter coefficient determines the background luminance or glare produced by the driver's own headlights. In considering gross fog levels of significance to vehicle operation, it is felt that sufficient accuracy can be obtained by assuming that $\beta_\pi = 5.7 \times 10^{-2} \sigma$. Thus our primary consideration will be directed toward the measurement of the extinction coefficient. As the extinction coefficient embodies the combined effects of attenuation by both scattering and absorption ($\sigma = K_s + K_a$), one must use precaution in its application. For the case of natural fog, $\sigma \approx K_s$; i.e., only scattering attenuation is significant. When strong concentrations of gaseous pollutants or smoke exist, the absorption attenuation may not be negligible, in which case the approximation of β_π is in error on the high side.

AVAILABLE INSTRUMENTATION

The measurement of extinction coefficients in fog on an operational basis has only recently become an area of significant concern.

Fog measurement instrumentation is just now becoming a standard measurement tool in large commercial and military airports, and only a relative few types have been extensively proven in the field. The instruments considered to be of possible use to the highway fog problem and for which at least a manufactured prototype exists fall under the general classifications of backscatter, forward scatter, total scatter, and transmission. Most of these devices are normally obtained already calibrated in terms of Koschmieder's or Allard's definition of visibility, but could just as easily be calibrated in terms of extinction coefficient or highway visual range according to our models. All of the standard scattering types of measuring devices are incapable of accurate measurements when significant absorption exists; thus they are useful only when relatively clean fog exists.

<u>Transmission Measurements</u>

The attenuation over a specified path of a collimated beam of light can be measured by the placement of a telephotometer at the termination of that path. The transmittance of that path can thus be determined through Bouguer's law. Instrumentation exists for such measurements, taking the form of the Douglas transmissometer-the standard in the U.S. The mean extinction coefficient for the measurement path can be extracted from these measurements and is representative for both scattering and absorbing atmospheres. The Douglas transmissometer has been developed by the National Bureau of Standards over many years and is considered the most reliable means of measurement at this time. Numerous NBS, FAA, and National Weather Service test reports exist that evaluate its merits.

The transmissometer, however, is not considered the best form of instrumentation for the highway fog problem for many reasons. Capital costs are high. Installation must be optically precise, possibly incurring costs equaling equipment costs. Installation is permanent, requiring rigid mounts separated by 250 to 500 feet with an unobstructed line of sight. Maintenance requires specialized technicians and must be performed in the field. Dirt and grime on optical windows are detrimental to accuracy, and recalibration can only be acquired on very clear days. The fixed baseline prevents detection of fog patches unless

they move through the transmissometer's measurement path. It is out of the question, considering its fixed mounting, to change location according to needs. Other reasons can be listed, but these alone are felt sufficient to justify not considering the transmissometer for use in this program or on an operational basis.

<u>Total Scatter Measurements</u>

The measurement of light flux scattered in all directions (4π steradians) by a sample of the scattering medium leads directly to the value for the scattering extinction coefficient through the application of classical scattering theory An instrument for making such measurements is called a nephelometer. Its use is valid only when absorption is negligible. The Meteorological Research, Inc. (MRI), integrating nephelometer is the only commercial device offered for field use uncovered in this study capable of approximating a total scatter measurement. In operation, a sample of the fog or other scattering medium is continuously pumped through the device. Within a tubular measurement cavity, strategically spaced optics make the required scattering measurements. In theory, these measurements produce an accurate evaluation of the scattering attenuation coefficient. The resultant information must be applied with the assumption that the sample is representative of the entire local environment. The validity of any measurement technique that introduces a possible disturbance to the medium being measured is open to question, and evidence of such a disturbance was uncovered during an evaluation test conducted by the Air Force Cambridge Research Laboratory at Cutler, Maine, in 1970. A full report on these tests has not been released. A new visibility measuring instrument (called Visiometer Model 1580) employing open cavity measurements was developed to correct this problem and has been put into production. No independent test data are available at this writing.

<u>Backscatter Measurements</u>

The measurement of the intensity of light scattered through 180° by a representative volume of fog can be correlated to the scattering attenuation coefficient (or the extinction coefficient in the absence of absorption). Devices for this purpose typically transmit

pulses of light to a volume of fog located 20 to 50 feet from the instrument. This volume is simultaneously monitored by a backscatter detector mounted very close to the projector. It has been shown by independent studies of this technique that an overall accuracy of 80 percent can be expected. In practice, better accuracy has been obtained, especially when an instrument is calibrated for and used only in that particular geographical fog regime.

