NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 95

HIGHWAY FOG

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HIGHWAY FOG

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- TRANSPORTATION ADMINISTRATION
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HIGHWAY RESEARCH BOARD
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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 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 Bureau of Public Roads, United States Department of Transportation.

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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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This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area

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FOREWORD

By Staff
Highway Research Board

This report will be of interest primarily to those concerned with highway safety and traffic control and operations, traffic engineers, automotive engineers, highway designers, roadside development personnel, and highway maintenance personnel. It reviews suggested and tested methods for dissipating fog, including disadvantages as well as advantages of the various techniques. Preliminary investigations resulted in recommendations of ways and means of obtaining effective fog abatement and vehicle guidance systems to combat reduced visibility due to fog.

Fog impairs the safe and efficient operation of motor vehicles. Attempts have been made to prevent or abate fog and to improve visibility and guidance through fog; however, no satisfactory solution to this highway hazard has been found thus far. Fog abatement methods now in use consist of ground-based and aerial seeding of dense natural fog, the use of helicopters, and planting of vegetation. Guidance systems have been classified as active, passive, or signaling—depending on whether the illumination source is a part of the vehicle (headlights), independent of the vehicle (daylight, street lights), or is internal to the guidance target (taillights, turn signals, traffic lights).

The project was undertaken with a view toward improving safety of highway traffic in environments where fog is encountered. The objectives of the Cornell Aeronautical Laboratory in the research reported here were to (1) review and report on past and current research of warm and cold fog as it affects highway operation, including such factors as fog abatement, guidance systems, measures of visibility, and effect on traffic operations; (2) determine the effects of day and night fog levels on driver performance and traffic operations; (3) explore the feasibility of warm and cold fog abatement and of vehicular guidance systems under highway conditions; (4) test fog abatement methods and guidance systems under highway conditions; and (5) suggest ways and means of obtaining maximum effectiveness of systems to combat reduced visibility due to fog.

This report shows that the research was successful to varying degrees in these objectives. However, much work remains to be done in the total problem area, particularly in respect to determining the day and night fog levels (standards of visibility) that produce significant detrimental effects on driver performance and traffic operations. Funds for additional research have therefore been allocated from the FY 1970 program, and this work is expected to begin in late summer of 1970. In addition to determining the needed standards of visibility, this research has the second objective of further exploring the feasibility of active and passive guidance systems for freeways and expressways to inform and warn the motorist of prevailing roadway fog and traffic conditions ahead and to guide and control traffic more safely and conveniently through the fog area.

CONTENTS

ACKNOWLEDGMENTS

The study reported herein was conducted under NCHRP Project 5-6 by members of the Applied Physics and Transportation Research Departments of Cornell Aeronautical Laboratory with Warren C. Kocmond and Kenneth Perchonok serving as Co-Principal Investigators. Roland J. Pilié, Assistant Head of the Applied Physics Department, made important contributions throughout the course of this investigation. Gratitude is also expressed to members of the Atmospheric Physics and Dynamic Meteorology Sections and to personnel of the Transportation Research Department, who participated in various aspects of this study and who helped in the writing and editing of this report.

Special mention is made of Glenn Banfield, Manager, Chemung County Airport, Elmira, N. Y., for his cooperation and assistance during the fog abatement tests. Finally, thanks are due the New York State Department of Transportation for permission to use N. Y. State Route 17 during the traffic measurement portion of the program.

HIGHWAY FOG

SUMMARY

A review of the literature shows that fog has had the following effects: (1) a slight reduction in accident frequency, (2) an increase in the likelihood that an accident will result in a fatality, and (3) an increase in the likelihood that accidents will involve either a single vehicle or more than three vehicles.

Traffic measurements made during this project indicate that: (1) speeds were slightly lower in fog, (2) the probability of overdriving one's visual range was greatly increased, and (3) lateral location and vehicle interactions were not affected by fog. It is concluded that drivers exercise more caution in fog, but that the increase in overdriving probably explains the increased severity of accidents.

Field tests have demonstrated that visibility in dense fog can be improved by seeding with practical amounts of carefully sized hygroscopic material. Additional studies are needed to refine seeding procedures and to determine the scope of application for highway fog abatement. Other concepts (e.g., vegetation barriers to influence the movement of shallow fog, monolayers to inhibit evaporation from water reservoirs, use of helicopters to mix drier air with fog) have limited application and may be tailored to specific types of highway fog. These concepts are discussed in this report.

Previously suggested vehicle guidance procedures were studied. It was determined that specially designed lights mounted near the road surface, producing an area of illumination directed about 110° to the direction of traffic flow can be used to effectively provide illumination for night driving in fog.

A vehicle guidance system involving the use of polarized headlamps was evaluated in field experiments and judged impractical as an aid to drivers in fog.

Measurements of the effect of vehicle lighting on visibility showed that rear lighting systems can be improved to allow better detection of vehicles in fog.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

The occurrence of dense fog on highways is an obvious hazard capable of impairing the safe and efficient operation of motor vehicles. Attempts have been made to prevent or abate fog and to improve visibility and guidance through fog, but to date no satisfactory solution to this problem has been found.

The project has had the following objectives:

1. Review past and current research of warm and cold fog as it affects highway operation.
2. Prepare a state-of-the-art summary of fog abatement procedures, guidance systems, measures of visibility, and effects of fog on traffic operations.
3. Determine the effects of day and night fog levels on driver performance and traffic operations.
4. Explore the feasibility of warm and cold fog abatement and of vehicular guidance systems under highway conditions.
5. Test fog abatement methods and guidance systems under highway conditions.
6. Suggest ways and means of obtaining maximum effectiveness of systems to combat reduced visibility due to fog.

This report summarizes the research findings.

CHAPTER TWO

FINDINGS

LITERATURE REVIEW AND STATE-OF-THE-ART SUMMARY

A review of pertinent literature was made to assess the state of the art of fog abatement, methods of vehicle guidance in fog, and past and current research related to the effect of fog on highway operations. In preparing the summary, consideration was given to several other areas directly related to highway fog. For example, supplementary discussions of the physics of fog formation, visibility in fog, and a fog climatology for the United States are presented in the summary with the intent of providing a rather broad background to the researcher interested in the highway fog problem. The completed summary is presented in Appendix A of this report. (A listing of all references used in preparing the state-of-the-art review is included as Appendix H.) Important findings of the review are presented in the following.

Effect of Fog on Accidents and Traffic Flow

The effect of fog on accidents has received only minor attention in the past in terms of empirical research and is not well understood; this is due primarily to the difficulties associated with the collection of valid data describing traffic exposure to fog and nonfog conditions. On the basis of studies of individual accidents, it can be said that fog is capable of inducing accident involvement. On the other hand, results of an investigation in metropolitan Melbourne (Foldvary and Ashton, 1962) showed that fog significantly reduced the probability of casualty accidents. These findings suggest that fog has mixed effects in the sense that it is a hazard with which drivers attempt to cope, but not all are successful in doing so.

In a sample of accidents on California freeways (Johnson, 1965), the fatality rate in fog was essentially twice as high as in nonfog conditions. In another California sample [*Reduced Visibility (Fog) Study* (1967)],* it was found that accidents occurring in fog had an increased probability of involving either a single vehicle or more than three vehicles. Based on these studies it is reasonable to conclude that fog acts to modify the nature of accidents.

Data obtained on selected sites on California freeways and expressways in both day and night conditions indicate that the effects of fog on traffic flow are not large. Mean speeds were reduced by only 5 to 8 mph; speed variation also decreased. In addition, there was a decrease in the number of very short and very long headways. The decreased speeds and increased uniformity attest to the fact that drivers recognize fog as a hazard requiring some increased caution in driving.

* Hereafter referred to as *RVFS*

Guidance Systems Designed to Reduce the Fog Hazard

A review was made of a wide variety of vehicle guidance systems proposed for use during conditions of reduced visibility. In general, procedures using artificial lighting have been most effective in improving a driver's perception in fog. Visibility in both day and night fog has been shown to be dramatically improved when artificial lights are employed as (1) lane delineators and (2) specially constructed street lamps which have been modified to produce a narrow beam of illumination. The use of street lamps having a narrow beam spread, with the beam perpendicular to the driver's line of sight, was studied by Pritchard and Blackwell (1959) and Spencer (1961). Field studies by Spencer on a section of the New Jersey Turnpike demonstrated that lights placed at low elevations alongside the roadway were quite effective in improving traffic operations in dense fog. Good results were reported in Europe from a lighting system which involves cylindrical lanterns placed about 3 ft above ground level and producing a fan-shaped beam directed at about 110° to a driver's line of sight. The low lighting system is said to have significantly improved vehicle guidance in dense fog (*Illum. Eng.*, 1967).

In contrast, tests involving reflectorized pavement markings (beaded lane delineators and edge striping) resulted in only slight increases in visibility and had virtually no effect on traffic flow during daytime fog conditions. Interviews with a sample of drivers revealed that at night, however, the reflectorized treatment alone provided as much information as full overhead lighting.

A guidance system involving polarized fog lamps (Nathan, 1957) was evaluated by the research agency in the laboratory and in field experiments. The concept was shown to be impractical for use on highways. Additional discussion of the field tests appears in "Vehicle Guidance Investigation" in this chapter.

Very recently, a gated laser technique has been advanced by Laser Diode Laboratories (*Prod. Eng.*, 1969), for use during periods of poor visibility. The hand-held system employs a pulsed gallium arsenide laser that emits in the infrared and receives reflected light from objects on a photocathode image converter tube. At present, the system is said to have a range of only 300 ft, although work is continuing to develop a capability for greater range.

Research also has been conducted in the area of traffic control during periods of fog. In one study (*RVFS*, 1967), speed limit signs were effectively used to reduce speeds of vehicles by 5 to 10 mph over the reduction attributable to fog alone; the technique was effective only as long as the posted speeds were greater than 40 mph. The presence of police patrol cars has been found to be effective in reducing the speed of drivers in fog (*RVFS*, 1967). The results revealed that speed reductions averaging 3 to 6 mph could be obtained by using moving or parked patrol cars along the roadway. In night fog, however, only parked patrol cars had an effect on average vehicle speed.

Fog Abatement Systems

As part of the literature review, an examination was made of warm and cold fog modification concepts to determine whether, and to what extent, previously suggested abatement systems could be used on highways to alleviate the fog problem. Of those considered, four concepts were judged more promising than the others. They are:

1. Fog seeding.—Briefly, this concept involves disseminating prescribed amounts of carefully sized hygroscopic materials into fog to cause a favorable redistribution of drop sizes, which results in improved visibility. At present, a seeding technique, which was developed at the research agency, is being used at some airports in the United States for warm fog modification. The technique is described in "Fog Abatement Investigation" in this chapter. Results of the CAL-NASA fog seeding tests are presented in Appendix B. The concept may be useful for general highway application, provided that reliable and easily maintained equipment can be installed along the roadway. Equally important in the efficient use of this technique will be the development of improved methods of disseminating the sized hygroscopic nuclei into the fog.
2. Helicopters.—Recent experiments conducted by the Air Force (AFCRL) have shown that it is possible to dissipate 1,000-ft-thick stratus clouds by using very large helicopters to mix the saturated air with drier air from aloft (*OAR Res. Review*, 1968). The technique can be used equally well for dissipating certain types of radiation fogs that are capped by warmer drier air. The system requires that the humidity of the drier air be 90% or less, because mixing nearly saturated air with the fog can cause the cloud to become more dense. It is possible that, for highway application, effective dispersal of fog could be achieved by seeding from the air using helicopters to disseminate hygroscopic materials. The benefits of both techniques might then be realized.
3. Forest stands and vegetation barriers.—The proper use of vegetation to block movement of shallow fog from higher elevations to low-lying surrounding areas appears to be applicable to many highway fog situations. Because no maintenance or operating costs are involved, implementation of the concept would be inexpensive. Airborne surveys could be conducted to determine regions where vegetation barriers might be used to influence fog movement.
4. Supercooled fog dispersal.—The dissipation of supercooled fog is an operational reality at many airports. For those areas of the United States where the incidence of supercooled fog is sufficiently high (e.g., Northwest states), standard cold fog seeding techniques can be employed to cause dissipation over heavily traveled sections of highway. The same problems that limit the hygroscopic nuclei seeding technique also hamper efficient use of this concept (i.e., installation, maintenance and operation of the equipment).

At the end of this chapter recommendations are made for use of fog abatement techniques on highways.

INVESTIGATION OF THE EFFECTS OF FOG ON TRAFFIC

The changes in traffic associated with reduced visibility due to fog are not easily predicted. The difficulty arises primarily from the ability of drivers to compensate for impaired vision. Specifically, reduced visibility tends to decrease the driver's ability to coordinate vehicular control with environmental demands. On the other hand, the driver can be expected to exercise more caution; this increased care may or may not result in overt changes in vehicle movement. For some measures of vehicle dynamics and their relationships with the environment, the two effects can be expected to essentially cancel one another so that no changes occur. For example, drivers in fog may desire to maintain uniform traffic flow and yet be unable to see well enough to do so. Although such cancelling effects need not always occur, this potential interaction is capable of producing situations in which predictions of change, and even observations of change, are simply not available.

Before proceeding with a discussion of the observed effects of fog on traffic, a brief summary of the experimental design is given Data were collected on six different days on a four-lane, divided, rural highway, near Elmira, N.Y. The analyses were performed primarily in the context of a two-way layout in which any particular variable could be studied as a function of visual distance for a given time of day. The visual distance was taken as the maximum distance from which the rear of a vehicle could be seen. (The rationale for choosing this measure of visual distance and the method of its determination are discussed in Appendix F.) Visual distances for purposes of analysis were grouped into 100-ft intervals. Time of day, in intervals of 1 hr, was chosen as a control variable, so that the effects of changing visual distance could be studied within each such time interval. Selecting time of day as a control variable minimized contamination of the results due to changes in driver population and changes in traffic volume.

Data describing volumes, sample sizes, and the variation of volumes within time intervals are given in Appendix F.

Only those variables having essentially monotonic relationships with visual distance are discussed in this section. Other detailed analyses, which include the study of lateral placement, use of passing lane, time headway, vehicle spacing, a measure of the time within which speed or lane must be changed to avoid collision, and the variance of all behavioral measures, are treated in Appendix G. It is important to recognize, however, that although no systematic changes were found between fog density and the variables discussed in Appendix G, the findings are germane to the program objectives. In Chapter Three the significance of the findings is evaluated.

Speed

The effect of fog on driver speeds is plotted in Figure 1. The data show that for the 7 AM (7 to 8 AM) and 8 AM (8 to 9 AM) periods there was a general tendency for speeds to decrease as visual distance decreased. Notice, however, that the speed reductions are not large, being in the neighborhood of 4 to 5 mph. It can be seen that reduction in speed starts to occur well before visual distances are as low as 500 ft. According to the AASHO *Geometric Design*

(1965), the stopping sight distance for 65 mph on a dry road is 489 ft, allowing 2.5 sec for driver perception and reaction. (The road surface was dry during all data collections made in the program.) Thus, drivers begin to reduce speeds in response to reductions in visual distances which are greater than stopping sight distances.

Speed also was studied for a subsample of vehicles (which will be referred to as isolated vehicles). This subsample included only those vehicles for which the previous vehicle, in the same lane, was estimated to be at least ½ mile away. These isolated vehicles, then, were virtually unconstrained by traffic with regard to speed; they also were provided with only minimal guidance by traffic ahead.

Figure 2 shows the mean speeds of the isolated vehicles as a function of visual distance. Although the numbers of observations are not high, the mean speed of the vehicles follows essentially the same trends observed for those of the complete sample. The main difference is that the isolated vehicles averaged approximately 3 mph higher speeds.

A second type of analysis was applied to study potentially hazardous conditions as a function of visual distance.

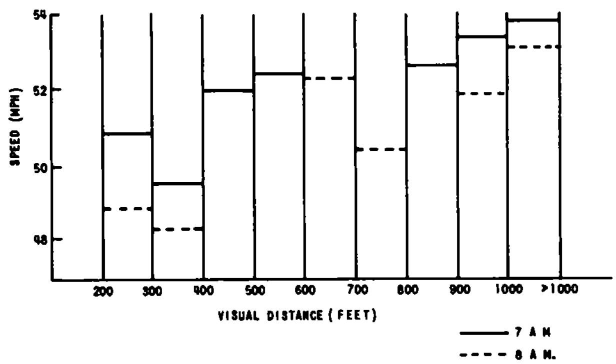

Figure 1. Mean speed as a function of visual distance.

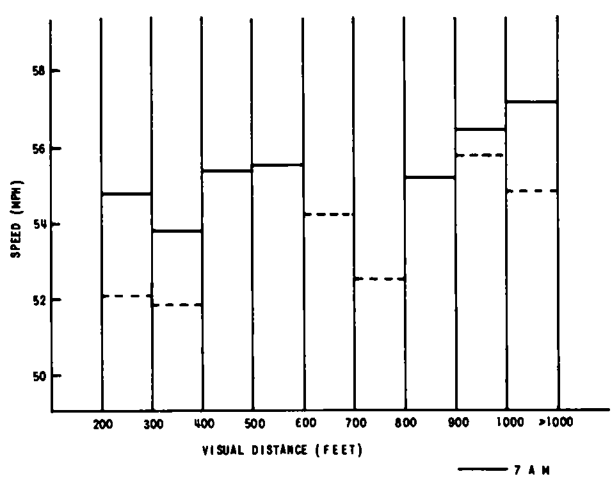

Figure 2. Mean speed as a function of visual distance for isolated vehicles.

In this analysis the probability of high speeds was investigated. There was some difficulty in selecting that speed which was to be used as the threshold of risk-taking. If an extreme value had been used, the numbers of drivers exceeding that value would have been low and reliability would have become questionable. If a value which was not extreme had been used, the element of risk could have been lost and the results would have tended to simply reflect the curves obtained by plotting means. Therefore, the threshold value was chosen so as to minimize the characteristics of either extreme.

Figure 3 shows the probability that speed exceeds 60 mph for the various visual distance intervals. It can be seen that the likelihood of high speed decreased as visual distance dropped. In the 200- to 300-ft range there is a total of 12 drivers exceeding 60 mph. Although this frequency is low, it is important to point to this evidence that some drivers were willing to tolerate the inherent risks (i.e., even if most of the drivers had chosen to drive slowly, some did not).

Stopping and Stopping Sight Distances

One measure of safety of traffic flow is the probability that the speed and visual range relationship is such that a driver could not stop his vehicle before striking a nonmoving object in the road. This occurs when the distance traveled during the time required to observe, perceive, make a decision, react, and decelerate to a stop is greater than the visual range. This act of overdriving is relevant only to those situations in which the driver might come across an object with essentially no velocity in the direction of traffic flow. This is normally not the situation; however, it is probably the mechanism whereby foggy weather accidents involving few vehicles are extended to accidents involving many vehicles.

Because the time required prior to overt response can be estimated only roughly it is difficult to determine which formulation of stopping sight distance to use. For that matter, simple response time itself is not available in terms of a single precise number. Furthermore, one might well expect drivers to be more attentive in fog than in clear weather conditions, thus rendering clear weather times invalid. In view of these problems, two measures of the

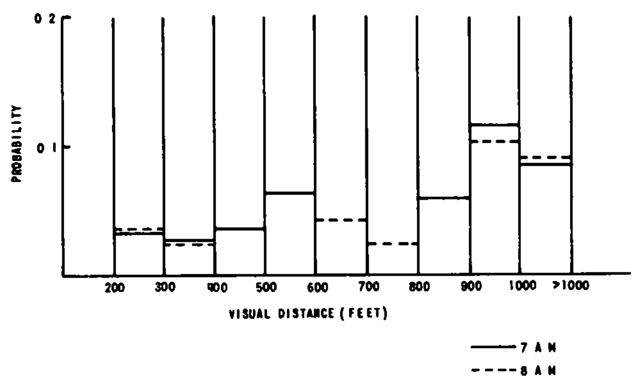

Figure 3. Probability that speed is greater than 60 mph.

TABLE 1

PROBABILITY OF OVERDRIVING AS A FUNCTION OF VISUAL DISTANCE

ITEM	TIME (AM)	PROBABILITY					
		ALL VEHICLES			ISOLATED VEHICLES		
		201–300 FT	301–400 FT	401–500 FT	201–300 FT	301–400 FT	401–500 FT
S10	7–8	0.05	0.01	0.00	0.14	0.00	0.00
	8–9	0.25	0.02	—	0.32	0.04	—
S25	7–8	0.82	0 50	0.00	1.00	0.80	0.00
	8–9	0.88	0.39	—	1.00	0.58	—
No of observations	7–8	141	155	202	7	10	24
	8–9	185	230	0	28	26	0

time, and hence distance, required to stop have been used in the analysis of fog data. All of the stopping distance formulas are based on information given in the AASHO *Geometric Design* (1965). The analyses determined the probability of overdriving, with stopping distance based on (1) 2.5 sec for "perception" and reaction time, plus braking distance (labeled S25), and (2) 1.0 sec for reaction time plus braking distance (labeled S10).

Table 1 gives several relevant factors. As expected, the probability of overdriving increased as visual distance decreased. Second, because it has been shown that speeds were higher for isolated vehicles, it is not surprising that the probability of overdriving tends to be greater for isolated vehicles. The most important fact revealed by this analysis is that the probability of overdriving in the low visible distance intervals is substantial. It is seen that one-fourth of the drivers are overdriving their visual ranges when in dense fogs.

A separate analysis was performed to measure the mean difference between visual distance and stopping sight distance for isolated vehicles. For most fog levels mean visual range exceeded mean stopping sight distance. In only two cells was this not true. The mean of S25 minus visual distance was —87 ft in the visual distance interval of 201 to 300 ft, and —45 ft for the 301- to 400-ft interval (mean stopping sight distance exceeded mean visual distance only for the 7 AM data).

For purely descriptive reasons the probability that spacing was less than visual distance was computed for each visual distance range. This probability is equivalent to the probability that the lead vehicle could be seen. Results are given in Table 2. The data show that as visual distance diminishes, the likelihood of driving without being aware of, or getting cues from, a lead vehicle becomes substantial.

TABLE 2

PROBABILITY THAT A LEAD VEHICLE WAS WITHIN VISUAL DISTANCE

VISUAL DISTANCE (FT)	PROBABILITY	
	7–8 AM	8–9 AM
201–300	0 45	0.31
301–400	0.50	0 30
401–500	0.52	—
501–600	0.63	—
601–700	—	0.53
701–800	—	0 52
801–900	0.73	—
901–1,000	0.74	0.71
>1,000	0.90 [a]	0.88 [a]

[a] These values are based on an assumed visual distance value of ½ mile

Summary of Findings for Effects of Fog on Traffic

The following summary of findings is based on the analyses described in this section and the results discussed in Appendix G.

1. Speeds in daylight fog tend to decrease by approximately 4.5 mph as visual distance decreases from more than 1,000 ft to approximately 250 ft. This result holds for the complete sample as well as for a subsample of isolated vehicles. Reductions in speeds were observed even when visual distance exceeded 500 ft.

2. The probability of overdriving increases sharply as visual distance decreases. This probability is higher for isolated vehicles.

3. The likelihood of driving without a lead vehicle in sight reached 55 to 69% for the denser fogs.

4. No meaningful relationships were found between visual distance and (1) use of the passing lane, (2) lateral position, (3) probability of short headways, (4) vehicle spacing, and (5) collision course time (see Appendix G for definition).

It should be mentioned that although the results presented in this section are based only on daytime data, the night and dawn data were similarly analyzed, in spite of their small sample sizes, with the result that virtually no contradictions with the daylight findings occurred.