Backscatter measurements of this type are usually, as with the nephelometer, point measurements. That is, a relatively small volume fixed in space is sampled. Such measurements are not always representative for nonhomogeneous conditions, such as patchy or rapidly varying fog. It is possible to provide fog patch probing capability to backscatter devices with the addition of ranging functions and substantial added cost. No devices with this capability are known to be on the market at this time. The major disadvantage to backscatter intensity measurements is that caused by optical degradation produced by condensation or dirt on optical windows. Since the calibration depends on constant backscatter per degree of fog density, the loss of transmission through optical windows can be severely detrimental. Essentially, two backscatter visibility devices are considered commercially available: the Impulsphysik Videograph B and the AGA Corporation RTM-1 fog detector. A third device, the Hoffman Electronics Corporation VMS-508A fog detector has been tested by the National Bureau of Standards, but its availability is not certain at this time. The first two devices were tested by the U.S. Coast Guard, and the results given in U.S.C.G. Office of Research and Development Report #512, "Fog Detectors for Unmanned Aids to Navigation". The Videograph has been recommended for qualified acceptance by the Coast Guard testing agency.

<u>Forward Scatter Measurements</u>

There exists a school of thought which maintains that a better correlation with visibility may be obtained by the measurement of scattering in the forward direction. In principle, a volume of fog particles is illuminated by a light projector. This volume is then monitored by a light detector placed so that light emitted from the side opposite the illuminated side can be measured. In various ways, direct transmission is blocked so that only

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the light scattered to one side of the projector axis is detected. The intensity of this scattered light is an empirical measure of the scattering coefficient (or extinction coefficient in the absence of absorption.) The disadvantages of this measurement technique are similar to those of the backscatter method. In practice, the projector and receiver are facing each other and separated by a few feet. A relatively small fog volume is sampled at one point in space. Only fog passing through the instrument is sampled. Thus patches and banks of fog cannot be detected when they are remote to the instrument location. Condensation and dirt on optical windows are detrimental to measurement accuracy, as with the instruments previously discussed. As with backscatter or nephelometer type instruments, the measurement accuracy depends on the calibration, which must be obtained from an independent source of visibility information such as the transmissometer. Thus it is expected that ultimate accuracy is in the region of 80 percent, similar to backscatter techniques.

Commercially available examples of forward scatter visibility meters are found in the EG & G, Inc., FSM-1; the Impulsphysik Fumosen; and the AEG/FFM, popularly known as the Telefunken forward scatter meter. The FSM-1 was developed for the Air Force and fully tested at Cutler, Maine, and Otis A.F.B., Massachusetts. AFCRL Report 71-0315 describes the results of the Cutler, Maine, tests but omits mentioning the results associated with other visibility devices tested simultaneously (AEG/FFM, MRI nephelometer, and an AFCRL experimental backscatter device). In brief, the report states that during homogeneous dense fog conditions the correlation between the FSM-1 and transmissometer measurements was 91 percent, with a standard error of estimate of 26 percent. Large disparities were noted during high frequency fog density fluctuations attributed to differences in volume sample size of the two instruments. (Note that similar discrepancies were found with the Videograph.) Recent modifications of the FSM-1 and subsequent testing at Otis AFB have produced excellent correspondence with transmissometer results under fluctuating conditions.

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There are no known available independent test results for the Impulsphysik Fumosen. This relatively new device was built to fulfill the need for low cost gross fog level measurements. It is reported to have a measurement range of from 50 to 5000 meters meteorological visual range. Three adjustable relays can be pre-set to react to any of three visibility levels within the measurement range. This seems to be in line with present thinking with respect to requirements for the measurement of a highway visibility index.

Optical Contrast Measurements

A different and more direct approach toward determining visibility in fog is being exploited by the Photobell Company in their Visibility Distance Sensor. The device makes a measurement of the apparent contrast of a target typically 250 feet away. As with the transmissometers, different baselines can be selected but the dense fog of concern to highway operations favors the shorter baselines. This type of device provides a close analog to visibility fog under daytime viewing conditions. A headlight is provided to illuminate the target and the fog under night conditions.