FOG ABATEMENT INVESTIGATION

The principal objectives of the fog abatement study have been twofold:

1. The researchers have sought to determine if any previously suggested concepts for fog modification could reasonably be applied to the highway fog problem.

2. Based on the findings, the researchers have sought to test promising techniques for fog dissipation.

The results of the first objective are set forth in Appendix A and are briefly reviewed in the summary of program findings in this chapter. In short, the researchers found that several techniques of fog abatement are effective and may have limited application to highway fog suppression The techniques include: (1) seeding fog with sized hygroscopic nuclei, (2) the use of vegetation barriers to influence the movement of shallow fog, (3) helicopters to mix drier air from aloft with fog-laden air, and (4) seeding supercooled fog with ice-nucleating agents to promote visibility improvement. Numerous other concepts examined appear less promising for fog suppression.

In the area of fog abatement testing, research at the research agency has focused on a seeding technique involving the use of sized hygroscopic nuclei to improve visibility in dense natural fog. Field studies, conducted during 1969 (Project Fog Drops, NASA Contract NASr-156) have demonstrated the validity of the seeding concept and have suggested to the researchers of this report areas where additional research can be conducted to refine techniques. In Appendix B results of the field program are discussed in detail In this portion of the report the major findings of the fog abatement tests are presented.

To briefly review, theoretical and laboratory studies of several concepts for fog dissipation have been made by the research agency over the past 5 yr (see NASA reports CR 72, 368, 675, and 1071). One concept, involving the use of carefully sized hygroscopic materials, has shown more promise for warm fog abatement than others. Laboratory tests in a 600-cu-m cloud chamber suggested that it was possible to significantly improve visibility in dense fog by seeding with micron-sized hygroscopic particles. In these tests, laboratory fogs having a visual range of about 200 ft frequently were improved to more than 1,500 ft with as little as 4.0 mg of NaCl per cubic meter.

The principle of the seeding concept involves the redistribution of drop sizes in natural fog without the necessity of altering liquid water content. It can be easily demonstrated that whenever the drop size distribution in a fog is modified to cause the liquid water to be concentrated in a few large droplets, rather than the normal large number of small droplets, visibility will be improved. Seeding natural fog with a relatively few giant hygroscopic nuclei can effect such a redistribution in drop sizes. Calculations and experiments suggest that for highway application, NaCl particles of about 4μ radius are best, although larger particles are necessary if rapid clearing is desired.

With the intent of testing this concept in the field, preparations were made for seeding experiments at the Chemung County Airport near Elmira, N.Y. This location was chosen because of its high fog frequency during the late summer and early fall months. Of importance in the airport selection was the proximity of a nearby four-lane highway (N.Y. State Route 17) suitable for making measurements of traffic in fog. The intent was to first evaluate the seeding technique using a ground disseminator and, if necessary, attempt aerial seeding in later experiments.

Observations in fog were made using: (1) a twin-engine agency-owned aircraft for obtaining drop samples and temperature profiles in fog during take-off and also for photoreconnaissance of the seeded area, (2) an instrumented van equipped to measure drop sizes, liquid water content, visibility, nucleus concentration, and temperature in fog, and (3) three transmissometers for measuring visibility in fog.

Fog Seeding Results—Ground Seeding

A total of 25 ground seeding experiments were performed, most of which resulted in some observed improvement in visibility. Seeding was usually accomplished in dense fog situations in which visibility was less than 1/16 mile. In more than half of the experiments the seeded air mass passed between the instrumentation sites and, consequently, quantitative data could not always be taken. In spite of this difficulty, several reasonably successful experiments were performed in which detailed information was obtained on fog characteristics (e.g., drop size distributions, visibility and liquid water content).

Results of these tests, which are described in Appendix B, indicate that seeding from the ground *can* be effective in producing visibility improvements in fog. The principal drawback of the ground technique, as tested, is that only a relatively small area of fog can be treated during a given time interval using a single seeding unit. Lesser problems associated with the shape and irregularity of the seeding plume, and effective distribution of the seeding material throughout the fog volume were complicating factors It was concluded from these tests that, for highway application, a series of smaller seeding units would be preferable to a single unit disseminating an equivalent amount of material. For advection fogs (i.e., fogs accompanied by wind) larger nuclei would be desirable, because rapid clearing is required. These and other considerations are treated in more detail in Chapter Four.

Fog Seeding Results—Aerial Seeding

Aerial seeding techniques were performed during the latter part of the experimental period. Seeding was accomplished from the air using a Piper Pawnee aircraft to disseminate presized NaCl nuclei into the fog. The most successful seeding procedure involved flying perpendicular to the prevailing wind and disseminating the hygroscopic material in evenly spaced rows over the fog top. For these experiments the area to be cleared of fog was approximately ¼ by ½ mile.

Results of aerial seeding trials were particularly encouraging. Within a few minutes after seeding, narrow paths could be detected in the fog, increasing in size until, after about 15 min, large areas of the fog were completely dissipated. In experiments in which quantitative data were collected, the clearing persisted for about 20 min before unmodified fog began to reduce visibility in the seeded area. This would indicate that, for highway application, seeding would be required every 15 to 20 min to maintain clearing over the roadway. Results of the data analyses show that the combined effects of drop size differences and liquid water changes were responsible for visibility improvements that occurred in seeded fog.

In summary, these experiments have shown that it is possible to improve visibility in dense natural fog by seeding with practical amounts of hygroscopic material (approx 4.0 mg of NaCl per cubic meter of fog). It was concluded from the tests that the technique of using sized hygroscopic nuclei for dissipating warm fog can be applied on a limited scale to the highway fog problem. It is likely, for example, that the method could reasonably be used to clear fog at intersections or along short stretches of highway (e.g., <1 mile). More research is needed to isolate noncorrosive chemicals for use on highways and to develop improved methods of particle dissemination. In the tests, aerial seeding techniques were most effective in dissipating natural fog. Use of helicopters to disseminate particles could provide added mobility and increased accuracy in seeding a target area. For example, helicopters normally employed for traffic surveillance could effectively be used to seed fogs in areas of particular danger (e.g., the area surrounding an accident). This procedure could be instrumental in preventing chain reaction accidents from occurring and in assisting in the safe cleanup of vehicles involved. The principal disadvantage in aerial seeding, of course, is that the entire fog depth must necessarily be treated, which, from a highway standpoint, is not required. At present, there are a number of problems relating to effective particle dissemination and equipment design that must be studied before widespread application of this technique can be assured. In spite of these drawbacks, however, the technique has been shown to be effective for fog dissipation, and warrants additional study to determine the scope of application.

Vehicle Guidance Investigation

The principal objectives of this phase of the research have been to explore the feasibility of vehicle guidance procedures under highway conditions and to test promising techniques when possible.

In the state-of-the-art summary the subject of vehicle guidance in fog is reviewed in some detail and for this reason not all techniques of guidance are discussed here. Instead, basic visual guidance concepts are considered and promising techniques within those concepts are enumerated. A cross-polarization technique, originally suggested as a possible means for improving drivers' vision in dense fog, is briefly discussed in this section. Results of an experimental study designed to evaluate the effects of vehicle lighting on visibility in fog also are presented.

Conceptualization of Vehicle Guidance Systems

Improvements in vehicle guidance under low visibility conditions can be placed in two general categories. First, these are fully automatic systems requiring no visual aids and no driver inputs (e.g., electronic guidance). This type of system can be designed to be completely independent of prevailing visibility conditions. Although automatic guidance could be 100% effective in fog conditions, its implementation from an economic standpoint may not be practical.

The other category, in which all other means of improving vehicle guidance will be placed, is called "visual guidance augmentation." As the term implies, visual inputs of some kind are required and the driver remains in the guidance and control loop.

Visual guidance systems can be broken down into three basic types (after Nathan, 1957): active, passive, or signaling, depending on the illumination system involved. Briefly, an active system requires a source of light moving with the vehicle which illuminates the target or scene. Operation of a motor vehicle at night, on an unlighted road, using only the vehicle headlights for illumination, is one example of the use of an active system. The active system involves two-way light transmission over essentially the same path.

Passive systems require that the target (road surface, highway signs, etc.) be illuminated by fixed light sources that are independent of the vehicle. The light sources may be the sun (daylight) or some type of artificial light (street or highway lights, etc.). Operation of a vehicle during normal daylight hours or at night on a well-illuminated highway makes use of a passive system. Passive systems require light transmission over two distinct optical paths—from source to target and from target to observer.

A third type, the signaling system, employs self-illuminated targets and requires one-way light transmission over a single path (i.e., from target to driver). Taillights, brake lights, turn signals, and traffic lights are working examples of this type of a vehicle guidance system.

Many operational systems provide the mixed benefits of more than one of these categories. For example, headlights constitute an active system for the vehicle on which they are located, but fall into the signaling and passive system categories for the driver of an approaching vehicle. Highway lamps are basically passive systems, but also serve as signaling devices if used as highway markers to help delineate road geometry.

In the following discussion the three system concepts are treated independently in an attempt to indicate strong and weak points of each. Consideration of multiple usages of any given equipment must be given when contemplating vehicle guidance systems.

Active Systems

The active system is the normal method of vehicle guidance used for night highway driving and the one which offers the most difficulty under dense fog conditions. The headlight beams must penetrate the fog to the target and the reflected light must pass from the target back to the observer. In addition to the two-way transmission loss, which lowers the target brightness, light is scattered from both paths into the target background. Of particular importance is scattering from the very brightly illuminated region of fog nearest to the vehicle. Theory predicts that the inherently poor signal to noise ratio of active systems cannot be affected by changing the wavelength of radiation, at least over the visible and near infrared spectrum. A study of Nathan (1957) suggested that considerable improvement in visibility could be attained by proper use of polarized headlights. The method was considered applicable only for night driving because in daylight the principal source of airlight is scattered sunlight. In Appendix C, the theory behind the polarization technique is reviewed.

Another active system which involves the proper use of vehicle headlights in fog was examined by Pritchard and Blackwell (1959). Their results indicated that headlights should be mounted as far as possible from the driver's line of sight and aimed so as not to illuminate the fog directly in front of the vehicle. Such schemes are now used with some success on trucks and buses where headlights (fog lights) are mounted near the ground and the driver's seat is very high. For drivers experiencing a high incidence of night fog driving the use of fog lamps is recommended.

Passive Systems

Degradation of visual reference in a passive system, as in the active system, is due both to attenuation and to reduction of contrast by light scattering into the observer's eye. With a passive system, however, it is not necessary that the driver look through the brightly illuminated portion of the fog nearest the light source. During daylight hours, improvement of visibility is not likely to be possible using passive guidance systems (except by target design), because ambient light will override any artificial light sources that could be used for illumination. At night visual reference can be improved through appropriate fixed roadway lighting. The use of lights having a narrow beam spread, with the beam perpendicular to the driver's line of sight, has been studied by Pritchard and Blackwell (1959) and by Spencer (1961). Field studies by Spencer on a section of the New Jersey Turnpike demonstrated that specially designed lights placed at low elevations alongside the roadway were quite effective vehicle guidance measures in dense fog. This system takes advantage of three factors in reducing the amount of light scattered into the eyes of the driver: (1) the angular distribution of scattered light from water droplets, (2) the restricted illumination of fog droplets, and (3) shortened total optical path from source to observer (as compared to the active system, for example).

The scope of this highway fog project did not permit building and testing of a highway lighting system. Thus, work in this region was confined to suggestions for improvement of existing systems and areas where useful studies could be made Included here, then, are some areas where advances should be possible.

From Mie scattering theory it is known that light scattering in a fog is a minimum at 110° from the direction of direct illumination. Significant advantage can be gained by restricting the illumination cone from the luminaire both in the horizontal as well as in the vertical, by directing the cone at 110° to the center line of the road, and by mounting light sources as close to the surface as possible. European lighting systems designed in this way have been shown to be effective in aiding drivers in dense fog (*Illum. Eng.*, 1967).

To take full advantage of a passive system in fog, the headlights of the vehicle should be turned off. Backscatter from the vehicle headlights will degrade the system in spite of a carefully designed luminaire. It is suggested that studies be made of possible methods of removing the necessity for use of headlights under special conditions and special roadway lighting systems. With a properly designed luminaire system, headlights would not be necessary as an active system, but some type of signalling device on the vehicle would clearly be desirable.

Other guidance systems that appear promising and should be tested further in night fog conditions include pavement edge striping, reflectorized paint on pavement, and roadside signs and beaded lane delineators. Pavement edge striping, for instance, is a simple as well as economical guidance system that should be used on sections of roadway where fog is a problem. One obvious problem, of course, is keeping the striping free of dirt after application.

The Signaling System

At present, signaling schemes involve lighting that is used primarily for intervehicle communication (e.g., stop lights, brake lights). Because signaling systems are self-illuminating, very high intrinsic contrast is easily obtained. Furthermore, because only one-way light transmission is involved, contrast degradation due to scattering is not as severe as with either active or passive systems. Signaling systems, therefore, should provide visual information at the maximum range possible for given meteorological conditions. Certain disadvantages, however, are inherent in the signaling system. For example, the quantity of guidance information would necessarily be small: all targets along a road cannot be self-illuminated. In practice, it might be necessary to settle for light source delineators along the road or perhaps only along the lane in use. Guidance would therefore be reduced to a line of reference points stretching out ahead of the vehicle.

To produce the most efficient edge delineation system the brightness of each signaling source must be highly dependent on direction relative to the approaching traffic. To see the delineators at maximum useful range, more light must be directed toward the approaching traffic than would be required for detection of the delineator when it is nearest the vehicle (i e., when the delineator is at near right angles to the direction of approaching traffic). In clear air, the dependence of brightness on direction need only account for the square law dependence of intensity on range. In fog, additional consideration must be given to the exponential extinction of light due to scattering. The dependence of airlight on both distance to the delineator and also the angular dependence of scattering relative to the direction of incident light must be considered. Clearly, a detailed investigation of these effects would be required to establish the optimum configuration of the delineators. Such an investigation, though not possible under a program of this limited scope, should be considered in the design of edge delineation signaling systems.

An improvement on the continuously lighted delineators could possibly be obtained by strobing the lights, as in the high-intensity strobed runway approach lights used at airports for landing aircraft. Two distinct advantages could be gained by the strobed delineators. First, and probably most important, is that because only one pair of lights would be on at any given time, interaction between nearby lights and those at maximum range would be very greatly reduced or eliminated. The optimum strobe frequency, and forward propagation speed is not known but could be determined in field tests. A second feature of the high-intensity strobed delineators is that they may be the only practical vehicle guidance system effective in daylight during very low visibility conditions. Finally, high-intensity flashers could be used with small average power consumption.

As in the passive system discussed previously, to make maximum use of the signaling method, headlights should not be used, because headlight backscatter will reduce contrast of the delineators. Operation of a good signaling system may produce one rather serious consequence. The driver is intentionally led into overdriving his vision (aside from the guidance system) and pedestrians, animals, disabled vehicles, etc., become a more serious hazard.

Results of Cross-Polarization Tests

As previously observed, studies by Nathan (1957) have indicated that considerable improvement in visibility in night fog could be attained by using a polarization technique to reduce the amount of light scattered into the eyes of drivers. Other studies by Pritchard and Blackwell (1958) and Marsh (1958) were equally encouraging. In view of these findings the researchers elected to examine, first in laboratory experiments, then in the field, the actual improvement in visibility that could be derived from a workable polarization system.

In addition to Nathan's, several scaled laboratory studies have been made of the cross-polarization technique (Marsh, 1958; Pritchard and Blackwell, 1958). All these studies indicated that substantial improvement in visibility could be obtained with a polarization scheme. The researchers' own laboratory tests in a 600-cu-m cloud chamber showed that the technique could be used to significantly reduce the amount of light scattered into a driver's eyes by droplets in a fog. In these tests a sealed beam headlight with attached polarizer was used. Observers viewing a target board through a polaroid analyzer were asked to evaluate the effect of viewing an object by this scheme. In each experiment, observations indicated that although the contrast between object and background was improved, the 75% reduction in light intensity (due to the effects of the combined polaroid sheets) limited the utility of the concept. It was believed, however, that the disadvantage of rather severe light loss might be overcome by using a higher intensity lamp.

The concept was next evaluated in the field using a 1966 Ford station wagon equipped with a polarizer on each of the low beam headlamps. Tests at the Elmira, N.Y., airport in dense fog again demonstrated the need for high-intensity lamps to compensate for light lost using this system. Observers driving on the airport grounds in a fog of visibility less than 300 ft noted the distinct impression of too much light (due to scattering of light by droplets) when driving without the polarizers, but felt the need for improved lighting when viewing objects through the analyzer.

To provide better lighting the vehicle was equipped with a 300-watt high-intensity aircraft landing light. During the next dense fog, drivers were allowed to proceed along a concrete roadway of the airport and observe a pedestrian standing on the pavement. In these tests, no significant improvement in the ability to detect the target pedestrian was noted when using the polarizers. The feeling was still one of not having adequate lighting when viewing objects through the analyzer. Use of higher intensity lamps is not recommended because a hazardous condition might exist for an oncoming vehicle when approaching a car equipped with such lamps, particularly when driving in patchy fog. Only during conditions of unrealistically dense fog (visibility less than 100 ft) does the concept appear practical as a navigational aid. In view of these limitations it is recommended that no further tests be conducted and that the concept be considered of marginal value as an aid to drivers in dense night fog.

Experimental Study of Vehicle Lighting

To better understand the nature of visibility restriction in foggy weather driving, a study was conducted to investigate the effects on visibility of (1) the lighting of a target vehicle, (2) the lighting of the vehicle in which an observer is seated, and (3) the interaction of the two lighting conditions. A simple experiment was designed to provide information that would give a practical description of the effects on visibility of these lighting conditions. The basic procedure was for an observer to drive toward a target vehicle and note the distance at which he could first see it. (The details of the procedure and the instructions to the observer are discussed in Appendix F.) This procedure was followed for three lighting conditions of the observer's vehicle: no lights, low beams, and high beams. For each configuration there were five lighting conditions of the target vehicle. no lights, taillights, taillights plus turn signal, low beam, and high beams. Thus, 15 conditions were observed during the nighttime phase of the study. Transmissometer readings were recorded for each data point. These readings were averaged to yield one mean reading for each of the 15 conditions. Average values varied between 175 and 225 ft; this variation was assumed to be insufficient to markedly affect results.

Because of physical constraints at the test site the maximum measurement could not exceed 1,112 ft. Results are given in Table 3 which gives the mean of the observations for each observer's vehicle-target vehicle combination.

As expected, the more light generated by the target the greater the distance at which it can be seen; this relationship held for any lighting condition of the observer's vehicle. It is interesting to note that the effect of adding the flashing turn signal increased visual range by approximately 200 ft without introducing any intolerable glare due to increased light intensity.

It is also clear that for most target conditions (hence, most distances) best vision was achieved with no light from the observer's vehicle; the worst visual condition results from the use of high beams. This, of course, is due to light scattered by fog droplets into the eyes of the observer.

The results for the unlighted target vehicle show that the trend was reversed (i.e., visual range was greatest when the lights of the observer's vehicle were turned on).

Perhaps the most important information supplied by these data is obvious; nonetheless, its importance suggests that it be emphasized. No matter which of the lighting conditions of the observer's vehicle is used, the difference in visual range between an unlighted target vehicle and one with taillights alone is over 300 ft. This could well be crucial on roads where speeds are such that stopping distances are over approximately 150 ft. According to the AASHO *Geometric Design* (1965) values for dry roads, the corresponding speed threshold would be in the neighborhood of 30 mph, if time for perception and reaction are included. This illustrates the desirability of self-illumination of vehicles stopped in the roadway and any important off-road sources of information.

A second descriptive analysis was applied to these data augmented by similar observations made in daylight conditions Here, however, only data collected with no lights on the observer's vehicle are included. Of course, as ambient light increased, the distinction between seeing the body of the target vehicle and seeing the lights on the vehicle becomes less meaningful. To avoid this problem, values associated with target vehicles lights were reported for those distances at which the observer detected the lights as being on The results are shown in Figure 4. Dawn, as shown in the figure, corresponds to that time at which the observer first detected any increase in sky light. Transmissometer readings have been included in the figure; however, as daylight competes with the light source in the transmissometer, the readings lose reliability.

The predawn data points show the same ordering of target lighting conditions discussed previously. The general shape of the curves reflects predawn fluctuations in fog density The post-dawn shapes show the interactive effects of decreasing fog density and ambient lighting. The major point of interest, however, is the comparison of curves for the unlighted vehicle, taillights, and taillights plus turn signal. Notice that in the area of 7:30 to 9:00 AM, the curve for the unlighted vehicle crosses the other two curves. This is not surprising, but it does show little benefit is to be expected from taillights in such a daytime fog condition. Headlights on the target vehicle continue to be of some value, however.

TABLE 3

MAXIMUM DISTANCE AT WHICH TARGET VEHICLE COULD BE SEEN

TARGET VEHICLE	VISUAL RANGE FROM OBSERVER'S VEHICLE (FT): NO LIGHTS	LOW BEAMS	HIGH BEAMS
No lights	120	170	170
Taillights	570	550	510
Taillights and turn signals	840	810	670
Low beams	>1,112[a]	1,107	990
High beams	>1,112[a]	>1,112[a]	>1,112[a]

[a] Because of physical constraints at the test site the maximum distance measurement could not exceed 1,112 ft

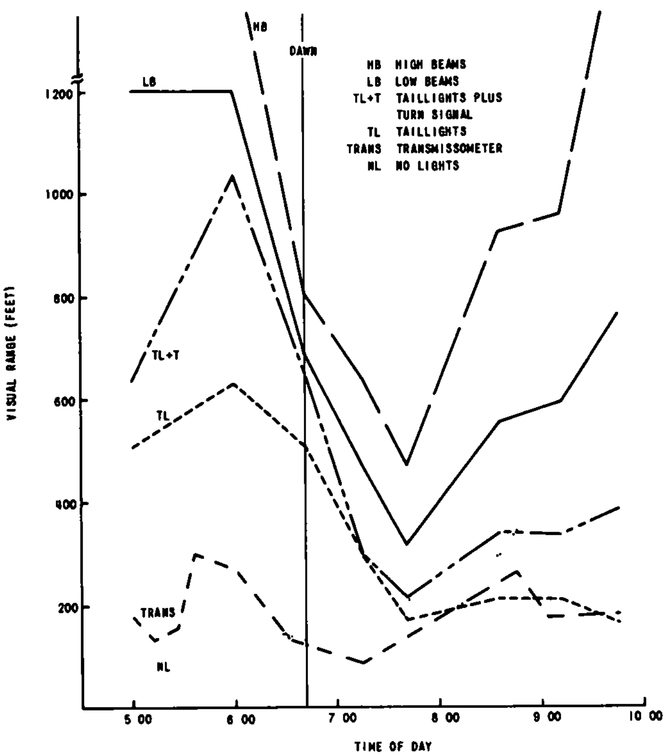

Figure 4. Visual range for various lighting conditions of the target vehicle.

RECOMMENDATIONS

Based on the results of the investigation of the highway fog problem the following recommendations are made for ways of obtaining maximum effectiveness of fog abatement and vehicle guidance systems to combat reduced visibility due to fog.

1. In the area of fog abatement, it is suggested that a study be implemented to determine the feasibility of seeding highway fog with carefully sized hygroscopic nuclei. Agency research has demonstrated that the seeding technique can be used effectively to dissipate natural fog. Additional research must be conducted to refine seeding techniques, isolate noncorrosive and ecologically safe chemicals for use on highways and to determine areas of the United States where seeding is likely to be most effective.

2. Further, it is recommended that surveys be conducted to determine those areas where highway fog is a hazard (e.g., New Jersey Turnpike), followed by a study of the mechanisms of fog formation in those areas to determine

the best method of fog abatement. In many instances, for example, simple barriers to cold air drainage in valley regions can effectively limit fog formation.

3. With regard to vehicle guidance procedures in fog it is recommended that roadway lighting systems be designed to reduce the scattering of light into a driver's eyes during periods of night fog. This can be accomplished by the use of lights placed at low elevations along the roadway and directed at 110° from the direction of direct illumination.

4. Additional consideration should be given to delineation systems employing self-illuminated delineators for guidance in fog. The very high intrinsic contrast and one-way light transmission losses involved with this type of system make the concept appealing for highway application in fog. Additional research is needed to establish the optimum configuration of such delineators. The simultaneous quantitative design of both illumination and delineation systems is required to provide maximum guidance in fog.

5. It is suggested that consideration be given to the design and testing of roadway control systems to alert drivers to dense fog. An operational system would involve the installation of visibility monitors along sections of roadway experiencing frequent fog and a signaling system several miles away to provide a warning of the hazardous conditions ahead. Implementation of such a system need not be expensive, because relatively simple warning devices can be used.

6. Rear lighting systems can, and should, be improved so as to increase the distance at which they can be seen in fog. Although research to select optimum systems would be of value, little research would be required to provide some improvement over current rear lighting schemes.

In short, no single technique of abatement or guidance is likely to eliminate the fog problem; however, judicious use of a combination of the suggestions just outlined can significantly reduce the hazardous effects of highway fog. In Chapter Four, several areas where additional research should be conducted are discussed in more detail.

CHAPTER THREE

INTERPRETATION AND APPLICATION

The discussion in this chapter is intended to provide an interpretation of the findings presented in Chapter Two and also an understanding of how the results might be applied in a practical sense. Three areas of the research conducted on this project have special importance and are therefore considered in more detail here.

INTERPRETATION OF TRAFFIC MEASUREMENTS IN FOG

Initially, the information pertaining to the effects of fog on accidents and traffic flow appears to be somewhat inconsistent. It has been found, for example, that drivers reduce speeds, but the likelihood of overdriving increases; fewer accidents were reported in Melbourne, Australia, but a higher fatality rate was found in California; accidents were more likely to involve four or more vehicles in fog, but they also were more likely to involve just one vehicle. It is the purpose of this discussion, therefore, to offer some explanations of these results and to clarify their meaning.

First, it appears that drivers recognize, to some extent, that foggy weather driving demands increased caution. This is supported by the reduction in speeds observed in California and verified in the researchers' own study, as well as by the reduction in accidents reported in Melbourne. At the same time, the data imply that the cautious attitudes by some drivers are inconsistently applied. The reduction in speed was not sufficient to preclude increases in the probability of overdriving. Secondly, in this study there was little indication that drivers tend to minimize interactions with other vehicles; the use of the passing lane was not diminished, nor was the occurrence of relatively short CCT's (collision course time). These results suggest that some drivers recognize a need for increased caution but do not know how to manifest it.

On the other hand, it is clear that a driver can be careful by means other than those reflected in vehicle control behaviors. In fog, the driver can, and probably does, reduce the distance needed to stop by simply paying closer attention to the events ahead. Such a driver, if he is suspicious of any images ahead, can probably reduce the time needed to react to about 1 sec. It is well known, for example, that pilots are extremely adaptable to demands placed upon them; they are capable of maintaining rather constant performance almost to the point at which the aircraft becomes unflyable (Harper, 1956; Kidd and Harper, 1963). It is similarly not unlikely that the adaptability of the driver allows him to successfully cope with reduced visibility without degrading his measurable performance.

As an example of the adaptability of the driver, the state-of-the-art section includes two field studies in which vision was improved, yet no differences in driver behavior were found. Apparently, the drivers were capable of adapting to the reduced visibility conditions that existed prior to improvement.

With regard to accident frequency, there is evidence that fog does induce some accidents and accident involvement; however, there is no evidence that the net effect of fog is to increase the accident rate. The only source of germane information shows accidents to be less likely in fog. Even if one were to generalize these results, this still does not imply that accidents in fog constitute a negligible problem. Instead of viewing fog as a less important problem, it would seem more appropriate to view driving in fog simply as a different problem, that is, one involving more severe accidents with different involvement rates. In addition to the effect of fog on accidents, the reduced efficiency of traffic flow is a source of economic loss.

Restricted visual range can be used to explain much of the accident data discussed in the literature. Overdriving one's visual range is not a problem until the driver's expected path is blocked, when this happens, avoidance of a collision may be impossible. The data showing that accidents in fog are less likely to involve two or three vehicles and more likely to involve four or more vehicles strongly suggest that accidents of the former type are converted into those of larger sizes by drivers who were unable to respond early enough to the initial collision. The higher probability that an accident involved only a single vehicle in fog, as compared to clear weather, is not unreasonable because in most single-vehicle accidents the vehicle comes to rest somewhere off the road; such an accident is therefore less likely to be converted to a multivehicle accident, no matter what the weather conditions

Interviewed drivers claimed, for the most part, that vehicles which they struck did not suddenly appear; this in no way weakens the suggested effects of reduced visibility. It does imply that vision in fog is not simply a matter of seeing or not seeing. Rather, it is a question of how much information the driver needs before his perceptual, decision-making, and response mechanisms will serve him in successful ways.

With regard to the increased fatality rate on California freeways, this is probably attributable to reduced visibility precluding early evasion attempts. This delay, in turn, is likely to be reflected in higher impact speeds; thus, greater accident severity.

Based on the data collected in this study, those from the literature, and the researchers' interpretations, it appears that the fundamental mechanism whereby fog induces accidents is overdriving one's visual range. There are at least three ways to cope with this problem. The first is to reduce the distance required to stop, or otherwise change the vehicle's path. This, in turn, can be done in two ways: (1) improved methods of speed control, and (2) driver training for emergency conditions.

The second approach is to increase visual distance. A large portion of this report is responsive to this problem, and it is not discussed here.

The third method of minimizing the effects of fog is that of reducing the effects of accidents which do occur. This area includes work in crash-worthiness, occupant restraint, etc The implication here is that consideration should be given to the view that, at this time, the greatest reduction in deaths due to fog accidents might be achieved through occupant protection as opposed to approaches directly related to speed and visual range.

The study of the effects of vehicle lighting yielded three relevant results. First, the visibility of taillights and turn signals is poor in daytime fog. This is particularly dangerous because a driver is likely to assume that if he can see the body of the vehicle ahead he can also see its signal lights; this, it has been shown, is not always true. Furthermore, though not explicitly studied, the same difficulty is likely to arise with some of the lower intensity brake lights.

Secondly, it was shown that in a night fog having a visual range of about 200 ft, the distance at which taillights can be seen is over 500 ft; the combination of taillights and turn signals can be seen at 670 to over 800 ft, depending on the lighting of the following vehicle. In this regard, the combination of taillights and turn signals produced no debilitating glare.

Finally, visual distance was far more sensitive to target vehicle lighting than to the lighting of the observer's vehicle. This implies that with regard to improving the detection of vehicles ahead, primary attention should be given to the lights on the lead vehicle.

These results yield the following conclusions: (1) there is a need, particularly in daytime fogs, to provide rear lighting which can be more easily seen; and (2) rear lighting systems for vehicles can be designed to provide earlier detection. This is not to say that the most appropriate design is obvious. there are limits on the light intensities to be used. If the intensity is too low, information transfer would not be enhanced; if the intensity is too high, debilitating glare will result. Furthermore, these limits would be a function of ambient light.

Application of these findings might result, for example, in multifilament taillights which could be used to achieve greater luminous intensity for use in fog. (Of course, dual filament bulbs are already in use so that a single bulb can act as both a taillight and a brake light.) Such a system could provide three levels of illumination: one for normal night driving, one for use in fog at night, and one for use in daytime fog. A study would be required to determine the lighting configuration that would provide the optimum guidance in fog.

Although these thoughts were generated by the observed improvements in visibility due to turn signals, it is recognized that some of the improvement may have been attributable to the intermittent nature of turn signals. If this is the case, it too is suggestive of another system to improve visibility in fog. Here, however, consideration must be given to ways of providing systems in which flashing lights would not be confused with turn signals; the use of a low-frequency short pulse light, for example, might be acceptable.

Such improvements not only would provide better detection of lead vehicles, they would also facilitate guidance in fog by vehicles ahead, and, in some cases, allow earlier detection of accident vehicles.

FOG ABATEMENT STUDY

The findings of the fog abatement study have immediate application for use in developing a rational approach to highway fog dissipation. The technique of seeding dense fog with carefully sized hygroscopic nuclei was demonstrated at the research agency both in laboratory experiments and field tests conducted during 1968. The researchers consider the results of these tests to be sufficiently promising to warrant additional exploration of the concept for highway application. Improved techniques of particle dissemination and particle sizing are still required, however, before operational systems should be implemented. For example, it is reasonable to expect that dense fog in isolated valley areas can efficiently be modified using aerial seeding techniques now available. With improved ground-based seeding systems it may be possible to expand the seeding operation to treat larger areas of fog over significantly greater areas of roadway (heavily traveled sections of highway, thruway entrance ramps, exits, intersections, etc.). Experience shows that seeding from the ground using a single disseminator has limited effectiveness because of the unpredictable motion of the seeding plume and relatively small volume of fog that can be treated. One obvious solution is to use several particle disseminators in the vicinity of the target area. It is important to recognize, however, that even though several seeding units may be required to treat fog at a single intersection, the total amount of material necessary for seeding can be kept relatively small as long as *critically sized materials are used.* This point can be illustrated by the following example.

It can be shown that to seed an area of fog approximately ¼ mile by ¼ mile to a depth of 30 ft about 10 lb of 5μ radius NaCl nuclei are needed for a single treatment. If seeding were accomplished every 10 min for 3 hr, theoretically less than 200 lb of sized NaCl would be expended (assuming that conditions in the fog prior to treatment were typified by the physical fog model shown in Appendix A). On the other hand, if the material is not critically sized, and the only objective is to reduce the humidity of the air to 90% to cause evaporation of the fog droplets, then several thousand pounds of material would be required to effect dissipation. Such enormous seeding requirements would render the concept impractical. It is clear, therefore, that to effectively use the seeding technique advanced by the research agency, careful attention must be paid to proper sizing of seeding agents and effective dissemination of the material into the fog.

There are, of course, other important problem areas where additional research must be performed.

As part of a continuing fog study, the researchers are evaluating a variety of hygroscopic materials that are thought to be ecologically safe and noncorrosive to metals. These materials are being tested in large-scale laboratory experiments and will be tested further in field experiments (airport fog dispersal) if they show promise as efficient nucleating agents.

In summary, the researchers consider the results of the fog abatement tests reported here as an important first step toward highway fog dissipation. Additional research is required to refine techniques and develop seeding procedures that can be applied to the highway. If such procedures can be developed it is likely that operational programs can be implemented on highways to abate fog.

VEHICLE GUIDANCE

Results of the vehicle guidance investigation have been derived principally from a review of the literature and from an examination of basic principals of light scattering in fog. The findings described in Chapter Two can be used to help determine the types of lighting that should be implemented on roadways having frequent night fog.

Although the scope of this project did not permit building and testing of highway lighting systems, a number of suggestions have been made in this report for ways to improve existing systems to provide better visual guidance in fog. Specifically, it is recommended that roadway lights be mounted at low elevations along the highway, with the cone of light directed at approximately right angles to the direction of direct illumination. Anti-fog lighting systems in Europe have been designed in this way and have proved helpful to motorists as a means of guidance in fog. Signaling systems employing self-illuminated lane delineators also have been shown to be effective as reference cues for drivers. Additional studies should be made to determine the optimum configuration of such illuminator-delineator systems for use in fog. Other guidance techniques such as the use of fog lamps, pavement edge striping, reflectorized paint on roadway signs, and beaded lane delineators have all been partially effective vehicle guidance methods.

Results of the researchers' evaluation of a headlight polarization scheme, designed to improve a driver's perception in dense fog, have demonstrated that the technique is not practical for use on highways. It is recommended, therefore, that no additional tests of this concept be performed.

The results of the vehicle guidance phase of the program should be helpful in determining guidance procedures that can be employed to aid motorists driving in fog. Although only one system of guidance could practicably be tested on this program, suggestions have been made for ways to improve existing systems as well as areas where useful studies could be made.

CHAPTER FOUR

SUGGESTED RESEARCH

Several areas where potentially useful studies can be performed have become evident during this investigation of highway fog.

One of the most immediate research needs lies in the area of fog abatement. Techniques developed at the research agency for warm fog dispersal are currently being applied at some airports in the United States. Refining of the seeding procedures and optimization of methods of particle dissemination must still be achieved. Because of the wide variation in fog types, seeding procedures must be tailored to the particular type of fog being considered. Local surveys are needed to determine areas where fog frequency is high and where fog suppression techniques can be used. The mechanism of fog formation in those areas must also be established in order to determine the best methods of abatement. Additional research is needed to isolate chemicals that are noncorrosive and ecologically safe for application on highways. At present, some of this research is being conducted at the research agency as part of a continuing fog study; however, additional effort must be placed on highway fog abatement if a practical solution to the problem is to be achieved.

Additional attention must be given to highway lighting systems designed to reduce the amount of light scattered into a driver's eyes in night fog (Chapter Two). As previously noted, the use of lights placed at low elevations along the roadway and directed at 110° from the direction of direct illumination offers this capability and should be considered for installation on sections of roadway experiencing a high fog frequency. More research into self-illuminated delineation systems and combined illuminator-delineator systems is required to establish the optimum configuration for use in fog. Further, additional research is needed to optimize rear lighting systems in order to provide better detection of vehicles in fog.

With regard to vehicle speeds and overdriving, it is recommended that two areas of driver training be studied:

1 The feasibility of teaching student drivers means for determining visual distance and, hence, maximum acceptable speeds.

2. The incorporation of emergency skills in driver training curricula.

Finally, it is recommended that additional traffic measures of the type made on this project be obtained in very dense fog. The researchers' measurements have shown that, except for a slight reduction of average vehicle speed and an increased probability of overdriving one's visual range in fog, traffic behavior does not change significantly when visual range is lowered to about 250 ft. It is recommended that a special study be performed to determine the frequency of highway fogs in the United States that have visibilities of less than 250 ft.

CHAPTER FIVE

CONCLUSIONS

The conclusions that can be drawn from this investigation relate specifically to the behavior of traffic in fog, methods of fog abatement, and vehicle guidance procedures that can be used to reduce the hazardous effects of fog. In short, there are several potentially useful ways in which the visibility limiting effects of fog can be ameliorated

1. Fog seeding techniques using carefully sized hygroscopic nuclei have been shown to produce improved visibility in dense fog In the researchers' tests, aerial seeding procedures were more effective in dispersing natural fog than was ground seeding using a single disseminator. Before any firm conclusions can be drawn, however, ground systems designed specifically for highway use must be tested and also experiments must be performed to evaluate the effect of seeding fog with multiple disseminators. Several other potentially promising fog abatement concepts are discussed in this report.

2. A review of the literature has shown that at least one type of roadway lighting system can be used to improve visibility in night fog. This system involves the use of specially designed luminaires mounted at low elevations along the roadway. The luminaires are directed at an angle

of 110° from the driver's line of sight in order to minimize light scattering.

3. A guidance system involving the use of polarized fog lamps was evaluated both in the laboratory and in field experiments. It was concluded from these tests that the concept is not practical as an aid to drivers in fog and that further experiments are not warranted.

4. The most direct effect of fog on traffic flow is to reduce vehicle speeds. In spite of this, increasingly dense fogs produce conditions in which the probability of over-driving one's visual range is greatly increased. Although this has not been shown to increase accident rates, it does appear (from the literature) to contribute to accident severity in terms of increasing the number of vehicles involved and the likelihood of fatal injuries.

5. The distance at which a vehicle ahead can first be seen can be increased through the use of appropriate rear lighting systems. The need for such improvement is particularly evident in daytime fog.

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APPENDIX A

STATE-OF-THE-ART REVIEW

In this appendix the results of the state-of-the-art review are treated in detail. In preparing the summary, consideration has been given to several areas related to highway fog. For example, discussions of the physics of fog formation, visibility in fog, fog abatement procedures, and highway delineation systems are presented with the intent of providing a rather broad background to the researcher interested in the highway fog problem.

References appear in Appendix H, Bibliography

PHYSICS OF FOG FORMATION

Technically, fog is a visible aggregate of minute water droplets that is in contact with the ground or at least so close to it that visibility is seriously affected. It differs from a cloud only in that a cloud has its base above the earth's surface. By definition, fog reduces the visual range in the atmosphere to less than 1 km (0.62 mile); the terms mist and haze apply to meteorological phenomena producing less severe visibility restriction.

There are three generic forms of fog. Warm fog consists of a cloud of water droplets at a temperature above 32°F. Supercooled fog differs from the former only in that the droplets are in equilibrium with the atmosphere at 32°F or colder. A third form, ice fog, consists entirely of ice crystals and is most common in northern latitudes during the winter months.

In determining the severity of fog the weather observer considers a variety of meteorological variables, two of which are the horizontal visibility and fog depth. The "ceiling" visibility and "slant" range visibility have special significance to the airline pilot because these factors affect his approach and landing. To the automobile driver, the horizontal visual range in fog is most important and, for this reason, only dense fogs (visibility <¼ mile) are likely to have any effects on his behavior in traffic.

To aid in subsequent discussion, a fog classification system is outlined as follows according to a scheme first introduced by Willett (1928) and later modified by Byers (1959). Based on synoptic as well as physical considerations, the classification recognizes that, in principle, fog can form by (1) cooling moist air until it reaches the dew point, whereupon droplet growth occurs on the most favorable condensation nuclei (air mass fogs), or (2) increasing the moisture content of the air until saturated conditions are achieved (frontal fog). Mixing of two air masses is often considered a third way for fog to form, although mixing is actually a combination of heat and moisture exchange.

The classification, taken from Byers, is as follows:

A. Air mass fogs
  1. Advection fogs
     a. Land- and sea-breeze fog
     b. Sea fog
     c Tropical-air fog
     d. Steam fog
  2. Radiation
     a Ground fog
     b. High inversion fog
  3 Advection-radiation fog
  4. Upslope fog

B. Frontal fogs
  1. Prefrontal (warm front)
  2 Post-frontal (cold front)
  3 Front-passage fog

It is not important here to discuss in detail the physical processes important to every type of fog. Rather, a simplified but meaningful account of the mechanism of fog formation can be given with the aid of a phase diagram. In Figure A-1, the curved solid line represents the relation between specific humidity (mass of water vapor per unit mass of air) and wet bulb temperature. In the figure, a condition of supersaturation (relative humidity greater than 100%) is represented by any point lying above the solid curve. Under these conditions, and if sufficient condensation nuclei are present in the air, fog would form.

Consider first a parcel of air, A, at some specific humidity and temperature. Cooling of the air without altering its moisture content will cause the relative humidity to rise until saturation occurs (B). If cooling is continued the air will become supersaturated and droplet growth will proceed on suitable condensation nuclei to produce fog.

Consider next an air parcel, C, at some humidity less than 100%. If, for example, falling raindrops partially or completely evaporate within the air mass, the relative humidity will rise. Continued evaporation of precipitation could increase the dew point temperature (without the necessity of cooling the air) until fog is formed (D). These conditions are best fulfilled in stable cold air in advance of a warm front.

If, now, two parcels of air, E and F, having different temperatures and relative humidities are mixed, the dashed curve in the figure shows how fog might form due to mixing alone. Where the dashed line lies above the solid curve, fog would exist. The liquid water content of the fog is given by the vertical distance between the solid curve and the dashed line. It is obvious, on the other hand, that mixing of two parcels of air represented by points G and H would not produce supersaturation or fog.

In reality, a variety of mechanisms involving energy, heat, and moisture contribute to the formation of fog. These mechanisms, in turn, are associated with specific kinds of fog. Thus, although most fogs forming over land are caused, in part, by radiational cooling of the earth's surface and subsequent loss of heat from the lowest layers of air to the ground, cooling alone is not adequate to form dense fog except during calm wind conditions. Taylor (1917) determined that the radiation process can account for a fog of only modest vertical extent and concluded that, to produce deeper fog, some turbulence or vertical mixing was required. The mixing process not only helps transport some of the heat out of the fog to the conducting boundaries but also contributes to the heat and moisture exchange of the air masses. Rodhe (1962), who recognized the importance of both mixing and radiational cooling, comprehensively reviewed the subject of fog formation and suggested that more than one factor is usually important in any natural fog. It is obvious that the formation and persistence of most fogs represent a delicate balance of favorable meteorological conditions.

Additional insight into the mechanisms of fog formation can be obtained from a discussion of pertinent condensation processes. In the formation of natural fog, droplets undergo several stages of related growth. As the ambient relative humidity rises toward 100%, nuclei in the atmosphere that are both large and hygroscopic absorb water vapor from the atmosphere to form enlarged haze particles. As the humidity continues to increase, the haze particles grow and soon become dilute solution droplets, the size of which is dependent on the original mass and hygroscopicity of the nucleation substance. Droplet equilibrium is established with the environment at the ambient vapor pressure and temperature. Normally, haze begins to intensify at about 70% relative humidity, although the severity of haze depends on the number, type, and size of participating nuclei Understandably, haze is most frequently observed in areas where industrial effluents produce an abundance of condensation nuclei.

As soon as slight supersaturation is achieved, a limited number of the solution droplets begin to grow without limit and dense fog forms. The number of droplets present in the fog is determined by (1) the distribution of size and hygroscopicity of the nuclei and (2) the rate at which excess water vapor in the atmosphere is made available for droplet growth. Because of differences in the type and concentration of nuclei found over land and ocean, inland fogs differ markedly from coastal fogs. Some of the important physical characteristics of radiation (inland) and advection (coastal) fogs are given in Table A-1.

As given in the table, two important differences between radiation and advection fogs are the average drop diameters and the relative droplet concentrations. The greater surface visibility in the advection fog can be attributed to these differences. Although the liquid water content is actually greater in the advection fog, the drop size distribution is characterized by a relatively few large drops. Hence, if it were possible to modify natural fog along a turnpike, for example, in such a way as to produce fewer, larger drops, significant improvements in visibility would result. This conclusion can be drawn from the following discussion of visibility and light scattering of fog droplets.

VISIBILITY IN FOG

Visibility is commonly defined as the greatest distance at which an object of specified characteristics can be seen and identified. It is current practice in both the theoretical description and experimental measurement of visibility to exclude important and complicated problems of recognition by identifying visibility with a more rigorously defined quantity, *visual range*. During daylight hours, the visual range of an object is that distance at which the apparent contrast between the object and its background becomes just equal to the detectable threshold constant. At night, visual range is usually defined as the greatest distance at which a point source of light of given intensity can be perceived. To generalize these conventional measures of visibility to the complex highway situation, and to delineate the variables that influence highway visibility in fogs, it is necessary to consider the basic concepts of atmospheric visibility.