Since night lighting viewed by drivers can not be precisely duplicated, and because of taillights, etc., the instrument response is probably not the same as vehicle sighting distances at night. It may, however, provide close to the equivalent daytime sighting distance which would be useable.

No independent test results are currently available.

State Of The Art Techniques

Government sponsored research is being carried out by various organizations in the use of lasers for probing through fog and clouds, and measuring visibility. Much of this work has been conducted using high-powered ruby and neodymium lasers for probing to great distances. The use of high-power lasers along highways is not practical for obvious safety reasons. Other investigations have considered the use of low peak power, high prf GaAs lasers for probing visibility measurements. The Sperry Rand Corporation is currently developing a probing visibility meter for the U.S. Air Force. This visibility meter, which is intended for use at airports for measuring slant range visibility, is relatively complex

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and has considerably greater capability than can be readily justified for highway use. The development of a simpler visibility meter using this or similar techniques appears to be technically feasible, but as far as known is not being undertaken at this time. As no probing device is yet on the commercial market, the weighing of relative values is premature.

SUMMARY

Of the visibility devices presently available, all sample limited fog volumes. The transmissometer, although sampling perhaps the most representative volume, requires rigid emplacement. Present trends in research favor development of probing devices; that is, devices which can sample over extended paths from one fixed location. From practical highway fog measurement considerations two practical approaches exist: inexpensive small volume sampling, or probing techniques. In the first, many devices could be distributed along the highway for adequate coverage. In the latter, one more expensive device could cover, perhaps, one mile of highway. Table E-1 lists some of the competitive devices. In all cases, installation costs may be appreciable; particularly with devices requiring installation of two parts. Most of the devices have been made only in prototype or low production quantities.

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TABLE E-1

VISIBILITY METERS

Principle	Name, Model, Etc.	Manufacturer
Forward Scatter	FSM-1	E. G. & G., Inc. Cambridge, Mass.
	AEG/FFM	AEG (Telefunken) Germany
	Fumosen	Impulsphysik Germany
	Not Known	McGraw Edison
Backscatter	VMS-508A	Hoffman Electronics (?)
	Videograph	Impulsphysik (Sperry Ottawa)
	RTM-1	AGA (Sweden)
Nephelometer	Integrating Nephelometer	MRI, Altadena, Calif.
	Visiometer	MRI, Altadena, Calif.
Transmission	Transmissometer	Winslow Teletronics, New Jersey
	Skopograph	Impulsphysik Germany
	Not Known	Elecma (Snecma) France
	SM-4	Lear Siegler Inc. Englewood, Colo.
Optical Contrast	Not Known	Photobell Co., Inc. New York, New York

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APPENDIX F

HIGHWAY FOG COUNTERMEASURES SUMMARY

The subject of fog abatement was dealt with rather extensively in the previous NCHRP Study (1) and since abatement techniques are beyond the scope of this study, they will not be discussed in detail.

VEHICLE DESIGN FEATURES

Vehicle design changes take several years after they are introduced before they become the general rule, even on mandatory safety features, so they are somewhat limited in terms of immediate help for specific highway problem areas. They conceivably could be made a prerequisite for entry to turnpikes and similar controlled access highways, however, during periods of high fog susceptibility. They could also be included on specially equipped vehicles used for escort, convoy, "round robin", or similar duty.

Vehicle lighting improvements fall in the category of aiding visibility in fog. They are applicable primarily to improving visibility at night or under low ambient light conditions, and will provide no help during high ambient brightness daylight fogs. From examination of the analytic models and the principles involved, it is evident that visibility through fog can be increased if the light (or contrast ratio) at the target can be increased without at the same time illuminating the fog through which the observer must see. It follows, therefore, that a vehicle may be seen further away in the fog if the intensity of the taillights on the vehicle are increased. Lindae (11) has addressed this possibility. The chief limitation to indefinitely increasing taillight and stoplight intensities other than legal limitations are the glare and dazzle effects the higher intensity lights produce in the absence of heavy fog. Lindae, after making some tests on an unspecified number and age of subjects, suggests as a limit the point where glare, chiefly psychological, becomes bothersome, 250 candles. Although Lindae's work is limited (for example, a single value of backscattered headlight brightness was specified, whereas the actual values are a function of the fog density), there is no question that the visibility of vehicles ahead can be improved by increasing rear lighting intensities.