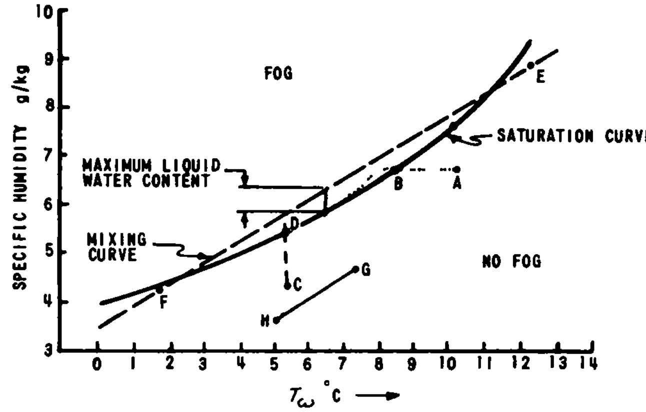


Figure A-1. Phase diagram of fog formation

General Theory of Visual Range

Underlying the general theory of visual range is the ability of the human eye to detect the difference between the apparent brightness of an object and its background down

TABLE A-1

PHYSICAL FOG MODELS [a]

FOG PARAMETER AT THE SURFACE	FOG RADIATION (INLAND)	ADVECTION (COASTAL)
Average drop diameter (μ)	10	20
Typical drop diameter range (μ)	5–35	7–65
Liquid water content (mg/cu m)	110	170
Droplet concentration (per cu cm)	200	40
Vertical depth of fog (m):		
Typical	100	200
Severe	300	600
Horizontal visibility (m)	100	300
Nuclei (μ):		
Diameter	0.08–0.8	≥0 5
Type	Combustion products	Chlorides & nitrates

[a] After Jiusto (1964)

to a level called the threshold of brightness contrast, defined as

$$\epsilon = |(Bo - Bb)/Bb| \qquad \text{(A-1)}$$

in which Bo is the apparent brightness of the object under consideration and Bb is the apparent brightness of its background. In meteorological determinations of visual range, the standard value of 0.02 has been adopted for ϵ (Middleton, 1951). Experiments have shown, however, that the value of threshold contrast is subject to a wide range of variation, depending on the general brightness of the visual field as a whole, the angular subtense of the object, and such individual factors as the state of adaptation of the observer's eyes and his visual search pattern (Blackwell, 1946, Middleton, 1952, Duntley et al., 1964). Although threshold contrast varies with color, it should be emphasized that any important influences of color in connection with highway visibility problems in fogs should apparently be restricted to identification or recognition performance at suprathreshold levels of contrast (Middleton, 1952; Duntley et al., 1964). An additional factor that has been shown to have an important influence on threshold contrast is the modulation of object brightness (Middleton, 1952).

The effect of the droplets on light transmission through a fog is to scatter or diffuse the light, true absorption being negligible in the visible portion of the spectrum. It can be shown (Koschmieder, 1924; Duntley, 1947, 1948; Middleton, 1952) that the apparent brightness, Bo, of an object of intrinsic brightness, Bo^*, as observed through a fog is given by

$$Bo = Bo^* \exp[-\sigma x] + Bf(1 - \exp[-\sigma x]) \qquad \text{(A-2)}$$

in which x is the distance between the object and the observer, σ is the extinction coefficient due to scattering of light by the fog droplets, and Bf is the apparent brightness of the fog itself due to the scattering of external illumination. The first term on the right of Eq A-2 represents the direct attenuation of the intrinsic brightness of the object by scattering due to the fog droplets The second term represents the additional contribution to the apparent brightness of the object of "airlight" or external illumination from all directions which is scattered into the eye of the observer by the fog droplets. It is assumed that no specular reflections are present

Similarly, the apparent brightness, Bb, of the background of intrinsic brightness, Bb^*, as observed through the fog is

$$Bb = Bb^* \exp[-\sigma x] + Bf(1 - \exp[-\sigma x]) \qquad \text{(A-3)}$$

The apparent brightness contrast between the object and its background, at the observer, is therefore

$$C = (Bo - Bb)/Bb = C^*[1 - (Bf/Bb^*)(1 - \exp[+\sigma x])]^{-1} \qquad \text{(A-4)}$$

in which

$$C^* = (Bo^* - Bb^*)/Bb^* \qquad \text{(A-5)}$$

is the intrinsic contrast. If the extinction coefficient σ is not constant along the path between the object and the observer, as assumed in the preceding development, the $\sigma\, x$ product in the exponentials must be replaced by an integral of the extinction coefficient, σ, over the path length, x.

If the absolute value of the apparent contrast is equated with an appropriate value of the threshold contrast ϵ, Eq. A-4 may be solved for the value of x corresponding to the visual range under these conditions. Denoting this value of x by V results in the following general expression for the visual range

$$V = \sigma^{-1}\ln\,[(Bb^*/Bf)(|C^*|/\epsilon - 1) + 1] \qquad \text{(A-6)}$$

If the fog is so dense that the background is fully obscured, $Bb^* = Bf$, and Eq. A-6 reduces to

$$V = \sigma^{-1}\ln\,[|C^*|/\epsilon] \qquad \text{(A-7)}$$

in which C^* now becomes

$$C^* = (Bo^* - Bf)/Bf \qquad \text{(A-8)}$$

In the special case where the object is a black body of zero intrinsic brightness, $Bo^* = 0$, and Eq. A-7 reduces to

$$V = \sigma^{-1}\ln\,\epsilon^{-1} \qquad \text{(A-9)}$$

If the standard value 0.02 is adopted for ϵ, this gives an expression for the *meteorological visual range*

$$V_m = 3\,912/\sigma \qquad \text{(A-10)}$$

Because V_m depends only on the extinction coefficient, σ, it can be determined by a transmission measurement alone. Although the meteorological visual range is a widely used measure of visibility, the assumptions involved in its definition are so restrictive that it is of limited usefulness in describing visibility in complex highway situations.

The general theory of visual range shows, therefore, that fog droplets degrade visibility by scattering external illumination from all directions into the eye of the observer, and by direct attenuation through scattering of light emanating from an object and its background. The former effect has an important indirect influence of increasing the general brightness level of the visual field, and thereby increasing the threshold contrast level, ϵ, of the observer. In addition, it should be noted that unless an object or its background are self-luminous, their intrinsic brightness may be significantly reduced in fog by scattering of the external illumination.

Referring to Eq. A-6, it is apparent that a light transmission measurement alone will not in general suffice to determine visual range for highway purposes. Any experimental determination of visibility in highway fog situations must include an assessment of the degrading effects of the external illumination which is scattered into the eye of the observer. This is particularly important in cases of highly non-uniform external illumination, where the airlight contributions to apparent brightness cannot be expressed in the simple form of Eqs. A-2 and A-3, and the development of a detailed theoretical expression for visual range under each specific set of circumstances would be prohibitively difficult. In principle, the use of a photometer which can provide an absolute or relative measurement of apparent brightness is the most direct way of accomplishing such an assessment.

Based on the general theory of visual range, it can be seen that visibility in fog can be improved by increasing the intrinsic contrast between an object and its background, by altering the physical properties of the external illumination to decrease the scattering of light into the eye of the observer. To further delineate the variables which influence visibility in fog, this report turns to a consideration of the light-scattering properties of fog droplets, paying particular attention to the dependence of scattering on wavelength, droplet size, scattering angle, and polarization of the incident wave.

Light Scattering in Fog

In natural fogs, the mean spacing between fog droplets is large compared to wavelengths in the visible spectrum ($\lambda = 0.4\mu$ to 0.7μ). Under this condition, the scattering of light by the fog droplets is incoherent and the total light scattered by a population of fog droplets is equal to the sum of the portions scattered by the individual droplets (Houghton and Chalker, 1949). Because absorption is negligible in the visible spectrum, the extinction coefficient in a fog becomes

$$\sigma = \sum_i n_i \, \pi \, r_i^2 \, Ks \qquad \text{(A-11)}$$

in which n_i is the number of fog drops of radius r_i per unit volume, and the product of the geometric cross section of a droplet, πr_i^2, with the dimensionless scattering area coefficient, Ks, is a measure of the total light scattered by a fog droplet regardless of the state of polarization of the incident light. The scattering area coefficient, Ks, is a function of the parameter, $\alpha = 2\pi r_i/\lambda$, in which λ is the wavelength of the light.

The transmission of a parallel beam of light through a fog is given by

$$E = Eo \exp\left[-\sigma x\right] \qquad \text{(A-12)}$$

in which Eo is the flux density of the incident beam and E is the flux density of the beam after passing a distance x through the fog If the light is not monochromatic, Eq. A-12 must be integrated over the spectral interval involved.

As α becomes large, $Ks \rightarrow 2$, and the total scattering cross section $\pi r_i^2 Ks$ approaches twice the geometric cross section of the droplet. For the scattering of visible light by water droplets, this limiting behavior obtains to a good approximation for a droplet with a radius of 2 microns or greater (Houghton and Chalker, 1949). Hence, as long as the relative contribution of droplets of less than a few microns radius to the extinction coefficient is small, the value $Ks = 2$ can be substituted in Eq. A-11, resulting in the simplified expression

$$\sigma = 2\pi \sum_i n_i \, r_i^2 = N \, 2\pi \, r^2{}_{rms} \qquad \text{(A-13)}$$

in which N is the total number of droplets per unit volume and r_{rms} is the root mean square radius of the fog droplets. In this situation, which is apparently true of most well-developed natural fogs, light transmission through the fog is essentially independent of wavelength for wavelengths in the visible spectrum (Middleton, 1952; Arnulf and Bricard, 1957).

Because the liquid water content, w, in a fog is given by

$$w = (4\pi/3) \, \rho \sum_i \, n_i \, r_i^3 = (4\pi/3) \, \rho N r^3{}_{mvr} \qquad \text{(A-14)}$$

in which r_{mvr} is the mean volume radius of the fog droplets and ρ is the density of water, Eq. A-13 can be written in the form

$$\sigma = (3w/2\rho)\,(r^2{}_{rms}/r^3{}_{mvr}) \qquad \text{(A-15)}$$

It is seen from Eq. A-15 that the extinction coefficient in a fog can be reduced by causing a shift in the fog droplet size distribution to larger sizes without the necessity of effecting a reduction in the liquid water content of the fog. Eq. A-15 is sometimes written in the approximate form

$$\sigma = 3w/2k\bar{r} \qquad \text{(A-16)}$$

in which $\bar{r}$ is the mean radius of the fog drops, k is a parameter of order unity related to the width of the droplet size distribution, and the density of water, ρ, in the cgs system has been replaced by unity. If this expression for σ is substituted in Eq. A-16, the well-known Trabert formula for the meteorological visible range in the cgs system is obtained.

$$Vm = 2.6 \, k \, \bar{r}/w \qquad \text{(A-17)}$$

In the large α scattering regime, which applies to most well-developed natural fogs, the scattering is predominantly in the forward direction (Gumprecht et al., 1952; Spencer, 1960, Deirmendjian, 1964). Appreciable reductions in the airlight contributions to contrast degradation in highway fog situations are potentially possible by designing illumination systems to eliminate or minimize the forward scattering of light into the eye of the driver by the fog droplets. For droplet size distributions occurring in most natural fogs, the scattered light is at a minimum for a scattering angle of approximately 110° with the axis of the incident beam in the forward direction.

In addition, it should be noted that one-half of the light scattered by a fog droplet in the large α scattering regime is diffracted into a small angle of order $\theta = 2.62 \ \lambda/r$ radians around the axis of the incident beam in the forward direction (Sinclair, 1947; Hulst, 1957). In the experimental determination of the extinction coefficient in fog by a transmission measurement, it is therefore important to assure that the reception cone of the detector is small enough to exclude most of this diffracted light. Otherwise the extinction coefficient may be underestimated by a factor of up to 2.

Whereas the total light scattered by a fog droplet is independent of the state of polarization of the incident light, the angular distribution and polarization of the scattered light depends on the state of polarization of incident light (Sinclair, 1947; Gumprecht et al., 1952; Nathan, 1957, Deirmendjian, 1964). Within the intense forward scattering region, however, there is no significant depolarization for any state of polarization of the incident wave. The same is true for backscattering, although the angular region over which there is no significant depolarization is, in general, much smaller. In addition, when the incident light is linearly polarized, the light into the plane of polarization or the orthogonal plane containing the direction of propagation of the incident wave retains its original polarization. Nathan (1957) has proposed a cross-polarization technique using this latter property of light scattering in fogs to reduce the amount of scattered light which the driver observes and to improve driver visibility in fogs.

THE EFFECT OF FOG ON ACCIDENTS

A review of the literature reveals that the relationships between fog, accidents, and traffic flow have received little attention in terms of empirical research. Before proceeding with the discussion of the literature, however, it should be pointed out that consideration was given to the value of accident reports as a source of useful information. First, few states make provisions for the specification of fog. For those that do, there is no way, for the most part, of determining fog level or the contribution of fog to the accident. Second, even if these data were available, the necessary information about exposure to fog is not included. Although general fog records are kept by various types of agencies, the levels used are so gross as to be of little value in studying effects on traffic phenomena. Even in the *Reduced Visibility (Fog) Study* (1967),* for which accident reports were used, the results shed little light on the problem. As examples, their conclusions were that there were more accidents in fog at those times, and in those locations, where there was more fog Thus, it seems very little could be gained by examining accident records, at least relative to the cost involved

The literature review did provide some information which documents the fact that fog does precipitate accidents. In one report—National Transportation Safety Board (1967)—an accident was described which involved 11 vehicles, 24 injuries, 5 fatalities, and approximately $75,000 damage This accident was initiated and allowed to develop by the not-too-unreasonable behavior of drivers who simply could not see sufficiently far ahead. In another paper (Miller, 1967), a series of accidents is described which occurred on a single road during a foggy evening and which involved at least 110 drivers.

From such reports it is possible to conclude that fog does induce accidents. On the other hand, it is likely that fog induces increased caution on the part of drivers. It is therefore unclear at this point as to whether the net effect of fog is to increase, or to decrease, the likelihood of an accident.

In Australia, Foldvary and Ashton (1962) conducted the most comprehensive study in the area of fog effects on accidents. Data were collected every day in 1960 in the Melbourne metropolitan area. An attempt to correct for the effects of day of the week and seasonal variations was made.

Considering only casualty accidents (of which there were 8,007), 620 occurred on the 29 days which were foggy in nature. The remaining 7,387 casualty accidents occurred on the other 337 nonfog days. Then, comparing the mean number of accidents on foggy versus nonfoggy days, the values were 21.38 accidents per day and 21.92 accidents per day, respectively. Thus there was, on the average, 0.54 fewer accidents on each of the foggy days. It is interesting to note that if the nonfog rate had applied for the 29 foggy days, there would have been an expected increase of 15 to 16 casualty accidents that year.

Following this analysis, Foldvary and Ashton attempted to correct their results for day of the week and seasonal effects. This was done by determining, for every day of the year, an expected daily accident frequency based upon average frequencies for each day of the week and each fortnight of the year. Then the ratio of the actual accident frequency divided by the expected daily frequency was computed for each day of the year. Thus, if the actual number of accidents for any given day was higher than expected, considering daily and fortnightly effects, the "accident relative number" would have exceeded the value of 1 Using this approach, an average accident relative number was computed for foggy days, and one was computed for nonfog days; the values were 0.911 and 1.015, respectively. The difference was statistically significant ($P = 0.05$), and showed that fog tended to reduce casualty accident frequency. It should be noted that such attempts to correct results for the effects of extraneous variables are commendable, highly desirable, and completely lacking in other similar studies.

Foldvary and Ashton followed the same procedures for all accidents—property damage as well as casualty. Here, the average number of accidents per day was 66.90 in fog, and 66.41 on nonfog days. This apparent increase for foggy days, however, vanished when the correction procedure was applied. The average accident relative number was 0 943 for foggy days, and 1.015 for nonfog days. Although the difference did not reach statistical significance at the 0.05 level ($P = 0.10$), it certainly is suggestive that there is a depressing effect on accident occurrence associated with fog.

Foldvary and Ashton also attempted to relate their accident relative number ratio to visual range. Its correlation with highest visibility each day was an insignificant 0 03; however, its correlation with lowest visibility each day was a statistically significant 0.11 ($P = 0\ 05$).

In general, Foldvary and Ashton conclude that the results could be attributed to the driver's awareness of fog as a hazard.

Attending to accident severity, Johnson (1965) presented information pertaining to the relationship between fog and fatal accidents. His data were based on accident reports in California from 1961 and 1962; again, the difficulties imposed by accident reports should be recalled. Nonetheless, the following results were presented. For all roads in the state in 1961, the probability that an accident was fatal was 0.027; in fog, the rate was 0.025. This, of course, represents essentially no difference. Attending to freeways alone, however, the rate increased from 0.016 in all weather to 0.029 in fog; no test of significance was performed.

Johnson did, however, present sufficient information to compute rates and to test them for the combined data from 1961 and 1962 on freeways; this was done by the researchers of this report. Based on these data, the researchers' findings indicated that the fatality rate increased from 0.018 in clear weather to 0.036 in fog; this increase was statistically significant ($P = 0\ 01$).

From the *RVFS* (1967) it was noted that most fog accidents occur between the hours of 6 AM and 9 AM. Johnson gave the distributions of times at which fatal and nonfatal accidents had occurred. Using these data the researchers attempted to determine if Johnson's fog accident results

* Hereafter referred to as *RVFS*

could be attributed to the nature of traffic at these times. The researchers computed the fatality rates for accidents within the 6 AM to 9 AM time period and for accidents at other times. The resulting rates were 0.012 within the time period, and 0.019 at other times. Thus, it can be seen that the increase in fatality rate in fog cannot be attributed to the fatality rate during the morning rush hours.

In the last study relating accidents to fog (*RVFS*, 1967) the likelihood of multivehicle accidents was studied as a function of fog. This study was based on reported accidents on the rural California State Highway System. The results for 1964 show the probability that an accident involved four or more vehicles is higher in fog than in clear or cloudy weather. To correctly interpret this result, a distinction must be made between the probability of a four-or-more-vehicle accident and the probability that an accident involves four or more vehicles. The first probability refers to a joint event of having an accident, *and* having that accident involve four or more vehicles. The second probability refers to a contingent event that an accident involves four or more vehicles, *given* that an accident occurred. The *RVFS* (1967) conclusion is of the latter type, saying the probability of four or more vehicles being involved in an accident, given that an accident has occurred, is greater in fog. This does not imply that the probability of a four-or-more-vehicle accident is greater in fog. To validly draw this conclusion (viz, four-or-more-vehicle accidents are more likely to occur in fog), one would need to know that the accident rate in fog equalled or exceeded the accident rate in clear weather; this information is not available.

If one makes the assumption of equal accident rates in clear and foggy weather, the data can be analyzed to determine the degree to which fog increased the total number of vehicles involved in accidents. This can be done by comparing the actual numbers of vehicles involved in accidents in fog to the number of vehicles which would have been involved if the clear and cloudy weather involvement rates applied. For example, of the 1,033 accidents which occurred in fog, 449 were single-vehicle accidents; this is 43.5% of the fog accidents. However, of the clear or cloudy weather accidents only 38.9% involved just one vehicle. If this involvement rate had applied to the fog accidents, the expected number of accidents involving one vehicle would have been 401.8 (1,033 × 0.389). That is, if the clear weather rates for the number of vehicles involved in accidents would have applied to the 1,033 fog accidents, the expected decrease in vehicles involved in single-vehicle accidents would have been 449 — 401.8, or 47.2 vehicles. This analysis was applied to two-vehicle accidents, three-vehicle accidents, etc. The results are given in Table A-2.

Thus, it can be seen that if the clear weather involvement rates had applied to the accidents in fog, there would have been approximately 47 fewer single-car accidents, 151 more vehicles involved in two- and three-vehicle accidents, and 131 fewer vehicles in accidents involving four or more vehicles. Summing these, it can be seen that if the clear weather involvement rates had applied to the 1,033 accident vehicles in fog, there would have been only approximately 27 fewer vehicles involved in accidents; this, as compared to a total of 99,900 accident vehicles for the whole sample.

Summarizing the results of these three statistical studies:

1. The data do not suggest that fog increases accident rates. In primarily urban regions, fog may induce sufficient caution to reduce rates.
2. On freeways, fog tends to increase fatality rates.
3. Fog increases the likelihood that an accident will involve either one vehicle or more than three vehicles.

Finally, Miller (1967) gives some interesting information pertaining to the role played by visibility in fog accidents. His results are based on questionnaires sent to the drivers of 110 accident vehicles. Of those 36 drivers who

TABLE A-2

HYPOTHETICAL EFFECT OF CLEAR WEATHER RATES FOR FOG ACCIDENTS

		NO OF FOG ACCIDENTS		DECREASED NO. OF	
NO OF VEHICLES INVOLVED	CLEAR WEATHER RATE	EXPECTED, IF CLEAR WEATHER RATE APPLIED	ACTUAL	ACCIDENTS	VEHICLES
1	0 389	401.8	449	−47.2	−47 2
2	0 502	518 6	462	+56 6	+113 2
3	0.084	86.7	74	+12 7	+38.1
4	0.020	20.7	24	−3.3	−13.2
5	0.004	4 1	12	−7.9	−39.5
6	0 001	1.0	5	−4.0	−24.0
7	0.000	0.0	4	−4.0	−28 0
8	0.000	0 0	1	−1 0	−8 0
9	0.000	0 0	2	−2 0	−18.0
10	0.000	0.0	0	0.0	0.0
11+	0.000	0.0	0	0 0	0 0
All	1.000	1,032.9	1,033	−0 1	−26.6

stated that their first collision was with the vehicle ahead, 22, or 61%, said this vehicle was in sight before the incident occurred and did not "suddenly appear." This suggests, perhaps, that one major problem is associated not with seeing the vehicle ahead, but with being unable to see ahead of him and, thus, being unable to anticipate his actions. Another problem might be in the inability of a driver to detect the more subtle actions of the lead vehicle.

Miller also presented results cross-indexing estimated visual range and speed prior to impact. The researchers of this report used those speeds to determine required stopping distances with the aid of the AASHO *Geometric Design* (1965); perception time, one of the factors in total stopping distance, was set to zero on the assumption that drivers in fog tend to pay close attention. Of the 37 vehicles that could be judged, 25, or 68%, had speeds requiring stopping distances that exceeded the visual range. In this context, however, Miller observed, on a nonfog night on the same road, that speed and vehicle spacing was such that headways were also insufficient for emergency stopping. Again, perhaps this indicates the importance of the driver being able to see beyond the vehicle immediately in front of him. It is interesting that during the nonfog observations there was, in fact, a 13-vehicle accident Therefore, it cannot be determined whether the nonfog speed and spacing observations were normal or were more representative of the unusually unsafe condition.

TABLE A-3

STANDARD DEVIATION OF SPEEDS AS A FUNCTION OF VISIBILITY

VISIBILITY (FT)	STANDARD DEVIATION, BY DATA COLLECTION 1	2	3	4	5	6	7	8	9
0–100	7 1	3 5	7 2						
100–200	5.3	5.4	6 7						
200–400				4.8	3.9	5 1		5 2	
200–500	6 9	5.2	7 7						
400–500							6.5		
500–700					4.0		6.7		6.4
400+				6.3					
500+	6.6	6 1	7 4						
700+					5 4	5 6	5 8	6 5	7.6

TABLE A-4

HEADWAYS, IN SECONDS

	HEADWAYS (SEC)			
	67TH PERCENTILE		85TH PERCENTILE	
VOLUME (VPH)	FOG	CLEAR	FOG	CLEAR
1,200	4.8	5 0	8 9	>12
1,800	3 3	3 8	6.7	8.8
2,400	3 1	3.4	6.3	7.6

THE EFFECT OF FOG ON TRAFFIC

The only empirical study of the effects of fog on traffic flow known to the researchers is the *RVFS* (1967). In it, the effects of fog on speed and headway were studied on freeways and expressways in the Sacramento area. The data showed that, in general, fogs (all levels—day and night) tended to reduce mean speeds by 5 to 8 mph.

The report also stated that there was no general effect of fog level on speed variation. However, the data on which this conclusion was based included observations on roads where experimental speed limit signs were in use. Because these signs could well have influenced vehicle speeds, and, hence, speed distributions, it was decided to review only those data collected in places where the normal California maximum of 65 mph was in effect.

Table A-3 gives the standard deviation of speeds as a function of visibility. Each column in the table represents a separate data collection from a different combination of site traffic volume level, and/or day-night condition. The differences between columns are not important, because attention is focused within columns.

It can be seen that in all but two columns (1 and 7) there is an obvious trend for decreased speed variation with decreased visibility With regard to the data in column 1, a line fit to the four data points would reveal a slight trend in the same direction. Ignoring the strength of the trend for each column, the probability, assuming independence of visibility and speed variation, of observing eight or more trends in the mentioned direction is 0 02. This suggests a rejection of the hypothesis of "no trend" in favor of a hypothesis of "decreased variation in speeds as visibility decreases."

With regard to headways, the *RVFS* tends to show a relatively smaller number of short headways in foggy conditions (*RVFS*, Table 13). It should be noted, however, that inasmuch as speeds are reduced in fog it is possible that the relative frequency of short vehicle spacings is not materially changed.

On the other hand, if one compares the headway data in Figures 17 and 18 of the *RVFS* the approximate data in Table A-4 can be obtained.

Now, for example, considering the 85th percentile headway at 2,400 vph, one sees that in fog 15% of the drivers had headways over 6.3 sec. However, in clear weather 15% of the headways were over 7.6 sec; thus, for this condition, well over 15% had headways greater than 6.3 sec. It can be concluded that there were more long headways in clear weather than in foggy weather. This statement is shown to hold for all three volume conditions and at both the 67th and 85th percentiles. Thus, at least at the high volume levels, these data show fewer long headways in fog; this is in agreement with a hypothesis that in fog there is a tendency for drivers to shorten headways to maintain visual contact with the vehicle in front.

It should be pointed out that, given a fixed volume, the presence of long and short headways are not independent events. As the number of short headways increases, so must the number of long headways. Thus, it may be that, in fog, tailgating is unacceptable to the driver; as a result, vehicles spread out more, grouping becomes less evident, and very long headways decrease in number. Or, it may be that, in fog, vehicle spacing exceeding visual range becomes unacceptable; as a result, spacing becomes more even, and short headways decrease in number. The true mechanism reducing the numbers of large and small headways therefore could not be determined from these data.

Changes in vehicle lateral placement, as a result of fog, were also investigated. Two sections of a state highway (curve and straight) were selected for the tests. Observations revealed that for the curve test segment, the proportion of vehicles crossing the center line during fog (day and night—all densities) was greater than during clear weather. However, these results were not considered significant ($P = 0.05$). Furthermore, there was no change in encroachment on the pavement edge (all conditions tested).

GUIDANCE SYSTEMS DESIGNED TO ELIMINATE THE FOG HAZARD

A variety of methods designed to aid the driver during periods of reduced visibility has been proposed and experimentally tested. Beaton and Rooney (1966) evaluated the use of different types of raised reflective lane delineators (beaded and nonbeaded buttons and wedges, raised reflectors enclosed in acrylic plastic) for a variety of weather conditions (day—rain, dry; night—rain, dry). They found that, at night, reflex reflector and beaded pavement markers provided the best delineation. However, during the day these markers proved unacceptable because of their tendency to blend with the pavement.

The usefulness of the beaded type of lane delineator for guidance in fog was investigated in the *RVFS.* The marker was tested on a California state highway during daylight hours only. Judgments by trained observers indicated that the improvement in visibility (all fog densities) was negligible. However, Beaton and Rooney showed that the beaded marker offered the greatest visual improvement during the night. Therefore, before any conclusions can be drawn concerning the usefulness of this type of marker for guidance in fog, nighttime tests should be conducted.

The use of reflectorized paint on both the pavement and roadside signs is another technique that has been proposed to increase the driver's visual range. Huber (1961) used this technique to increase visibility and provide information at a freeway interchange. He painted the on-ramps and acceleration lanes a reflective yellow and the exit signs, off-ramps, and deceleration lanes a reflective blue. By varying the illumination from existing overhead streetlights he was able to study the effects of five levels of day and night visibility. His observations were made only during clear and dry weather and indicated that none of the experimental test conditions had any effect on the flow of traffic (vehicle headway, speed or placement) through the interchange. Interviews with a sample of drivers revealed that, at night, the reflectorization treatment alone provided as much information as full overhead lighting. Similar studies (Roth and DeRose, 1966; Darrell and Dunnette, 1960; Fitzpatrick, 1960) using reflectorized paint as a means of illumination have revealed essentially the same results.

The effectiveness of this type of experimental treatment for guidance in fog was tested in the *RVFS.* Reflectorized paint was applied to edge and gore stripes on the entrance (blue paint) and exit (yellow paint) ramps of a cloverleaf interchange. Traffic movement (encroachments on or across the gore and edge striping) was observed both in fog and clear weather before and after application of the experimental treatment. It was hypothesized that, if guidance was improved by the reflective paint, there would be less encroachment on the edge and gore stripes. Because of a lack of fog, and the observation that vehicles tend to cross the edge stripes to reduce the sharpness of the on and off ramp curves, the findings were inconclusive.

Warner (1958) recommended changes in the type and color of various highway markers (signs, lane and edge delineators, etc.). He claimed that primary emphasis must be placed on maximizing the contrast between the highway marker and the roadside environment. Even though a fog environment was not considered specifically, some of his suggestions might prove applicable and should be tested. For example, the use of two-tone reflectorized guide posts might prove to be an effective guidance system in both day and night fog conditions. Forbes, Pain, Fry, and Joyce (1967) confirmed the influence of environment on sign visibility: subjects observed sets of signs of varying brightness against different backgrounds. The subject's task was to pick the sign, from each set viewed, that was recognized first. The results revealed that signs highest in brightness were seen most frequently against a night and day hill (daylight with a hill covering a large portion of the picture) background. Conversely, signs lowest in brightness were seen most frequently against a day-snow background.

Pavement edge striping is another guidance technique that has received considerable attention. Basile (1961) designed a study to determine the effect of the use of this technique on accident rate. Weather was not included in the experimental design. Basile found that edge striping had no effect on the number of accidents occurring on the open road. However, at intersections and driveways, the accident rates were significantly reduced when edge striping was present. These results were confirmed by Music (1961). The effect of edge striping in fog was studied in the *RVFS.* Edge striping was installed on two test sections (curve and straight) of a state highway. The lateral placement of a sample of vehicles was used as a measure of the effectiveness of the striping. It was hypothesized that, if the striping was effective, drivers would be able to maintain their vehicles near the center of their lane, thus reducing the probability of conflict with vehicles in the adjacent lane or collisions with obstacles alongside the road. Observations were made in various fog densities and clear weather both before and after edge striping. The results indicated that edge striping had no effect on vehicle lateral placement (all test conditions). However, interviews with a sample of drivers revealed that the edge striping gave them a feeling of increased safety, especially during dense fog conditions.

Guidance systems using artificial lighting have proved to be effective in combatting the hazardous effects of fog. Finch (1961) proposed the use of small lights as lane and roadway delineators. He hypothesized that, during fog conditions, these lights would provide the driver with linear depth perception cues, enabling him to regain a measure of the orientation provided, during clear weather, by the edge of the road and normal lane delineators. Finch constructed an artificial fog simulator at the University of California to test his hypothesis. The experimental lights, set into the pavement, were almost flush with the road surface. Photographic results indicated that, during dense fog, the roadway and lane delineator lights are twice as visible as normal roadway and lane delineators (day or night). The effectiveness of the lights depended on their wattage and road spacing. Finch found that low wattage units spaced close together were more effective than high wattage units spaced farther apart. The low wattage reduced glare and the close spacing accentuated the linear depth perception cues. Finch and Curwen (1965), using photographic evidence and subjective evaluations, confirmed the effectiveness of this type of lighting system for all densities of day and night fog. Spencer (1966) developed a computer model to determine the percentage of light, generated by this type of delineator, that is scattered by the fog. Recall that the greater the scattering, the harder it is to distinguish the light from the background. The model indicated that, in extremely dense fog, these lights could be easily distinguished up to 200 ft away.

The use of streetlights as a means of increasing visibility in fog has been studied by Pritchard and Blackwell (1959). They experimented with different types of lighting in a small fog simulator (scale 25:1) Photographic results indicated that for optimal visibility in fog (maximum contrast, minimum glare), streetlights should have a narrow beam spread, with the beam perpendicular to the driver's line of sight. This could be accomplished with overhead lights or lights placed at low elevations alongside the roadway. Both these systems, with added refinements, were implemented by Spencer (1961) on a section of the New Jersey Turnpike. Field studies, at this location, revealed that in dense fog low-elevation lighting was best and that at least one of the three lanes could operate normally.

Anti-fog lighting systems in Europe (*Illum. Eng.*, 1967) have been designed in much the same way. Cylindrical lanterns mounted near the road surface are being used to direct a fan-shaped beam of light onto the roadway at an angle of about 110° from the direction of direct illumination The lighting plan has proved effective in helping motorists to navigate through fog.

Pritchard and Blackwell also tested various types of vehicle lighting systems. Their results indicated that, for maximum visibility in fog, the vehicle headlights should be mounted as far as possible from the driver's line of sight and designed so as not to illuminate the fog directly in front of the vehicle. Further tests using a polarized fog light with an orthogonal viewer revealed that this type of light was more effective than a normal headlight in increasing the contrast of most objects. Another study concerned with the operation of vehicle lighting systems in a fog environment simulator (scale 3:1) was reported by Marsh (1958). Photographic results showed that polarized spot lamps with cross-polarized viewers provided the best visibility. Beaded pavement markings and plastic reflectors were clearly seen in dense fog with the polarized fog lamps, but were practically invisible when viewed with normal headlights. It was also observed that increasing taillight candle power improved the contrast between the taillights and the surroundings. Nathan (1957) developed a polarization technique that could be used with either visible or infrared light. Experimental tests of this technique in fog, haze and smoke resulted in dramatic improvements in visibility.

Audio-communication has been suggested as a means of informing drivers that they are approaching a fog area. The feasibility of audio-communication has been tested by Covault and Bowes (1964). They equipped a random selection of vehicles, traveling on a limited access thruway, with specialized radio receivers. Between the receiver installation point and the receiver pickup point the drivers received messages pinpointing the locations of staged accidents and maintenance activities. They were also told what speeds would be safe in each of the experimental areas. The tests were conducted only in clear weather and the results indicated that audio-communication was an effective means of controlling speed in hazardous areas. The *RVFS* also examined the feasibility of an audio-communications guidance system. After conducting a rather limited test of a commercially available system they concluded that, with additional research to eliminate some disadvantages, the system would be feasible. They were unable to test the usefulness of this type of guidance device in fog, however.

A gated laser system, developed by Laser Diode Laboratories (*Prod. Eng.*, 1969) offers a capability for detecting targets during periods of poor visibility. The small hand-held system employs a pulsed gallium arsenide laser that emits in the infrared and receives reflected light from objects on a photocathode image converter tube. The complete unit costs about $3,000. At present, the system is said to have a range of about 300 ft, although plans call for advanced models with greater range.

Ricker (1953) pointed out the utility of any device which, when activated, would ensure a physical separation between vehicles passing through the fog area. The ground work for such a hypothetical device was developed by Cosgriff, English, and Roeca (1965). However, their system is severely limited and a long way from becoming a reality. Ricker also recommended the use of specially equipped control cars to lead convoys of vehicles through the fog area and, when control cars are not available, a reduction in the speed limit. The *RVFS* tested the effect of reduced speed limits during fog conditions. They found that at two test locations (an expressway and a freeway), posted speed limits tended to reduce mean speeds 5 to 10 mph over the reduction in speed caused by fog alone. However, this effect was observed only when the posted speeds were above 40 mph. This might in part be due to the fact that the police made no attempt to enforce the posted speed limits. It was also observed that the reduced speed limits considerably decreased speed variability on the expressway but not on the freeway.

In another segment of the *RVFS*, an effort was made to determine the effects of various types of police enforcement procedures on speed reduction in fog. Observations were made before and after increasing: (1) the number of moving patrol cars, (2) the number of moving patrol cars with the rear amber lights flashing and (3) the number of parked patrol cars with the rear amber lights flashing. The results revealed that all three of these techniques caused a reduction of approximately 6 mph in day fog conditions (visibility between 200 and 500 ft). However, during nighttime fog (all levels of visibility), only parked patrol cars had any effect on speed reduction (4 to 5 mph).

In summary, it can be stated that the guidance systems using artificial lighting proved to be the most effective in eliminating the hazardous effects of fog. Visibility in fog (day and night) was dramatically increased when artificial lights were employed as (1) lane delineators and (2) specially modified lamps mounted near the roadway surface. In contrast, reflectorized pavement markings (beaded lane delineators and edge striping) resulted in only a slight increase in visibility and had virtually no effect on traffic flow, during daytime fog conditions. However, before these devices can be discarded, more comprehensive tests are needed, particularly during nighttime fog conditions, where the contrast between the pavement markers and the surrounding environment is the greatest.

REVIEW OF PREVIOUSLY SUGGESTED FOG ABATEMENT CONCEPTS

Listed in the following are the primary methods that have been suggested in the past for fog dispersal. A brief resume of cold fog abatement procedures is presented in the opening section of the summary, followed by a review of the more numerous, but less successful, warm fog dissipation techniques. Admittedly, many of the concepts cannot be considered practical for highway use; however, to provide a complete portrayal of the state of the art of fog abatement procedures, the basic principles of each technique are given. Additional reviews of fog dispersal concepts can be found in Wayne and Bell (1953), Junge (1958), and Myers and Hosler (1965). *The National Plan for Warm Fog Modification Research* (NSF, 1967) and the *National Plan for Cold Fog Dispersal* (FAA, 1966) also should be reviewed.

Supercooled Fog Dispersal

The occurrence of dense supercooled fog (liquid water droplets colder than 32° F) is limited basically to northern areas of the United States during the winter months. Dispersal of cold fog has been successfully demonstrated by a number of investigators using dry ice, propane, silver iodide, and other ice nucleating agents (see, for example, Schaeffer, 1946; Vonnegut, 1947; aufm Kampe et al., 1957; Downie and Silverman, 1959; Jiusto and Rogers, 1960; and Hicks, 1966).

The principle of cold fog dispersal involves the nucleation and subsequent growth of ice crystals in the presence of supercooled fog droplets. Because the saturation vapor pressure of ice is less than that of water at the same temperature, growth occurs on the ice crystals while the natural fog droplets evaporate to maintain equilibrium with the environment. After a short period of time the growing ice crystals precipitate, thereby promoting dissipation of the fog.

Although there is a variety of feasible techniques that could be used for cold fog dispersal, only dry ice seeding is currently operational at airports in the United States (FAA, 1966). In practice, dry ice pellets or powdered dry ice is dispersed into the fog top from a light aircraft. The amount of dry ice varies from 50 to 600 lb per flight, depending on the micro-physical characteristics of the fog. It is reported that greater than 80% of the supercooled fog-seeding trials are successful at airports where operational seeding programs are in effect.

Other techniques, involving jet engine exhaust, infrared heat, and open flame burners to cause evaporation of supercooled drops, are not considered efficient methods for cold fog dissipation. For highway use, the dry ice seeding concept has limited application, because it is difficult to keep a cleared region over the highway for substantial periods of time. It is not impractical, however, to consider implementation of this technique at busy intersections or other congested traffic areas where supercooled fog is a problem.

Warm Fog Dispersal Techniques

In the United States a majority of fogs occur at temperatures warmer than 32° F (i.e., warm fog). Efforts to achieve a warm fog dispersal capability have occupied the attention of scientists for over 50 years, and to date no operational programs are in use for the dissipation of warm fog. Recently, however, significant advances have been made in the area of warm fog abatement, and these advances have encouraged investigators to be cautiously optimistic about achieving a fog dispersal capability.

Summarized as follows, then, and arranged under four general categories, are the principal methods that have been advanced in the past for warm fog dispersal. Conclusions regarding the possible use of these techniques are presented at the end of the section.

Thermal Methods (Evaporation of Droplets)

FIDO (Fog Investigation and Dispersal Operation).—During World War II an urgent need existed for an operational fog abatement technique that could be used at military air bases. The British demonstrated that fog could be dispersed by burning aviation gas at a high rate in open flame burners to heat the air above the dew point and cause the fog droplets in the vicinity of the burners to evaporate. Prior to the operational use of the method in the early 1940's, Houghton and Radford (1938), as well as Brundt (1939), had considered the idea. A number of successful tests were later run at Los Angeles Airport from 1948 to 1953 (Kelly, 1954).

For airport use under emergency conditions, the technique has proven useful (over 2,500 successful landings were made during World War II as a result of FIDO dispersal techniques). For commercial use, the method is less attractive because of the high operating costs and dangers involved when landing airplanes in the vicinity of open flames. Ordinarily the efficiency of a FIDO system is rather low, because a great deal of heat is dissipated without being effective in clearing fog For general highway use the system must be considered impractical, for economic reasons

Other thermal methods that involve convection of heated air to cause dissipation of fog include jet engine exhaust heating, electrically generated heat, and burning of coal. All of these methods, however, are infeasible for highway use.

Solar Energy.—A number of experiments have been performed by Van Straten et al (1958), and later by Lieberman (1960), to test the effectiveness of carbon black as a heating agent and also as a seeding material for dissipating fog, no definitive conclusions were drawn The particles serve as efficient absorbers of radiant energy and, once dispersed into fog in the presence of sunlight, accelerate the evaporation of fog droplets. Myers and Hosler (1965) discuss the possibility of dissipating shallow radiation fog by dispersing micron-sized particles of anthracite coal into the fog during the daylight hours. They point out that the temperature lapse rate is likely to have an important effect on the success of the technique—unstable conditions favoring mixing and consequently limiting the usefulness of the particles

During periods of shallow radiation fog the technique may have some value, but, for general fog situations (advection fogs or thick radiation fogs accompanied by cloudy skies), the method cannot be expected to work The problem of effectively dispersing ample amounts of material may also pose serious operational problems. For highway application the technique appears limited, at best.

Chemical Methods (Evaporation of Droplets and/or Altering the Drop Size Distribution)

Modification of Drop-Size Distribution by Seeding With Hygroscopic Nuclei—Recent experiments at the reasearch agency (Pilié, Kocmond, and Jiusto, 1967) have shown that it is possible to improve visibility in warm fog by seeding with micron-size salt particles. Visual range in laboratory fogs produced in a 600-cu-m chamber was increased by factors of three to ten with as little as 1.7 mg of salt/cu m being effective.

In field experiments, visibility in natural fog was improved significantly (visual range of 350 ft before seeding and 2,600 ft after seeding) by disseminating sized NaCl nuclei into the fog from an aircraft. The primary goal of these experiments was to cause a redistribution of the droplet sizes in fog without necessarily altering the liquid water content (as opposed to desiccation techniques in which drying of the atmosphere is required). In the current experiments only a modest reduction ($<1\%$) in relative humidity is involved.

An important aspect of the seeding technique is the use of properly sized hygroscopic particles for seeding. Calculations and experiments suggest that for airport application, particles between 5μ and 10μ radius are best. For highway use somewhat smaller sizes would be preferable, although, under conditions of fairly high wind, larger sizes must be used. In view of the magnitude of the highway fog situation, however, only limited use of the concept should be considered As with supercooled fog dispersal, this procedure may be useful at busy intersections or other congested traffic areas where fog is a hazard.

Fog Desiccation—The theory of fog desiccation involves lowering the relative humidity of the foggy air with a desiccant such as $CaCl_2$ or other hygroscopic material to cause evaporation of the fog droplets. This approach was originally advanced by Houghton and Radford (1938) and demonstrated successfully on a limited scale in field experiments. In their original experiments, saturated solution drops of $CaCl_2$ were dispersed into the fog to lower the relative humidity to about 90%. Although success in clearing a portion of the fog was achieved, serious objections were raised concerning the corrosive action of $CaCl_2$ droplets. Furthermore, large amounts of salt were required to clear a relatively small area of the fog (approximately 5l/sec or about 2 5g of $CaCl_2$ solution per cubic meter of fog were needed to lower the R. H to 90%, with clearing rates of 2,000 cu m/sec)

Houghton and Radford considered an alternate approach for desiccating fog in which relatively small quantities of fog-laden air were passed through a unit containing $CaCl_2$. The very dry air was then mixed with natural fog to produce a net reduction in relative humidity to something less than 100%. Subsequent evaporation of natural drops in the large volume resulted in improved visibility. Although the fog dispersal unit was carefully designed, the clearing it provided was not considered adequate to warrant operational use.

Polyelectrolytes.—Recently, a series of experiments conducted by World Weather, Inc. (Beckwith, 1968, private communication), under contract by the Air Transport Association, have shown some promise in dissipating warm fog. The tests, conducted at the Sacramento, California, airport, involved the use of solid and liquid chemicals (polyelectrolytes) that are dispersed into the fog. It is claimed that out of 24 seeding trials, 16 were successful in causing dissipation of a portion of the fog. Details of the chemicals have not been revealed Experiments conducted at the research agency in which laboratory fogs were seeded with various types of polyelectrolytes do not support the claims made by World Weather, Inc. In experiments at the research agency, no significant visibility improvement (i.e., greater than a factor of 2) was noted after seeding with the sized polyelectrolytes Furthermore, there does not seem to be a sound theoretical explanation of why polyelectrolytes should work. The results suggest that unless hygroscopic polyelectrolytes are used for fog dissipation work (in which case the factors responsible for fog dissipation will be the same as those in the research agency's seeding tests using sized NaCl) there will be very little reason to expect the chemicals to be effective as warm fog modifying agents.

Ammonium Nitrate.—Initial experiments conducted by the Naval Ordnance Test Station, China Lake, California, using ammonium nitrate solutions have also shown some promise in dissipating warm fog (St. Amand, 1968, private communication). The solution droplets, on entering the foggy atmosphere, grow at the expense of the evaporating natural droplets. Additional tests are planned during the summer of 1969. Some objections have been raised concerning the corrosive action of the solution droplets on aluminum alloys; however, it may be possible to limit the corrosive action of the chemical by using additives.

Condensation Nuclei Deactivation.—The possibility of inhibiting droplet growth in fog by treating the nuclei on which fog droplets form has been considered at the research agency by Jiusto (1964), and by Pilié and Kocmond (1967) Laboratory experiments with hygroscopic nuclei coated with hexadecanol demonstrated that droplet growth on treated nuclei could be substantially retarded. This result, although encouraging from a standpoint of modifying the drop sizes in fog, cannot be considered as a practical means for suppressing fog at the present time, because no reliable method for treatment of nuclei in the atmosphere is known.

Surfactants.—The use of ionic surfactants (organic molecules that separate into oppositely charged ions in water) has been postulated by Elton (1958) as a possible means of altering droplet surface change in fog to cause increased coalescence of natural droplets. Lieberman (1960) and later Jiusto (1964) investigated the diffusional growth and evaporation rates of droplets treated with surfactants but found no significant differences between treated and untreated droplets. Kocmond (1965) demonstrated in laboratory experiments that the coalescence of droplets treated with an ionic surfactant and impacting on a plane water surface was actually inhibited rather than enhanced. The concept is therefore not considered feasible for fog dissipation.

Chemical Monolayers.—The possibility of inhibiting the growth of droplets during the formation of fog also has been considered and extensively studied at the research agency (Jiusto, 1964). Results of laboratory tests indicate that the growth and evaporation rates of droplets can be dramatically reduced by treatment with chemical monolayers; for example, the lifetime of a 10μ radius drop, that normally evaporates in 1 sec at 20° C and 40% R.H., can be increased to 560 sec by treatment with a hexadecanol/octadecanol monolayer. To date, no effective means of treating natural fog droplets has been developed and, hence, the method cannot be considered practical for highway use. There is a distinct possibility, however, that fog that often forms over small lakes and swamps (and subsequently drifts over nearby roadways) can be suppressed by proper treatment of the water surface with monolayers. By inhibiting evaporation and limiting the supply of moisture required for fog formation, the incidence of fog in these areas can be lessened. A more thorough investigation of this possibility is suggested.