F-2

Headlights should be mounted as low with respect to the driver as possible and should avoid spilling light in the upper direction to avoid illuminating the fog through which the driver must see (particularly close in). If this is done, an increase in headlight intensity will be beneficial. The limitation is again glare and dazzle, in this case primarily for the oncoming driver, particularly with no or light fog.

On vehicles especially equipped for escort service, or where assurance can otherwise be provided that high intensities would be used only in restricted visibility conditions, very high intensities could be used. The intensity could possibly be made a function of fog visibility index.

The category of other-vehicle-mounted devices would most likely be equipment installed as part of a warning and guidance system. One example is the use of a roadside transmitter in conjunction with a vehicle receiver for disseminating localized fog and other hazard warnings. Specialized transmitters and receivers could conceivably be used to control special vehicle-mounted, high-intensity lighting systems. The use of vehicle-mounted equipment could simplify the implementation of block warning and guidance systems.

SPECIAL LIGHTING

At night, special luminaries can be of help. As with headlights, the objective is to illuminate the roadway, vehicles, and other objects to be seen without at the same time illuminating the fog through which the driver must see. This is impossible to achieve fully. However, low-mounted luminaires which direct the light across the road and slightly away from the driver can be a distinct help. The angle at which the light is directed makes a difference, since light is not scattered uniformly in all directions by fog. For most fogs, the least light is scattered in a direction about 110 degrees from the incident light. The precise angle is not critical, the minimum being quite broad. When driving to and from the sites of the on-road testing, it was noted subjectively that even standard overhead mounted luminaires frequently appear to improve visibility. The preferential scattering may have been a factor, since some of the intervening fog was also illuminated.

F-3

The New Jersey Turnpike has in the past tried two different types of special lights in the Newark area. One consisted of rather closely spaced high-intensity lights mounted above the roadway looking down and across the road, essentially normal to the line of vision of the drivers. They provided some improvement; however their use was discontinued because the fog was causing potential confusion with the approach lighting of nearby Newark Airport. The other special lighting tried in the same area consisted of fluorescent lights mounted low, looking across the road. These also improved visibility, but the nonuniformity of the lighting produced an annoying and potentially dangerous flicker effect on the drivers as they drove through the area. The difficulties encountered do not seem to be of a fundamental nature, however, and it seems likely that satisfactory luminaires and installation could be developed.

The chief limitation of improved or special lighting is that it offers little or no help in daylight when high levels of natural illumination override any reasonable levels of artificial illumination. As has been noted previously, in many areas daytime fogs appear to be more of a problem than nighttime fogs.

OPERATIONAL TECHNIQUES

The countermeasures listed in Table 2, warning signs through special escort and radio warning systems, can all be loosely grouped under the category of operational countermeasures. Several of these are interrelated, and they can be used in sequence or together as part of a more comprehensive fog warning and guidance system. Recalling that one of the major areas of concern is the increase in multi-vehicle accidents in fog, and that most drivers have been found to overdrive their visibility, particularly in the heavier fogs, a general lowering of speeds of the vehicles appears desirable, particularly if all of the vehicles could be made to reduce their speed to the safe stopping speed or lower. The lowering of speed limits is a direct approach. The lowered speed limits, however, must be communicated to the drivers, and the drivers induced to obey them, if they are to be effective. The intent of many of the operational techniques is to effect such a reduction in speed. Also desired is a reduction in the spread of vehicle speeds to reduce the

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relative velocities and therefore the potential for the initiating incident of multi-vehicle accidents. Procedures which significantly reduce the speeds of only half the vehicles are worse than nothing, even though the mean speed is lowered substantially. The independent and indiscriminate application of almost any of these techniques (other than road closings or special escort where direct control is exercised over the vehicle movements) has been found almost universally ineffective in either reducing accidents or appreciably lowering vehicle speeds. This was evident from the California "Reduced Visibility (Fog) Study" (2) and from discussions with turnpike operating personnel, state highway department personnel, etc.