Electrical Methods

Droplet Charging.—A number of investigators have suggested that fog might be dissipated if the coalescence and precipitation of droplets in fog could be enhanced by some charging mechanism. Pauthenier (1950) calculated the collection efficiencies of charged water droplets and found them to be extremely efficient collectors of liquid water. It was suggested by Pilié and Kocmond (1966) that the maximum electrical effect might be obtained by charging alternate adjacent regions of a fog positively and negatively by means of a corona discharge. The reasoning was that substantial electric fields might be produced between the adjacent regions to promote rapid mixing of droplets charged to opposite polarities, thereby promoting coalescences of droplets.

Calculations indicated and laboratory experiments demonstrated, however, that no significant increase in fog dispersal rate could be achieved by placing electric charge on fog droplets using practical system configurations. Because fog droplets are very small (approx. 5μ radius) the maximum amount of charge that droplets will accept in a practical electric field is far too small to cause significant attraction of oppositely charged droplets. Hence, droplet charging in an electric field cannot be considered as a practical method for fog dispersal.

Charged Particles and Sprays.—Alternate schemes for dispersing fog using electrical means include charging of nuclei in the atmosphere, electrically charging a spray to induce sweepout of fog droplets, and charging saturated salt solutions to combine desiccation and sweepout of droplets. All of these methods suffer from an inability to get sufficient amounts of the charged material into the fog Tests by A. D. Little (1955) using a charged spray to dissipate fog showed no visibility improvement that could be attributed to the spray. Effective fog dissipation using these methods does not appear feasible for highway use.

Mechanical Methods

Natural Vegetation to Suppress Fog Movement.—Observations of fog in central Pennsylvania by Myers and Hosler (1965) have indicated that very modest vegetation can effectively block shallow fog from spreading to nearby areas. It is likely that low-lying areas that are susceptible to cold air drainage could be protected from fog by judicious placement of tree stands. Landscaping schemes can easily be envisioned that might prove effective in protecting roadways from shallow radiation fog. The idea merits further consideration for roadway application.

A related experiment reported by Arkawa (1960) involves the use of a fog-shelter net to inhibit the natural movement of fog. The net consists of 1-sq-cm meshes (50 m × 50 m) and was originally tested in the area of Kegon Fall, Japan. Arkawa reports some success in preventing the advection of fog to surrounding areas; however, because of the vertical depth of most fogs, the scheme is not an appealing one. Natural vegetation barriers to fog movement appear more practical for highway use.

Droplet Removal by Forests.—Hori (1953) studied the effect of forest stands in removing fog droplets in the area of Hokkaido, Japan. The study was concerned with advection fog situations near coastal areas. Although it was established that droplet removal was effective, particularly on pine needles and for larger drops, no firm conclusions were drawn regarding the applicability of the technique. Only advection fogs could be treated by this method, because radiation fogs are not accompanied by significant winds. For highway situations the technique would have greater applicability than for airport use, because only a shallow layer of fog requires clearing. The method may have some applicability along coastal areas where advection fogs are frequent.

Fog Broom—Recently, a technique for fog dispersal has been advanced that involves the mechanical sweep-out of fog droplets on a grid of closely spaced nylon threads or wires (Scheer and Johnson, 1967). The apparatus is called a "fog broom" and consists of a paddle-wheel arrangement driven by a small electric motor. A number of brooms are being installed along sections of a New Jersey highway where the frequency of fog is high It is expected that a sufficient number of fog droplets will impact on the slowing turning grids to effect a change in visibility. Laboratory experiments were promising; however, the ability to influence a sufficient depth of fog over the highway may limit effective use of this technique. Encroachment of fog at the boundaries due to induced and natural turbulence may also affect the usefulness of this scheme.

Fans to Cause Mixing of Clear Air with Fog.—An idea for fog dissipation originally considered by Mitchell (1957) involves the use of large fans, mounted horizontally, to cause mixing of foggy air with surrounding clear air. Although originally proposed with ice fog in mind, the idea might be applicable on highways where patches of ground fog frequently occur. Only limited use could be made of this method, however, because many fogs are of a more general character and of sufficient thickness to prevent effective mixing with surrounding drier air.

Alternately, the idea of vertical mixing of dry air from aloft with shallow fog has been frequently discussed and almost as frequently rejected Junge (1958) reports that attempts at fog dispersal on the New Jersey Turnpike were made using vertically mounted fans, although no data are available regarding their performance.

More recently tests by the Meteorological Laboratory of AFCRL have been successful in dissipating radiation fog and stratus clouds by using very large helicopters to mix drier air from aloft with the foggy atmosphere. It is reported that openings in excess of 600 ft in diameter were attained in less than 1 min using the large helicopters. The method requires that the relative humidity of the drier air above the fog be 90% or less.

Although the technique can be considered useful on highways where the fog is less than 100 ft thick, the principal drawback is that in most circumstances the cleared area will fill with fog within minutes after the aircraft leaves the area.

Probably the greatest difficulty in effectively using the vertical mixing technique lies in the natural resistance of the atmosphere to vertical movement during the stable conditions that frequently accompany fog. Again, the idea may have some applicability on highways where patches of ground fog occur but, in general, the concept appears impractical for dissipation of widespread fogs.

Sweepout with Falling Particles.—Magona et al. (1963) have demonstrated that in certain situations when the atmosphere is unstable, but capped by an inversion, a falling spray of droplets is effective in dissipating fog. It is probable that downdraft of warmer air caused by the falling spray is responsible for the fog dissipation, particularly inasmuch as the incidence of droplet coalescence in fog is small. The idea has some value for airport fogs, but practical application to the highway would be limited.

Sonic Agglomeration—The application of high-intensity sound waves to enhance coalescence and cause precipitation of droplets in fog has been considered for at least 30 years. Investigations by St. Clair (1949) in the laboratory suggest that sound intensities far too great for field application would be required to promote coagulation of fog droplets. Later, Boucher (1960) studied the problem theoretically and concluded that the method might be used in conjunction with other techniques but was not practical by itself. It is generally agreed that the power requirements needed to produce sufficient intensities are excessive for field application. Recently, however, a Polish shipping line reports some success in dissipating thick sea fog (*New Scientist*, 1968) using a siren and parabolic reflectors to direct the ultrasonic waves in a controlled beam. It is reported that a visibility range of 300 to 400 m was produced using a prototype siren. It is difficult to assess the effectiveness of the technique, however, because no visibility data were given for the untreated portion of the fog.

In summary, only a few of the techniques advanced for fog dissipation have real merit, and fewer still have applicability for highway testing. Of those considered relative to the highway fog problem, three concepts appear more promising than the others.

1. For warm fog modification at busy intersections, seeding with micron-sized hygroscopic particles of carefully controlled size appears feasible. The concept may not be applicable for general highway use but easily could be implemented on a limited scale. The primary drawback to this technique lies in the installation and maintenance of equipment required to seed fogs.

2. The proper use of vegetation to block movement of shallow fog from higher elevations to low-lying surrounding areas appears to be applicable to many highway situations. Because no maintenance or operating costs are involved, implementation of the concept would be inexpensive. It is recommended that airborne surveys be conducted to determine those areas where vegetation barriers might best be used to influence fog movement.

3. The dissipation of supercooled fog is an operational reality at many airports. For those areas of the U. S. where the incidence of supercooled fog is high (e.g., the northwest states) standard cold fog seeding techniques can be employed to effect dissipation over heavily traveled sections of highway. The same problems that limit the hygroscopic nuclei seeding concept also hamper efficient use of this technique (i.e., installation, maintenance, and operation of equipment).

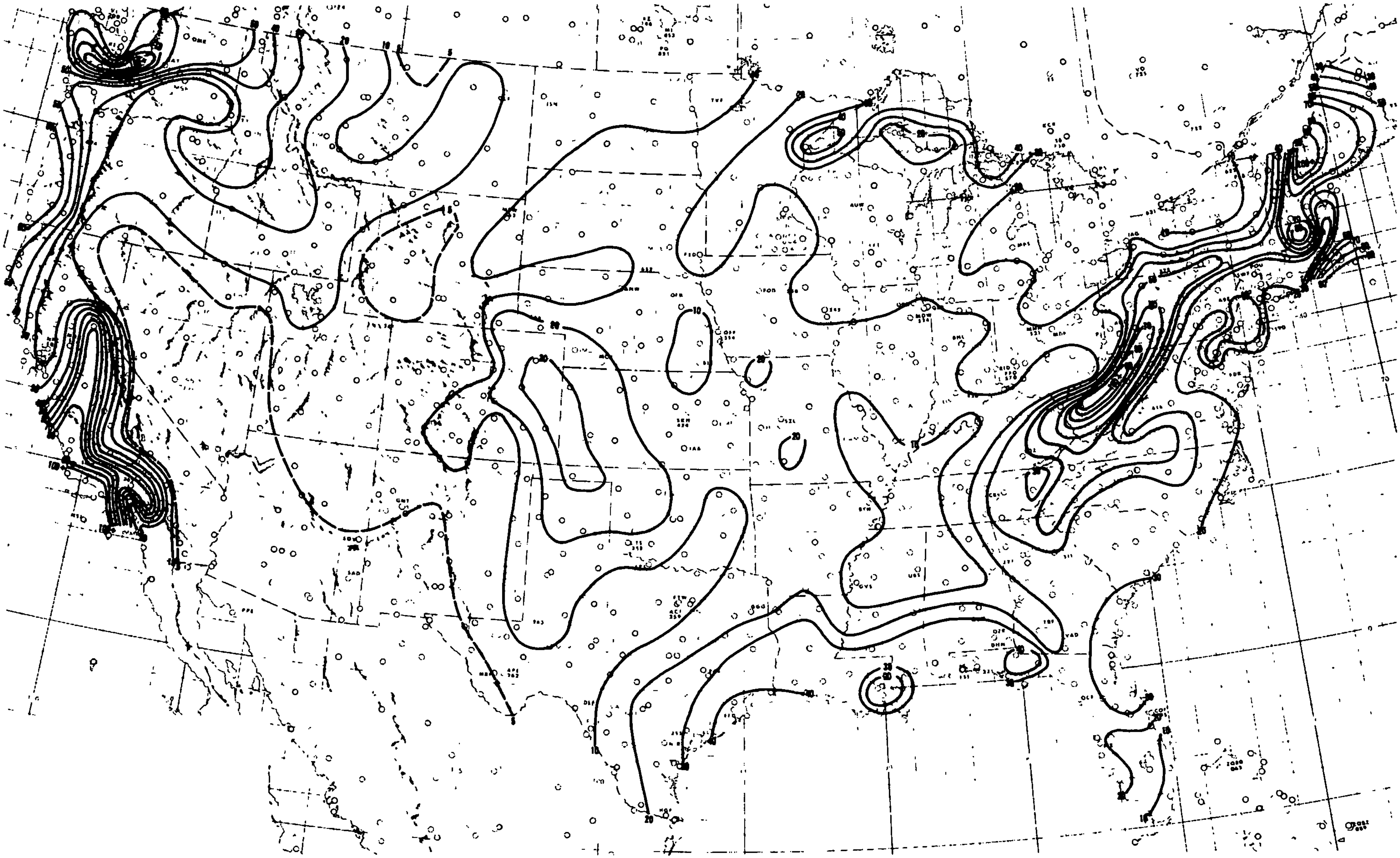


Figure A-2. Average annual number of days with dense fog in the United States.

Other techniques that have limited application and may be useful under certain conditions are:

4. The use of monolayers to inhibit evaporation from small ponds and lakes that lie near roadways. Numerous instances of ground fog that occur in the vicinity of small water reservoirs could be prevented if the supply of moisture provided by the reservoir could be retarded. Chemical monolayers, effectively spread over water surfaces, offer this capability.

5. Verticle-axis fans can be used to dissipate patches of ground fog. Mixing of fog with surrounding drier air can effectively eliminate radiation fog of modest vertical extent. The use of helicopters to dissipate certain kinds of fog also has been shown to be effective. More efficient dispersal of radiation fog may be possible by combining the use of helicopters with the seeding concept developed at the research agency.

6. In some locales, effective control of hygroscopic emissions from industrial areas offers a partial solution to the fog problem. By reducing the concentration of "fog" nuclei in certain areas, local patches of fog might be eliminated.

7. Although at the time of this writing a scientific basis for the use of polyelectrolytes for fog dispersal is not available, reports of preliminary field tests are encouraging. Knowledge gained through continued use of these chemicals may have a bearing on the fog problem in the near future.

Although marginal success has been reported with a number of the other concepts discussed, economic as well as engineering problems of warm fog abatement dictate the need for improved highway delineation systems to supplement (or even take the place of) fog suppression schemes that are now envisioned. In time, more efficient means of warm fog dispersal will become a reality, but, for the present, only limited application of any one technique can be considered for use on highways where fog is a problem.

CLIMATIC SURVEY OF FOG FREQUENCY

Of basic importance to the study of the effects of fog as a traffic problem is the frequency of fog occurrence. Because of the diversity of environmental factors (terrain, moisture sources, pollution, etc.) and conditions that produce fog, the occurrence of fog tends to be a local phenomenon that varies widely from place to place, year to year, and season to season. The frequency of fog in a given location, for a given period, often varies by a factor of 2 from the mean. It must be understood, therefore, that any summary of fog occurrence represents only a gross picture of inconsistent events.

In preparing a discussion of fog frequency for the conterminous United States, data were summarized based on occurrences of fog having visibility ≤¼ mile (dense fog). Although visibilities of ¼ mile rarely impair highway traffic, dense fog includes those fogs of a more severe character which do affect the transmission of information to drivers.

Definition of Terms

The terminology used herein is defined as follows:

Heavy fog. fog with visibility ≤½ mile.

Dense fog: fog with visibility ≤¼ mile.

Ground fog: generally, fog in which the top can be seen; fog in which the top does not reach the base of any clouds; or fog in which not more than 0.6 of the sky is obscured.

Supercooled fog: fog occurring when the air temperature is 32° F or colder.

Visibility: the farthest object that can be observed. In daylight, landmarks are used, but, at night, unfocused lights serve as reference points.

Dense Fog Occurrence in the Conterminous United States

A summary of the data has shown that dense fog constitutes a significant problem (occurring on more than 20 days per year) in over 60% of the areas where Weather Bureau observation stations are located.

Figure A-2 (Pilié, 1965) is a conventional isopleth analysis of the average annual number of days with dense fog in the conterminous United States. In most areas, local effects appear as random departures from the general pattern.

Despite the difficulties imposed by the type of data available and the largely local nature of fog, the analysis provides significant insight into the nationwide climatology of fog The differences in the degree of local influence from place to place are real and quite pronounced. It is obvious that dense fog is not a problem in the southwestern mountain region and only a moderate problem in the Great Plains. On the other hand, fog is most frequent and quite local in nature along the West Coast, in the Appalachian Mountains and along the New England Coast. Along the Gulf and Atlantic Coasts and in the Great Lakes region, fog is quite frequent (more than 20 days per year on the average) and local effects do not seem to be as significant as in other areas of high incidence.

Previous studies at the research agency (Jiusto, 1964) and United Airlines have shown that supercooled fog is a minor problem of conterminous United States, except for the Pacific Northwest, during December and January.

APPENDIX B

FOG ABATEMENT TESTS

The Office of Aeronautical Research of the National Aeronautics and Space Administration has authorized the research agency, under Contract No. NASr-156, to investigate warm fog properties and possible fog modification concepts. Analytical and experimental work during the first 4 years of research led to the development of a concept for fog dispersal by seeding with carefully sized hygroscopic nuclei. During the fifth contract year that concept was thoroughly tested in the laboratory and preparations were made for a series of field experiments. One of the objectives of the research has been to evaluate the effects of seeding dense natural fog. This report summarizes the results of the field experiments and of the subsequent data analysis.

References appear in Appendix H, Bibliography.

TECHNICAL DISCUSSION

During the late summer and early fall months of 1968, 31 fog-seeding experiments were conducted at the Chemung County Airport near Elmira, N. Y. The primary objective of these experiments was to determine the effects of seeding dense natural fog with carefully sized hygroscopic particles. The intent was to evaluate the concept by seeding fogs from the ground and, if necessary, perform aerial seeding experiments during the latter part of the fog season. A total of 25 experiments were conducted with ground seeding apparatus during the period May-September 1968. Six aerial seedings of dense valley fog were performed during a 3-week period in October 1968. Data collected during several of these experiments have been analyzed; the results are presented here.

Fog Seeding Experiments—Elmira, N. Y.

After reviewing the climatology of several candidate locations, the vicinity of Elmira, N. Y., was selected for fog seeding experiments because of its high fog frequency and proximity to the research agency. On the average, about 30 dense fogs formed in the Chemung Valley near Elmira between the months of May and October. Most of the fogs appeared to be of the radiation type, forming during cloudless nights between the hours of 12 midnight and 6 AM. The presence of a nearby airfield on one of the adjacent ridges made this site a particularly appealing one for airborne seeding trials.

Instrumentation and Equipment

Initially, fogs were seeded from the ground using the mobile seeding apparatus shown in Figure B-1.

During operation, hygroscopic nuclei of controlled sizes were fed from within the camper to a nitrogen-driven particle disseminator. The nuclei were then transferred by means of a high-velocity nitrogen stream through copper ducting to a region near the center of, and slightly above, a 9-ft-diameter, three-bladed propeller. Here, the particles were injected into the airstream and lifted to altitudes varying from a few feet to several hundred feet, depending on the prop speed and atmospheric stability. A protective steel shroud, which also enhanced air flow around the prop, was positioned around the propeller hub assembly. Dry nitrogen, used for transferring nuclei to the prop wash, was stored in large high-pressure cylinders mounted on the sides of the rig.

Instrumentation for making observations in fog included:

1. A Piper Aztec airplane equipped to measure drop sizes and temperatures at various altitudes in fogs and to provide photo reconnaissance of the seeded area. Photographic equipment consisted of two 70-mm Hasellblad cameras mounted in the fuselage of the aircraft.

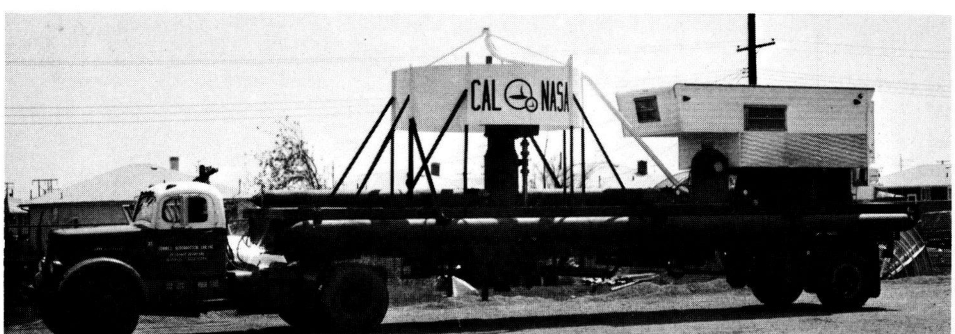


Figure B-1. Mobile seeding apparatus.

2. A mobile van carrying instrumentation for measuring drop sizes, liquid water content, visibility, nucleus concentration, and temperature in seeded and unseeded fog.

3. Four transmissometers for measuring visibility at selected locations on the airport grounds.

4. A vehicle for locating the path of the seeding material.

Fog Characteristics

Prior to seeding experiments, the Piper Aztec was sent aloft through the dense fog to gather data on drop sizes, vertical temperature distribution, and fog depth. Supplementary data, which included measurements of visibility, liquid water content, drop sizes, and nucleus concentration were obtained at the ground. In Table B-1 typical physical characteristics of the valley fogs in Elmira, N.Y., are compared with the radiation and advection fog models developed during the first year of this program (Jiusto, 1964). The data for the Elmira fogs represent averages of measurements made 4 ft above the surface in 13 fogs.

As given in Table B-1, the data for the valley fogs and the advection fogs are similar. In Figure B-2 vertical profiles of several pertinent fog parameters are shown for average data obtained in four Elmira valley fogs. The data were obtained during take-off and ascent of the Piper Aztec in the fogs. Values of drop concentration and liquid water content were computed from measured drop distributions, assuming a constant visibility throughout the fog volume. (It is recognized that visibility is not constant; however, the results of computations are intended to provide an indication of trends in the data rather than absolute measures.) Note the steady decrease in average drop diameter as a function of height above fog base. Accompanying the decrease in drop size is an increase in drop concentration, suggesting that conditions typical of radiation fog (i.e., high concentration of small drops) exist only in the upper portion of the fog. Similarly, the liquid water content in the valley fog decreases steadily from a high value near the fog base to somewhat lower values near the top.

In Figure B-3, selected drop size distributions are shown for four levels within a representative fog. Also shown for each distribution are the average drop diameter, and computed values of drop concentration, and liquid water content. Again, the rather pronounced shift in drop sizes toward smaller values near the fog top is apparent.

Repeated observations of the formation of fog at the field site suggest that mixing of the nearly saturated layers of air in the valley govern the fog formation process and shape the drop size distribution and liquid water content of the fog. As always, a variety of other mechanisms involving energy, moisture, and heat exchange are also important factors in fog development.

It was noticed that, during the early evening, moderate breezes frequently blow across the valley and prevent sig-

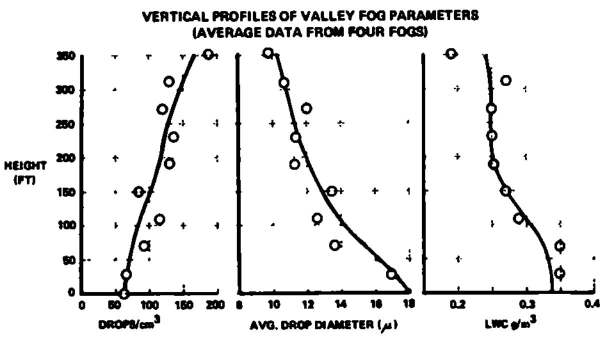


Figure B-2 Vertical profiles of valley fog parameters (average data from four fogs).

TABLE B-1

COMPARISON OF FOG CHARACTERISTICS

FOG PARAMETER	FOG RADIATION	ADVECTION	VALLEY— ELMIRA, N Y
Average drop diameter (μ)	10	20	18
Typical drop diameter range (μ)	4–36	6–64	4–50
Liquid water content (mg/cu m)	110	170	160
Droplet concentration (per cu cm)	200	40	55
Visibility (m)	100	300	100
Vertical depth (m)	100–300	200–600	100–200

nificant fog formation. As the ambient winds subside, drainage from the hills begins to predominate and surface winds in the valley become aligned with the orientation of the valley. Radiational cooling of the earth's surface and subsequent loss of heat from the lowest layers of air to the ground produce nearly saturated conditions close to the surface. Temperature profiles obtained shortly before fog formation at Elmira have shown that substantial inversions, frequently exceeding 3° C in 100 m, exist in the lowest few hundred feet of air. Once cold air drainage predominates, saturated surface air from the hillside tends to displace the somewhat warmer, nearly saturated air in the valley and, in the process, mixing occurs.

The phase diagram (Fig. B-4) shows typical conditions of the valley atmosphere prior to fog formation. If, as shown, two parcels of moist air, A and B, having different temperatures and relative humidities are mixed, significant supersaturation will occur and fog will form. The characteristics of the mixture of the two air masses will be represented by some point on the straight line connecting A and B.