Fixed fog ahead or fog area signs in particular seem to have little effect. This may be due to the comparative rarity of fog which tends to condition drivers to ignore the signs. The difficulty experienced by drivers in accurately judging actual visibility may also be a factor. This is particularly likely when the driver is not familiar with the area, when he has had little experience in judging visibility, and when driving in an area where there are few known types of objects upon which to base a judgement.

The deployment of special fog warning advisory and speed advisory or regulatory signs, or the similar use of manually operated warning signs has been tried a number of places, and is still being used to some extent. They have not in general proved effective, although under some circumstances possibly could be made to be. The experience of the Oregon State Highway Division on an approximately 6-mile section of I5 which has been particularly susceptible to fog is probably typical. This section had shown a particularly poor accident history during periods of reduced visibility, experiencing almost as many accidents as the remaining 300 miles of the road in Oregon.

Quoting from the interim report (12):

"In 1966, orange diamond-shaped warning signs were installed in the area on an experimental basis. The signs were installed with battery operated flashing lights fixed to the top of the post. With the onset of fog, they could be manually turned to face approaching traffic. This increased the work load of the already busy State Policemen. Fog duty required the activation of the signs, patrolling in an attempt to warn or aid, and apprehension of violators. Despite attempts to warn motorists and control speed, the results were discouraging. From eight to ten police cars were needed to hold speeds to a tolerable level within the fog bank."

This project was notable in that it was accompanied by rather intensive patrol activity. The signs were of substantial size, and were accompanied by flashing lights in order to attract the motorist's attention. They did not, however, contain a recommended speed. The project was considered a failure as a means of modifying traffic operations, and did not improve the accident history.

One of the problems associated with manually operated signs such as these is that after the fog is discovered and a decision is made to activate the signs, a patrolman must drive to the site of the sign, get out, activate the sign, get back in, and drive to the site of the next sign, and so on. Considerable time and effort was required and resulted in appreciable delays in the activation and deactivation of the signs. These delays contribute to a lack of credibility of the sign. The delay in the initial discovery of fog was probably not as great for this project as for many similar projects due to fairly intensive patrolling in fog-prone conditions because of the accident history, and also because a State Police Office is located at one of the interchanges in the area.

Because of the poor experience with manual warning signs, and because of a particularly severe fog-related accident in 1968, the Oregon State Highway Division initiated a comprehensive study of operating conditions in the problem section with consideration to possible corrective measures. As a result of this study, the section was selected for installation of a more comprehensive fog warning system incorporating variable message signs. Since the installation there have been fewer fog occurrences, and full evaluation of its effectiveness is yet to be made. On a preliminary basis, however, it appears to be much more effective than the previous signs. This installation will be discussed more fully in conjunction with fog warning systems.

Increased patrol activity by itself was not found by California in their "Reduced Visibility Study" (2) to be very productive in terms of appreciably influencing vehicle speeds in fog. Several different forms of patrolling were tried: increased in-view moving patrol, increased in-view moving patrol with rear amber lamp flashing, and patrol units parked on the shoulder with amber rear lamps flashing. In moderate daytime fog (200-500 feet) all three patrol activities caused a 5 to 6 mph additional reduction in the mean speeds. At night the parked patrol cars caused a 4 to 5 mph reduction in the extreme percentile speeds. No other improvements were noted under any of the conditions, including those with denser fog (200 feet). These tests were conducted on a rural four-lane freeway with visibility of the opposite lanes largely blocked by vegetation. This, coupled with fact that some improvement was noted for moderate visibilities in daylight, suggests that in part the effectiveness may have been limited by a lack of sufficient visibility of the patrol units. Another factor may have been that denser fogs in themselves reduced the speeds somewhat, so that drivers may have felt little legal pressure to reduce their speeds further, even in the presence of a patrol unit.

Special escorts - the formation of convoys, etc. - can be an effective, but somewhat drastic means of controlling traffic operations. The advantages of such techniques is that in addition to providing a positive control over the maximum speeds of the vehicle, they also greatly reduce the dispersion in speeds.

The "round-robin" type of activity employed by the California Highway Patrol during the past several years on an experimental basis may also be included in this category. The distinguishing characteristic of the round-robin is that instead of stopping the vehicles to form a convoy platoon and then proceeding, the patrol units cruise on the roadway at the desired speed, not allowing other vehicles to pass, and form a moving queue behind them. At the end of a patrol section, the patrol unit simply pulls off, turns around and starts pacing the traffic in the other direction, hence the name "round-robin." If the dense fog

continues beyond the end of a patrol section another patrol unit will then pick up the platoon. In cases where this has not been possible, it has been noted that the platoons tend to stay formed, and to continue on at about the same pace. This activity has been accompanied by an extensive educational program in the test area to inform the public of the existence and purpose of the round-robin procedure and the expected response. A fog alert program (known as "Fog Bound") has also been coupled with the overall operation in cooperation with all of the radio stations in the area to warn motorists of possible dense fog, and to inform them that the round-robin procedures are being instituted. The overall operation has been considered a success and is being extended to other areas.

The primary disadvantages of these procedures are twofold. First, there is a definite hazard associated with stopping high-speed traffic on a freeway, or in the case of the round-robin, "coupling" a faster vehicle to the back-end of a platoon, particularly under conditions of restricted visibility. Second, these procedures can be very expensive in terms of required manpower.

In car-following studies and similar studies, it has been determined that once visual contact has been well established, and the vehicles are "coupled", contact can be maintained at a greater distance, or under poorer visibility conditions than those required for the coupling process, i.e. in establishing contact. For this reason, it would appear that the true convoy system might be best suited to fog patch types of situations where the convoy can be formed just outside the dense fog so that the traffic can be stopped in an area where better visibility prevails. The true convoy system is also limited in usefulness to highways where full access control can be reasonably exercised over all entrances to the fog area. The round-robin will have greater applicability to areas where the dense fog extends over a distance of several miles or more, particularly where lighter fog extends over an extensive area. Full control over each entrance to the controlled area is not required. The problem of vehicles entering the controlled section is less severe since the closing speed of a vehicle approaching the end of a queue is reduced by the forward motion

of the platoon and a vehicle previously traveling in fog is not likely to be moving as fast. In situations of a dense fog patch in an otherwise clear area where the fog could be entered unexpectedly, the convoy system will probably be the more suitable of the two.

Roadway closings as a highway fog countermeasure are currently being used primarily by turnpikes and other toll facilities. Few other highways can readily establish control over the entrances in the short periods of time required to make such a step feasible. Insofar as is known, there are no facilities that currently restrict usage to certain classes of vehicles because of visibility conditions, although such control is being exercised for other conditions such as high winds. The closing of a highway is a rather drastic measure and is a step not taken lightly, since it is costly, both in terms of lost revenue to a toll facility and in terms of disruption to traffic operations and inconvenience to the public. In a sense, turnpike closing is frequently not a true solution to the highway fog problem in that in many cases the effect is to shunt the traffic off onto other roads which may be just as fog enshrouded as the turnpike. Unfortunately, there may be, at the time, no better course of action available to the operator and, although traffic operations are drastically reduced, overall safety is undoubtedly improved. The criterion for closing the roadway is generally based on an estimate of visual range by a patrol officer. The practice of the New Jersey Turnpike Authority, for example, is to close a section when the visual range estimated by the officer patrolling that section falls below one delineator spacing anywhere within the section, i.e. he should always be able to see at least one delineator ahead.

A need for restricting the class of vehicles using a highway during periods of restricted visibility has not been clearly established. Such a procedure could be of value in the future if vehicle-mounted equipment is made part of a warning and/or guidance system, particularly during a transition period before all vehicles become equipped. California's operation Fog Bound does involve a voluntary avoidance of the dispatching of trucks, particularly large oil tank trucks, into the fog areas. Trucking companies were requested to take this action since large oil tank trucks seemed to be disproportionately represented in the large multivehicle accidents. Compliance by the trucking operators has been good, the schedules and routes of the trucks were adjusted to provide deliveries, etc., to other areas until the fog cleared later in the morning.

RADIO AND AUDIO ALARMS

Radio presents a potentially valuable means of communicating warning information to the drivers. Radio communication can take several forms. One form in current use to a limited extent is commercial broadcast radio. Many radio stations currently provide traffic advisories on a regular basis, and normally provide information such as roadway closings, and general roadway conditions, including the presence of fog. Fog warnings, however, are generally provided on a somewhat haphazard basis. An exception is the fog warning advisories provided in central California as a part of their operation "Fog Bound". The cooperation of virtually all of the radio stations has been secured, and the warning advisories are broadcast at frequent intervals during a dense fog occurrence (generally early morning). This technique, although it has proved extremely valuable in the California operation, is limited in that there is no requirement that vehicles be equipped with radios or that the drivers listen to the radio prior to starting out on a trip.