In the formation of valley fog, initial mixing occurs near the base of the hills and fog forms there. As drainage continues, the mixing process persists and the depth of the fog increases. As the ratio of cold air from the hillside (point B) to the somewhat warmer valley air (point A) increases more water is made available for condensation on cloud nuclei and widespread fog develops. Near the fog base, the drops are large and the LWC (liquid water content) is high, but the concentration of droplets is depleted because of sedimentation and fallout

Near the fog top continued radiational cooling of the air results in slight supersaturation and additional fog formation. The continuous formation of new droplets with negligible terminal velocities accounts for the observed high concentration of small droplets near the fog top.

Although other explanations of the manner in which fog forms at the valley site may be plausible, most of the observations suggest that this reasoning is valid. It is obvious, however, that many additional measurements of the microphysical features of the fog would be needed to define how these changes take place with time. At present, the researchers are modeling the fog formation process in the computer by assuming various observed nucleus size spectra and producing fog by continuous cooling and also mixing. The results of these studies will be reported in a subsequent report.

Fog Seeding Results—Ground Seeding

As previously stated, fog seeding experiments were initially performed employing ground-based seeding apparatus. A total of 25 ground seeding experiments were conducted, most of which resulted in some observed improvement in visibility. In more than half of the experiments the seeded air mass passed between the instrumentation sites and, consequently, quantitative data could not be taken. In spite of this difficulty, several reasonably successful seeding experiments were performed in which detailed information was obtained on fog characteristics. Experiments in which a noticeable visibility improvement occurred in the seeded area are typified by results presented as follows. In this experiment (8 Sept. 1968) the seeded area passed over one of the researchers' transmissometers as observations of drop size were being made. Detailed analysis of the relationships between drop sizes, visibility, and liquid water content of the fog could therefore be made.

Prior to seeding, the Piper Aztec obtained data on fog characteristics. Fog had formed in the valley about 4:30 AM, and by 5 AM airport ground conditions were WOXOF (zero ceiling, zero visibility). Following take-off (6:30 AM), the airborne observer reported fog depth to be 100 m. Visibility at the ground was about 100 m and fog liquid water content was 170 mg/cu m. As was usually the case,

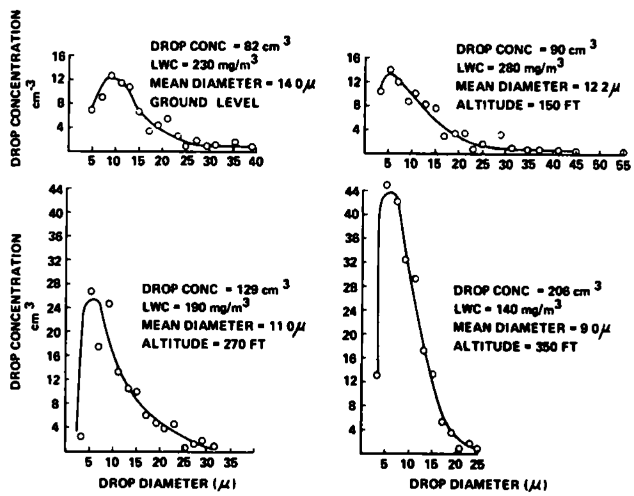


Figure B-3. Drop size distributions at four levels in a valley fog—Elmira, N.Y., August 30, 1968.

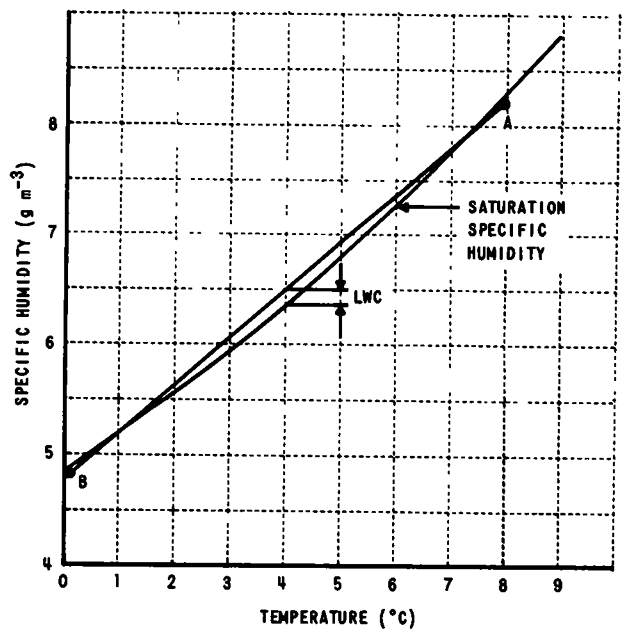


Figure B-4. Saturated specific humidity as a function of temperature.

a temperature inversion existed in the fog, amounting in this case to 3.1° C in 100 m. Wind velocity was 260° at 3 knots.

The initial plan was to seed the fog with 280 lb of sized NaCl * (5μ to 20μ diameter) at a dissemination rate of about 30 lb/min. The instrumented van was positioned a short distance from the seeding rig so that drop size data could be collected in the unmodified fog and in the seeded area as the plume moved downwind. Shortly after seeding was started, however, a 60° shift in wind caused the salt plume to drift away from the researchers' instrumentation and the airport. The experiment was therefore terminated after 4 min of seeding (approx. 130 lb of material were expended) and the rig was moved to a more favorable location.

The position of the seeding unit for the second experiment is shown in Figure B-5 (the original location of the seeding rig was on the approach end of Runway 10). Also shown are the locations of transmissometers used in this experiment The distance from the seeding unit to transmissometer (1) is 0.83 mile.

Seeding with the remaining 150 lb of material was scheduled for 7.25 AM. Fog density and liquid water content had not changed appreciably during the previous hour. Based on the wind direction and speed (240° at 6 knots) the researchers predicted that particles injected into the fog in the vicinity of Taxiway B would reside in the foggy air approximately 9 min before reaching the opposite end of the airport. According to the model, this would be ample time for the salt to have a significant effect on the natural drop size distribution.

Seeding was started at 7:25 AM and completed at 7:30 AM. The 30 lb/min dissemination rate was intended to provide approximately 3 mg of NaCl particles per cubic meter of treated fog. Droplet data obtained by ground observers indicated that the salt plume followed a path similar to that shown in Figure B-5. Visibility measurements obtained with transmissometer (1) indicate that visibility increased from about 300 ft to about 820 ft between 7:30 AM and 7:42 AM. No other transmissometers indicated any change in visibility during the same period of time. The improvement in visibility by a factor of 2.5 to 3 is typical of the results obtained in most ground seeding experiments.

Because of the large average drop sizes in the natural fog, the expected visibility improvement was less than was originally predicted. For example, seeding a fog consisting of 5μ-radius drops with 10μ-radius dry hygroscopic particles could be expected to give a 10-fold increase in visibility, according to the model Seeding a fog consisting of 9μ-radius drops, using the same material, could be expected to give only a six-fold increase in visibility, due to changes in drop size.

Figure B-6 shows the drop size distribution obtained in the seeded portion of the fog at about 7:40 AM The data were collected alongside transmissometer (1). A drop distribution from the adjacent unmodified fog, taken a few minutes earlier, is shown for comparison. As shown, a significant change had occurred in the drop sizes after seeding Also shown in the legend of the figure are the computed drop concentrations, liquid water contents, and mean volume diameters for the seeded and unseeded fogs. It is perhaps interesting to note that the liquid water content was higher in the seeded region than in the natural fog. All visibility improvement at the time of these measurements, therefore, resulted from a favorable shift in drop size distribution.

* Particle sizing done by Meteorology Research, Inc , Altadena, Calif

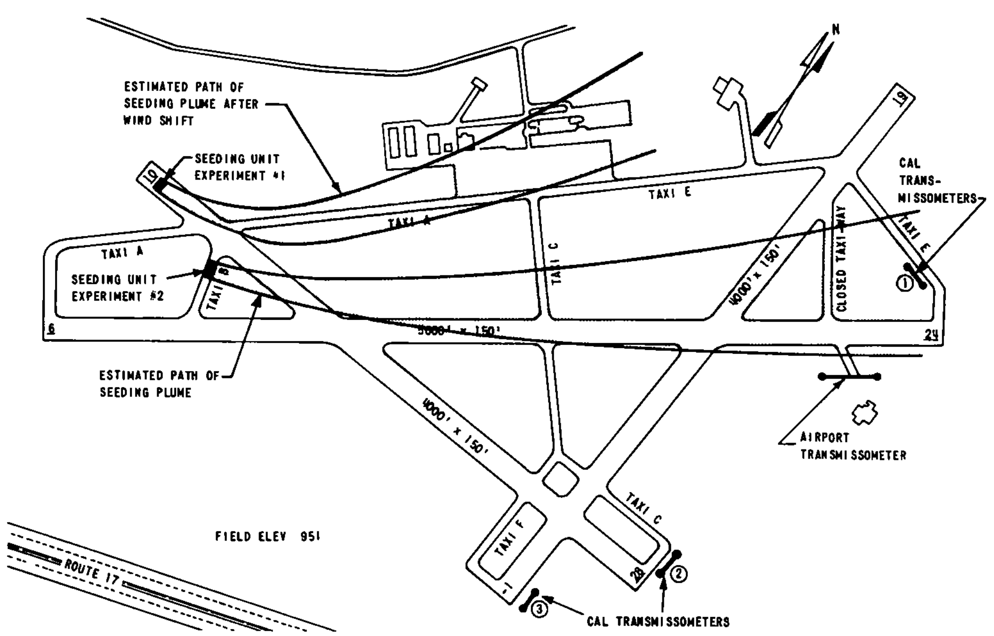


Figure B-5. Location of seeding unit and transmissometers at experimental field—Chemung County Airport, Elmira, N Y., September 8, 1968.

Variations in the calculated liquid water content can be expected, of course, depending on whether large saline droplets are encountered when the sampling is taken. It is frequently difficult to obtain statistically valid drop size distributions, particularly in seeded fog where drop concentrations are low. In spite of these difficulties the data suggest that, after seeding, the relative humidity was initially lowered by a few percent, an occurrence which is expected from theory and commonly noted in laboratory experiments. Somewhat later in time, after most of the largest drops settled out of the fog, visibility improvements greater than those measured probably occurred, but instrumentation was not suitably located for observation further downwind.

Results from early tests demonstrated that seeding from the ground, using sized hygroscopic nuclei, can be effective in producing visibility improvements. Although ground-based seeding did not improve visibility above the landing minimums, the nearly three-fold increase in visual range was encouraging. The principal problem seemed to be that of effectively distributing the seeding material throughout the fog volume. Mixing of unmodified fog with the narrow seeded region from a single seeding unit frequently limited the visibility improvement that could be achieved. Improved methods of particle dissemination must be sought if the ground system is to be adapted to airport use. These limitations prompted the researchers to test aircraft seeding techniques during the latter part of the experimental period.

Fog Seeding Results—Aerial Seeding

Aerial seedings of dense valley fog were performed during the first three weeks in October 1968. A Piper Pawnee aircraft (rented from EG&G, Boulder, Col.), designed for crop dusting, was obtained for the experiments. A total of six seeding trials were conducted using various aerial seeding methods. The plan was to seed the fog a prescribed distance upwind of the airport (depending on wind speed and direction) and allow the seeded area to drift over the ground instrumentation located near the runways.

On two occasions spiral seeding over the fog top was attempted, but difficulties in maintaining the prescribed flight pattern resulted in ineffective seeding. The seeding procedure that produced the most outstanding results involved flying perpendicular to the prevailing wind and disseminating dry particles in "evenly" spaced rows over the fog top. For these experiments the volume to be cleared of fog was approximately 3×10^7 cu m. The results of one seeding trial (16 Oct. 1968) are discussed as follows in some detail. In this experiment a significant amount of data was collected, both in seeded and unmodified fog.

Prior to seeding, routine procedures were followed in collecting data on fog characteristics. Fog depth was reported as 350 ft, with a layer of haze exceeding 1,000 ft lying above the fog top. Horizontal visibility measured 300 ft; liquid water content was about 280 mg/cu m. Representative drop size distributions at four different levels in the fog prior to seeding are shown in Figure B-7. Note the differences in drop concentration and size near the fog top as compared to the values near the base.

Seeding was accomplished with approximately 700 lb of NaCl * having a size range of 10μ to 30μ diameter. The aircraft completed seeding of the fog top in about 7 min, traversing an area approximately ½ mile by ¼ mile. The salt concentration within the fog was therefore about 10 mg/cu m. Three photos, taken during various stages of the experiment, are shown in Figure B-8. Note in the second photo the seeding aircraft and trailing salt plume. Within a few minutes after seeding, narrow paths began to open in the fog, increasing in size until after 15 min large areas of the fog were completely dissipated. (Visibility in the seeded area improved to approximately ½ mile.) The cleared region persisted for about 15 additional minutes before unmodified fog began to encroach into the seeded region and reduce visibility.

Figure B-9 shows a comparison of drop size distributions for the seeded and natural fogs. The curves represent data taken approximately 1 min before seeding began and again approximately 9 min after seeding had started. Tabulated in the legend of the figure are several fog parameters as determined from the data. Note the rather dramatic shift

* Sized material purchased from Meteorology Research, Inc., Altadena, Calif

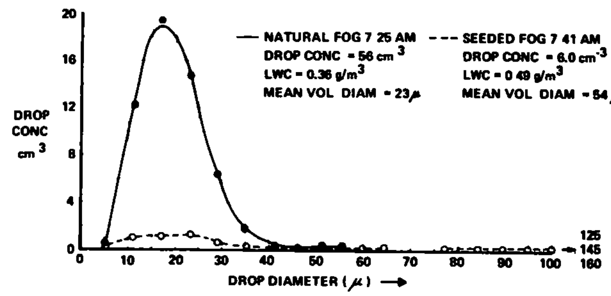


Figure B-6. Comparison of drop size distributions for natural and seeded fog, September 8, 1968.

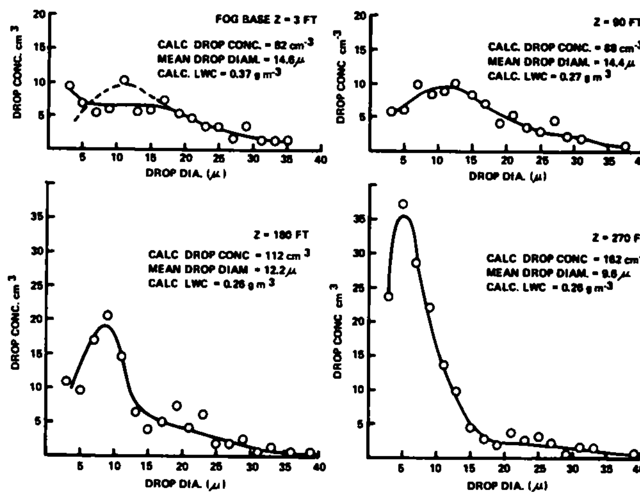
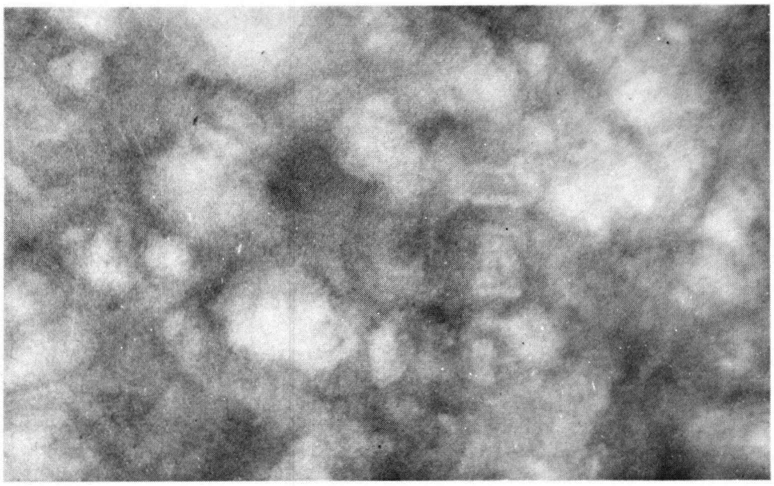
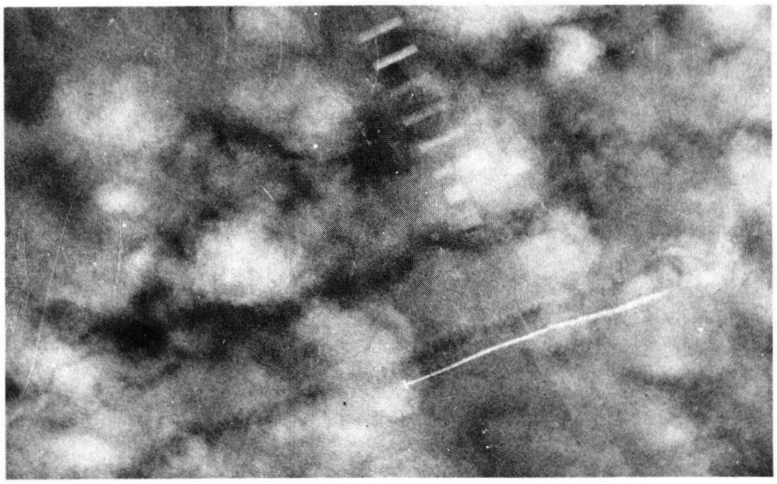


Figure B-7. Drop size distributions at four levels in a valley fog prior to seeding—Elmira, N.Y., October 16, 1968.

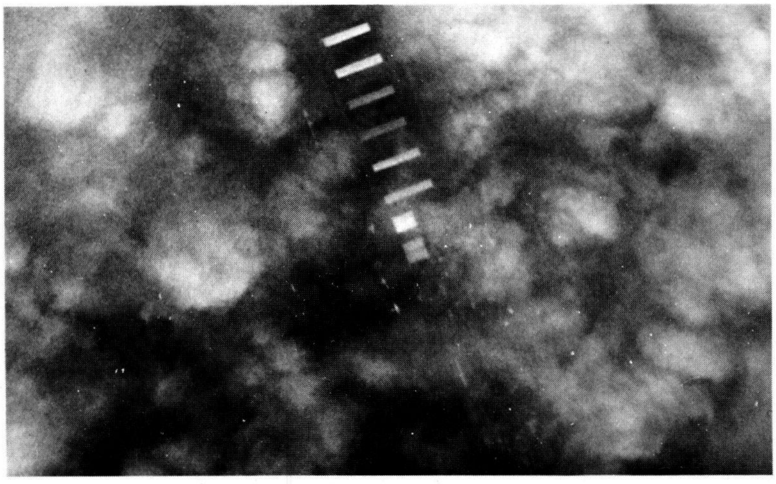
FOG TOP VIEW FROM AN ALTITUDE OF 10,000 FEET. NOTE THE HANGARS (200 FEET LONG) AND AIRCRAFT ON THE GROUND AFTER SEEDING.



TARGET AREA ONE MINUTE PRIOR TO SEEDING.



THE TARGET AREA DURING SEEDING (SALT PLUME AND SEEDING AIRCRAFT ARE VISIBLE).



THE TARGET AREA 15 MINUTES AFTER START OF SEEDING.

Figure B-8. Fog top viewed from an altitude of 10,000 ft. Note the hangars (200 ft long) and aircraft on the ground after seeding.

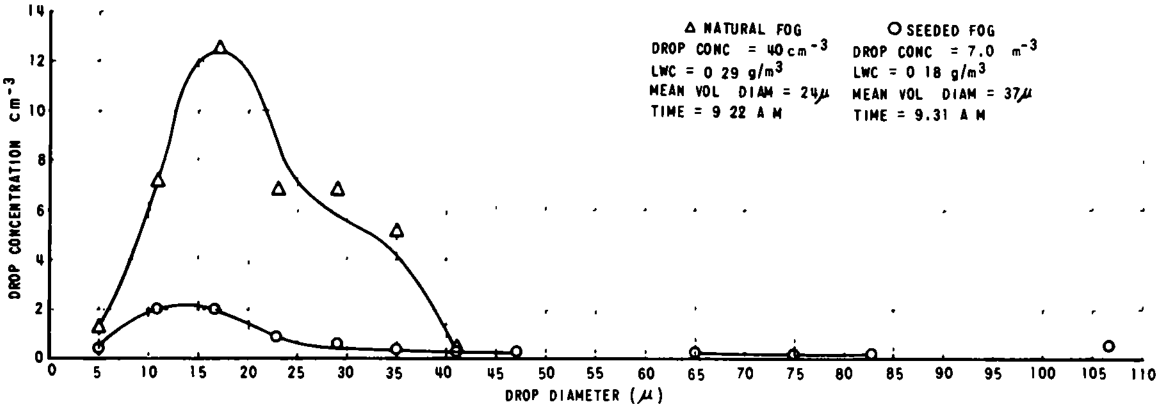


Figure B-9. Comparison of drop size distribution for seeded and unseeded natural fog—Elmira, N.Y., October 16, 1968.

in the drop size distribution after seeding. It is apparent from the data that the seeded fog was comprised of fewer droplets having somewhat large size. Accompanying the shift in drop sizes for the data shown was a decrease in liquid water content of the fog due to sedimentation of the largest saline drops. The combined effects of drop size differences and liquid water changes were responsible for the visibility improvements that occurred. Analysis of data has indicated that approximately 60% of the visibility improvement was accounted for by the decrease in fog liquid water caused by precipitation of the large saline droplets after seeding.

CONCLUSIONS

These experiments have demonstrated the validity of a concept for improving visibility in dense natural fogs by seeding with sized hygroscopic particles. Data analysis has shown that the initial visibility improvement in seeded fog is the result of a favorable shift in the drop size distribution (even though liquid water content is temporarily increased). Subsequent improvement in visibility is due to a reduction in liquid water content associated with precipitation of large saline droplets formed on artificial nuclei.

Airborne seeding experiments were most effective in causing fog dissipation. In the ground seeding experiments, it is likely that mixing of unmodified fog into the narrow seeded region limited the visibility improvements that occurred. Multiple seeding passes with the aircraft enabled the researchers to treat a much wider volume of fog and minimized the effects of mixing.

Several problems still exist. In most cases it was apparent in both airborne and ground-based seeding experiments that a substantial amount of clumping of seeding material had occurred. Thus, the efficiency of the seeding material was substantially reduced. More effective methods for particle dissemination must be devised.

An equally important problem is that of selecting and testing noncorrosive, ecologically safe chemicals to replace NaCl as the seeding material. Laboratory experiments have shown that several hygroscopic materials are almost as effective as salt for fog dispersal. Additional work leading to the selection of more suitable seeding agents is now under way. Field evaluation of one or two of the most promising materials is one of the objectives of the research agency.

APPENDIX C

POLARIZATION TECHNIQUE

The pertinent scattering theory that leads to the polarization technique is as follows:

1. Fog can be considered as a Mie atmosphere (distribution of spherical particles with diameters much larger than the wavelength of visible light and with a particle density low enough that secondary scattering is negligible).

2. When the incident radiation is linearly polarized, all radiation scattered into the plane of polarization or the

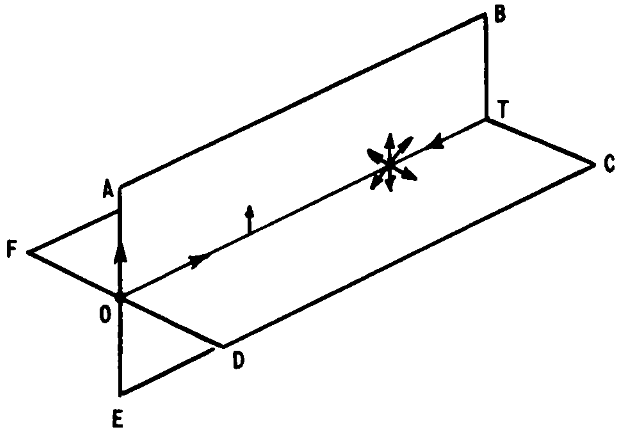


Figure C-1. Cross-polarization principle for reduction of air-light.

orthogonal plane containing the axis of propagation will remain completely linearly polarized with the original plane of polarization retained.