A second form is to transmit warning messages on a special frequency or group of frequencies within the broadcast band. This could be implemented by a high-power transmitter covering the entire area, in which case an FCC station license would be required. A more likely implementation would be to install a series of very-low-power transmitters, probably operated under Part 15 of the FCC regulations. This latter alternative has been implemented by a few highway facilities such as tunnels. It has the advantage that the message can be tailored specifically for a particular location. The principal disadvantage is again that there is no requirement that receivers be installed, nor any assurance that the

drivers would turn them on and tune in the advisory station (in place of his favorite program).

A third form of radio communication that has greater future potential is a special low-power short-range system using induction radio. Such a system would allow control of the specific time and place of the communication to ensure the most effective reaction, as with variable message signs. It could, however, transmit a more comprehensive and potentially less ambiguous message that can be readily modified to suit the requirement of the occasion. Receivers would be relatively inexpensive (in the \$10-15 range), and particularly for low-frequency induction radio, could be combined with an automatic vehicle identification system. The cost of a transmitter installation would be at worst comparable to a variable-message sign installation, and probably considerably less. The receiver output could be made to operate a visual indicator or display, which could reduce some of the information content to be transmitted. However for most situations, an audio alarm is more effective in attracting attention than a visual alarm. To be effective, such a radio system would have to be installed in the preponderance of the vehicles in an area, preferably all, of at least a given class. It would be most effective when installed on a national scale. This type of system would be of considerable use in transmitting other types of advisory and warning messages as well.

APPENDIX G

PERFORMANCE DEGRADATION CAUSED BY VISUAL SEARCH

The psycho-physical parameters of the visual contrast ratio threshold ϵ and the illuminance threshold E_T play extremely important roles in the analytic models. They have been extensively studied under static laboratory conditions (6, 7). These studies were made using experienced observers under near-ideal conditions, i.e., no distractions, opportunity to become dark adapted, etc. Driving in fog, however, imposes a dynamic visual load. The driver is denied the visual clues normally available to him which help to focus and direct his attention before a decision must be made, and he does not know precisely where to look for potential threats. A visual search is therefore required. The need for a visual search obviously degrades the contrast ratio sensitivity, as is evidenced by the effect of presentation time on the contrast ratio threshold.

Gold (8) presents an extension of these results for the case of target detection under conditions of limited search at a moderate brightness level of 3.1 foot-lamberts. It was found that searching causes greater performance degradation for small targets in the Ricco region (where the targets subtend an angle less than about 3 milliradians) than for larger targets. At 400 feet, the unlighted rear end of an automobile subtends an angle of 10 milliradians, well above the Ricco region. However, a taillight 7 inches across subtends an angle of 3 milliradians at 200 feet, so most driver sightings of taillights in fog will occur in the Ricco perception domain.

In the Ricco region, it is the illumination produced at the observation point which determines detectability of the target; that is, the product of target brightness and area, not simply the brightness alone, as is the case for larger targets. The illumination produced by a small source decreases inversely as the square of the distance from the source (Allard's law).

Gold (8) reported that the incremental target luminance had to be increased by a ratio of 1.7 for a 3-1/2-milliradian target in order to maintain 50 percent detection probability under the limited search mode, relative to fixated foveal sighting. For a target slightly less than 1 milliradian across, an increase in brightness from 3.43 to 3.97 foot-lamberts was required for 50 percent detection probability against a 3.1 foot-lambert background. Considering the 3-1/2-milliradian target to be above the Ricco region, this represents an increase in the required contrast ratio by a factor of 1.7. Considering the 1-milliradian target to be in the Ricco region, the brightness increase corresponds to a 16 percent increase in the required illuminance threshold.

In addition to requiring a larger stimulus relative to fixated viewing, the subject's reaction time was increased by the need to search while performing a distracting task. Reference 21 describes a laboratory experiment in which the test subjects were distracted by counting oncoming cars in a movie projection of a highway scene while the target appeared at various places in the field of view. Over a wide range of target stimuli, the reaction time varied from 0.55 to 0.72 seconds.

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