Consider the geometry of Figure C-1. If a searchlight placed at O is aimed at Target T, and if a polarizer is placed over the light with its optical axis oriented along OA, then any light scattered back into the planes OABT or ODCT by Mie scatterers located anywhere in the beam will be linearly polarized with orientation OA. Therefore, if an observer is placed behind O but in the plane OABT or ODCT, looking at the target through a polarization analyzer with its optical axis oriented in the direction OD, the observer will not see any scattered light. On the other hand, light reaching the target, and being reflected back, will be partially depolarized, depending on the target surface. Pure specular reflections are not depolarized; hence, smooth, shiny surfaces are undesirable. If only rough, diffusing surfaces are considered (such as earth, pavement, etc.), almost half the reflected light will be polarized in the direction OD. Thus, the observer will be able to see the target without background brightness due to scattering from the transmitted beam. Nathan's computations (1957)* show that the increase in contrast obtainable using this method is

$$\frac{C_x}{C_o} \sim P \frac{\rho_x}{\rho_o} \qquad \text{(C-1)}$$

in which

C_x = contrast with polarizers;

C_o = contrast without polarizers;

P = factor which determines the actual efficiency of the polarizing scheme in removing scattered light; and

ρ_x/ρ_o = ratio of depolarizing reflectivity to total reflectivity of target.

Measurements by Nathan indicate that for grey paint and dull finishes, $\rho_x/\rho_o = 0.3$. He also determined that for fog in the visibility range 50 to 1,000 ft, the P factor is of the order of 100 to 300. Thus, theory predicts a contrast improvement of from 30 to 100. Observations and photographs made in a 50-ft wind tunnel proved to be striking demonstrations of the effectiveness of the method.

* References appear in Appendix H, Bibliography

APPENDIX D

THE RELATIONSHIP BETWEEN TRANSMISSOMETER MEASUREMENTS AND VISIBILITY IN FOG

In natural fogs, the mean spacing between fog droplets is large compared to wavelengths in the visible spectrum ($\lambda = 0.4\mu$ to 0.7μ). Under this condition, the scattering of light by the fog droplets is incoherent and the total light scattered by a population of fog droplets is equal to the sum of the portions scattered by the individual droplets (Houghton and Chalker, 1949).* Because absorption is negligible in the visible spectrum, the light extinction coefficient in a fog becomes

$$\sigma = \textstyle\sum_i n_i \pi r_i^2 K_s \qquad \text{(D-1)}$$

in which n_i is the number of fog drops of radius r_i per unit volume, and the product of the geometric cross section of a droplet, πr_i^2, with the dimensionless scattering area coefficient, K_s, is a measure of the total light scattered by a fog droplet, regardless of the state of polarization of the incident light. The scattering area coefficient, K_s, is a function of the parameter $\alpha = 2\pi r_i/\lambda$, in which λ is the wavelength of the light.

As the parameter α becomes large, $K_s \rightarrow 2$, and the total scattering cross section, $\pi r_i^2 K_s$, approaches twice the geometric cross section of the droplet. For the scattering of visible light by water droplets, this limiting behavior obtains to a good approximation for a droplet with a radius of two microns or greater (Houghton and Chalker, 1949). Hence, as long as the relative contribution of droplets of less than a few microns radius to the extinction coefficient is small, the value $K_s = 2$ can be substituted in Eq. D-1, resulting in the simplified expression

$$\sigma = 2\pi \textstyle\sum_i n_i r_i^2 = N\, 2\, \pi\, r_{rms}^2 \qquad \text{(D-2)}$$

in which N is the total number of droplets per unit volume and r_{rms} is the root mean square radius of the fog droplets. In this situation, which is true of most well-developed natural fogs, light transmission through the fog is essentially independent of wavelength for wavelengths in the visible spectrum (Middeton, 1952; Arnulf and Bricard, 1957).

The transmission of a parallel beam of light through a fog is given by

$$E = E_o \exp\left[-\sigma x\right] \qquad \text{(D-3)}$$

in which E_o is the flux density of the incident beam and E is the flux density of the beam after passing a distance, x, through the fog. A transmissometer of path length x, then, yields a measurement of the light extinction coefficient in the fog,

$$\sigma = \ln\left[E_o/E\right]/x \qquad \text{(D-4)}$$

The *visual range* of an object is defined as that distance at which the apparent contrast between the object and its background becomes just equal to the threshold contrast of the observer. If a fog is so dense that the background of an object is fully obscured by the fog, it can be shown (Johnson, 1954) that the visual range of the object is given by the expression

$$V = \ln\left[|C^*|/\epsilon\right]/\sigma \qquad \text{(D-5)}$$

in which ϵ is the threshold contrast of the observer and

$$C^* = (B_o^* - B_f)/\, B_f \qquad \text{(D-6)}$$

is the brightness contrast between the object and the fog. B_o^* is the intrinsic brightness of the object and B_f is the apparent brightness of the fog due to scattering of external illumination

In the special case where the object is a black body of zero intrinsic brightness, $B_o^* = 0$, and Eq. D-5 reduces to

$$V = \ln\left[\epsilon\right]/\sigma \qquad \text{(D-7)}$$

If the standard value 0.02 is adopted for ϵ, one gets an expression for the *meteorological visual range*

$$V_m \approx 3.912/\sigma \qquad \text{(D-8)}$$

Because V_m depends only on the light extinction coefficient σ in the fog, it can be determined from a transmissometer measurement alone or in terms of Eq. D-4.

$$V_m \approx 3.912\, X/\ln\left[E_o/E\right] \qquad \text{(D-9)}$$

Although the meteorological visual range is a widely used measure of visibility, the assumptions involved in its definition are so restrictive that it is of limited usefulness in describing visibility in fogs under complex highway conditions. Indeed, in highway fog situations, where highly non-uniform illumination, specular reflections, self-luminous objects, and complex backgrounds are common, it is doubtful whether any combination of available physical measurements can suffice as a satisfactory universal predictor of the visual performance of drivers. The true value of a transmissometer is that it provides a consistent measure of one fundamental property of visual range—the extinction coefficient—against which other measures of visual distance can be intercompared.

* References appear in Appendix H, Bibliography

APPENDIX E

TRAFFIC DATA COLLECTION SYSTEM

DATA COLLECTION SITE

Data were collected on the westbound portion of New York State Route 17, adjacent to the Chemung County Airport, not far from Elmira. The road consists of a divided four-lane highway separated by a treeless median about 35 ft in width. Automobile traffic along this route is primarily local, providing transit between Elmira and Corning, New York.

The test site is shown in Figure E-1. Adjacent to each of the lanes is a 10-ft dirt shoulder. Measurement equipment was located approximately 30 ft downstream of a rest area where a recorder was housed in a parked car. The rest area itself was wide and also separated from the road by a broad shoulder so that parked vehicles were unlikely to influence traffic flow. Typically, two to four vehicles were parked in the rest area so that the recording vehicle was neither conspicuous nor unusual. The view in Figure E-1 is from the recording vehicle.

The right-hand shoulder immediately adjacent to the test area contained a white guardrail approximately 9 ft from the edge of the road; it is conceivable that this might be an aid to drivers in fog. There was a signal-controlled intersection 1.1 miles upstream of the test site, which probably induced some platooning among the observed vehicles. There was an intersection 0.7 mile downstream of the site with two-way signs controlling cross traffic; this road received slight usage.

TRAFFIC MEASUREMENT SYSTEM

The general approach was to determine the times at which vehicles passed detectors at known locations; hence, vehicle behavior was determined from time differences. The detector system consisted of three horizontal infrared light beams which provided two data points each: (1) the time at which the beam was interrupted by vehicle entry, and (2) the time at which the vehicle left the beam. Infrared sources were used to minimize the effect of the detector system on drivers.

Each infrared source was a 5-ampere, 5.9-volt lamp with a reflector and infrared filter. The lamp was driven by a 6-volt, heavy duty, automobile battery. Thus, each light source, which was located on the median, was self contained; there were no wires crossing the road. The infrared filters were extremely effective in blocking visible light; research agency observers were not able to detect emitted light, even at night. In Figure E-1, one light source can be seen near the left edge of the photograph; two are near the center.

The light sensors consisted of infrared sensitive photocells

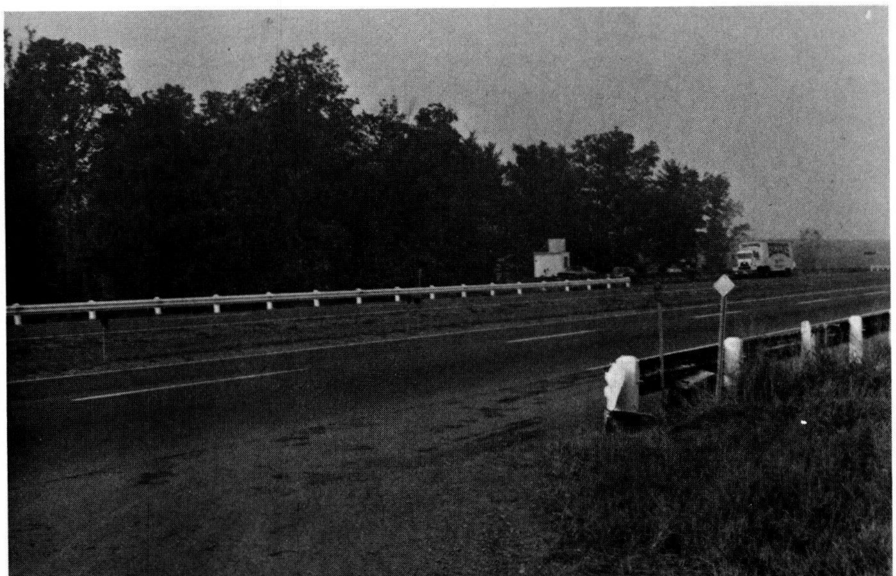


Figure E-1. Field site for obtaining measurements of traffic in fog.

mounted within a 9-in.-long blackened horizontally placed pipe. Each cell provided a voltage output sensitive to the presence or absence of vehicles blocking the light energy from the infrared source. The sensors were just above and behind the guardrail.

Data were collected on a two-channel, paper tape, Brush recorder. The response times of the infrared sensors and the recording pens were sufficiently fast that an ordinary car passing through a light beam resulted in a nearly perfect square wave. Precise determination of the time at which vehicles entered or left the light beams could therefore be made. During daytime operation, the sensors generated signals which were influenced by ambient light. In spite of the erratic shape of the recorded signal, the effects of a vehicle entering or leaving the beam was to superimpose a rather obvious vertical jump on the recorded trace; hence, in almost all cases, no difficulty was incurred.

A schematic diagram of the configuration of the light beams relative to the roadway is shown in Figure E-2. The two parallel beams, intended primarily for speed determination, were perpendicular to traffic flow and nominally 40 ft apart, the diagonal beam, intended primarily for determination of lateral placement, makes a nominal 45° angle with the direction of traffic flow.

DATA CHARACTERISTICS

The largest source of error in analyzing the data was associated with reading the blips on the paper data tapes (i.e., measuring their location with regard to the grid on the paper). These measurements were made to the nearest 0.2 mm, so that the standard deviation of measurement error can be very conservatively estimated as 0.1 mm. Because the tape was run at 25 mm/sec, this corresponds to a standard deviation of 0.004 sec. The recorder contained an independent timer providing a continuous record against which tape speed was compared. Sampling from this record showed the tape almost always ran 0.15 to 0.25% slow. This error was judged to be negligible; hence, no corrections were made.

Based upon the dimensions shown in Figure E-2, the equations for lateral position are:

$$L = S\,(t_D - t_1)\,0.99 - 8.64 \qquad \text{(E-1)}$$

or

$$L = 23 - S\,(t_2 - t_D)\,0.99 + 7.81 \qquad \text{(E-2)}$$

in which

L = distance from right-hand edge of the road (ft);

t_D = time of entering diagonal beam;

t_1 = time of entering the first parallel beam;

t_2 = time of entering the second parallel beam; and

S = vehicle speed (ft/sec).

(The two right-hand constants in the equations are not identical to the distances in Figure E-2, because the angle of the diagonal beam was not exactly 45°.) The equation involving the larger time difference was always used; this yielded the smaller error in lateral placement. It should also be noted that, instead of considering the times at which the beams are first interrupted, the equations can be applied by using the times when the vehicle left the beams. Using the entry times, the right side of the vehicle was located; using the departure times, the driver's side was determined.

The computation of vehicle speed was complicated somewhat by the geometry of the measuring system. Because there were four data points associated with the two parallel beams, the problem of determining speed was overdetermined if acceleration was assumed equal to zero (i.e., there are two variables, speed and vehicle length, and three independent equations). There were three approaches to the problem. (1) assume acceleration to be a variable, (2) use only two data points to determine average speed, (3) assume zero acceleration and determine the speed by fitting a straight line to the data points using least squares procedures.

With regard to the first approach, it was determined using a readily available computer simulation that, given the expected measurement errors, the standard deviation of the error in acceleration for a vehicle traveling a constant 88 ft/sec was 7 ft/sec². As such, it was decided that zero is likely to be a better estimate of acceleration than the computed value would have been. Then, assuming no acceleration, the least squares solution (3) was chosen over the simple solution (2), because the former approach was less sensitive to measurement errors. The resultant formula for speed was

$$S = 2D / \left[(t_4 - t_2) + (t_3 - t_1)\right] \qquad \text{(E-3)}$$

in which D is distance between beams (or 39.88 ft), and t_1, t_2, t_3, and t_4 are the respective times at which the vehicle enters beam one, leaves beam one, enters beam two, and leaves beam two. Notice that this expression is equivalent to the harmonic mean of the computed speeds for the front of the vehicle and the rear of the vehicle.

The least squares solution also provided the following estimate of vehicle length:

$$\text{Length} = S\left[(t_2 - t_1) + (t_4 - t_3)\right]/2 \qquad \text{(E-4)}$$

It can be seen that this expression is equivalent to the algebraic mean of the two directly computed values of length, one based on the first light beam and one based on the times

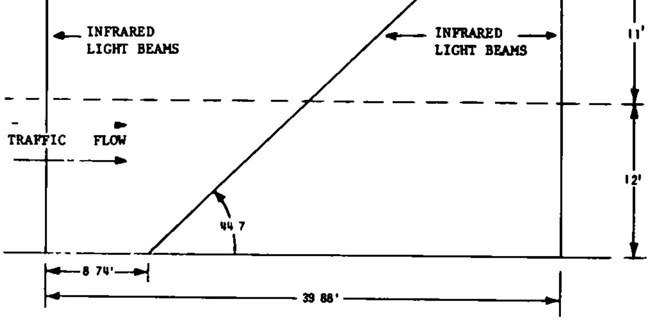


Figure E-2. Configuration of light beams for measuring traffic behavior.

for the second light beam. Running a computer simulation as before, data from vehicles of 88 ft/sec with no acceleration show a speed error with standard deviation of approximately 0.6 ft/sec.

The transducing of information from the data tapes to punched cards was a fairly tedious task, occasionally resulting in reading and copying errors. To cope with this problem, an edit program was written to detect errors associated with unreasonable or impossible values for arrival time, time headway, speed, lateral placement, vehicle length, and goodness of fit to the least squares best fitting line. Thus, the probability of errors entering into the analyses was kept to a minimum.

APPENDIX F

EXPERIMENTAL DESIGN

TRAFFIC MEASUREMENT STUDY

To study the effects of fog on traffic it was necessary to determine an appropriate measure of the visual effects of fog which were thought to most directly influence drivers. Two types of measures were available. The first related primarily to the physical characteristics of the fog; transmissometer readings are the principal example. The second class of measures is based on direct visual measurements. Although transmissometer readings are more reliable, they were unacceptable in this study for the following reasons: (1) the practical or intuitive meanings of transmissometer readings is unclear, particularly to the layman; and (2) such measures, in themselves, provide values of visual range which are intended to be independent of ambient lighting and the nature of the visual target. Because the ability to see is a function of all three conditions—fog level, ambient light, and target characteristics—the transmissometer does not provide a comprehensive measure of visual conditions in fog. Although it would have been possible to combine independently determined measures of fog density, ambient light, and target quality, it was thought that a simpler and at least equally reliable method would be to use visual measurements

Because target quality (viz, contrast) affects the greatest range at which the target can be seen, it was decided to determine visual range for the same targets used by drivers. Therefore, visual distance was determined for the bodies and taillights of vehicles during the collection of traffic data Specifically, the elapsed time between the arrival of vehicles and the point at which they could no longer be seen was measured. For some vehicles the observers attended to the body, for others they attended to the taillights. The elapsed time was recorded alongside the other data on the recorder tape. This was done for isolated vehicles; so, the assumption of constant speed could reasonably be made. The time and the computed speed for each vehicle were used to estimate visual range. Such a measure, then, incorporated the effect of fog intensity, ambient light, and target quality so as to provide a more meaningful measure of visual range.

After computing visual ranges, the values were plotted and curves were drawn giving estimated visual distance for any time during the data collections. The curves were drawn closer to the lower range of visual distances, to more closely approximate the visual range assumed by a reasonably careful driver. That is, if one can see some vehicles 400 ft away in fog and others no more than 200 ft away, the rational driver must proceed as if 200 ft were his maximum visual range.

There were two curves for any given time: one with taillights as targets, and one with vehicle bodies as targets. Because the test site was on a straight road, it was assumed that the primary hazard for each driver was associated with other vehicles, as opposed to the road or roadway structure. If, for example, the body of a vehicle could be detected 200 ft away, whereas its taillights could be seen 350 ft away, the larger of the two values was judged a better measure of visibility. Thus, in general, visibility was measured as the larger of the two visual distances. For most of the data collections this resulted in a U-shaped curve of visibility. The visual range at night prior to fog was associated with taillights and was long. As fog formed prior to dawn, the visual range decreased. Then, as ambient light increased, the bodies of vehicles became easier to see than the taillights. Finally, as the fog started to dissipate, visual range increased.

The final step in preparation of the visibility measure for statistical analysis was to break the U-shaped curve for each data collection into portions that were essentially linear. The visibility values at the end points of each linear segment were tabled as a function of time of day. Then, by linear interpolation, each vehicle, using its arrival time at the test site, was assigned a visibility value.

In preparing the general analytical procedure it was necessary to determine which extraneous variables must be controlled so as to preclude their influence on results.

Originally, the intention was to use procedures that would prevent the biasing of results by general light conditions (night-dawn-day) and traffic volume. As has already been seen, however, some aspects of light conditions are appropriately included in the measure of visibility. Furthermore, because the data collections took place over a period of approximately 8 weeks from August to October, ambient lighting changed considerably over that period as a function of time of day. Thus, for example, the dawn condition, which progressively occurred later, is likely to have involved driver population shifts for successive data collections.

To avoid these problems and to produce a relatively simple analysis, the data were divided into night, dawn, and day categories, with each of the three sets of data analyzed in the same way. Within each set, only one control variable was used; viz, time of day. It was assumed that within a fixed interval of time, variations in traffic volume and driver population would not be minimal and, hence, analysis of the effects of fog on traffic would be least distorted by these variations. (It should be noted that all data collections occurred on weekdays, thus avoiding major volume and population shifts)

STUDY OF VEHICLE VISIBILITY

These data were collected on the grounds of the Chemung County Airport. (This accounts for the somewhat different visibility levels obtained in this portion of the study, as compared to the traffic program.) The procedure consisted of an observer driving a test vehicle toward a target vehicle (black top and white body) until it could first be seen, the distance between the two vehicles was then recorded. (The accuracy of measurement of the distance was, at worst, ±30 ft.)

To obtain reliable measures, the observer was given explicit directions defining what he was to look for. He was to find that point at which there was sufficient evidence of something ahead, such that if he were in a traffic condition, he would attend closely to the image. That is, it is the point at which the driver begins to think there might well be a vehicle ahead; this point occurs before the time of positive identification. In this way, it was hoped to obtain distances closely related to those at which a driver could be expected to initiate preparatory evasive action, such as removing his foot from the accelerator.

This procedure was followed for three lighting conditions of the test vehicle: no lights, low beams, and high beams. For each such condition there were five lighting conditions of the target vehicle· no lights, taillights, taillights plus turn signal, low beams, and high beams Two observations were taken for each condition, giving a total of 30 observations.

VOLUMES: SAMPLE SIZES AND VOLUME VARIATION

Table F-1 gives one measure of the validity of acting on the premise of volume consistency for fixed times. In addition, these data are descriptive of the ranges of volumes encountered during the data collections. As given, the volumes were nearly constant for the 5 to 6 AM periods. The 7 to 8 AM and 8 to 9 AM periods show less consistency; however, this variation of volumes was judged to be an acceptable compromise because adherence to this design allowed some control of driver population.

Table F-2 gives the number of vehicles observed within each visual distance interval for specified times. As can be seen, no fogs with visual distances less than 200 ft occurred during the measurement program. Prior to analyses, the data were grouped into three categories corresponding to night, dawn, and daytime lighting conditions. The times delineating these categories are given in Table F-3.

As given in Table F-2, the number of observations for each fog level in both the night and dawn conditions was quite low. This was principally due to three factors: (1) the fogs, as observed, tended to develop shortly before sunrise, (2) the dawn period was rather short, and (3) traffic volumes before 7 AM were modest. As such, primary attention in analysis was given to the daytime data. Furthermore, examination of Table F-2 shows that the 7 to 9 AM periods contain the most dense fogs as well as most of the observations. Hence, the most thorough study was given to the 7 and 8 AM data. These data were used to determine the existence of relationships between fog and traffic behavior. All other data were processed similarly and then examined for departures from the 7 and 8 AM daytime data.

To determine potential effects of changing volume on traffic measurements, data were combined from the six data

TABLE F-1

HOURLY TRAFFIC VOLUMES FOR EACH DATA COLLECTION AS A FUNCTION OF TIME OF DAY [a]

TIME OF DAY (AM)	HOURLY TRAFFIC VOLUMES, BY DATA COLLECTION					
	1	2	3	4	5	6
5–6	68	58	59	(64) [b]	(58) [b]	(65) [b]
6–7	146	148	116	135	117	128
7–8	372	416	453	(342) [b]	417	529
8–9	(408) [b]	(298)	(388) [b]	(293)	—	(282)
9–10	—	—	—	268	—	—

[a] Numbers in parentheses represent estimated volumes based on less than 1 hr of observation

[b] Observation period of less than ½ hr

TABLE F-2

NUMBER OF OBSERVATIONS FOR VISUAL DISTANCE AND TIME OF DAY

TIME OF DAY (AM)	NO OF OBSERVATIONS, BY VISUAL DISTANCE (FT)								
	250	350	450	550	650	750	850	950	1000
5–6	0	0	0	0	4	10	75	10	173
6–7	0	0	83	83	92	50	58	84	341
7–8	165	292	320	234	4	0	170	310	762
8–9	186	231	0	0	135	109	9	100	162
9–10	0	48	82	56	48	34	0	0	0

TABLE F-3

TIMES USED FOR DELINEATING NIGHT, DAWN, AND DAY CONDITIONS

DATA COLLECTION	NIGHT	DAWN	DAY
1	5·55	6:40	
2	6:00	6:40	
3	6:10	6:40	
4	6:40	7:30	
5	6·40	7:15	
6	6:40	7:30	

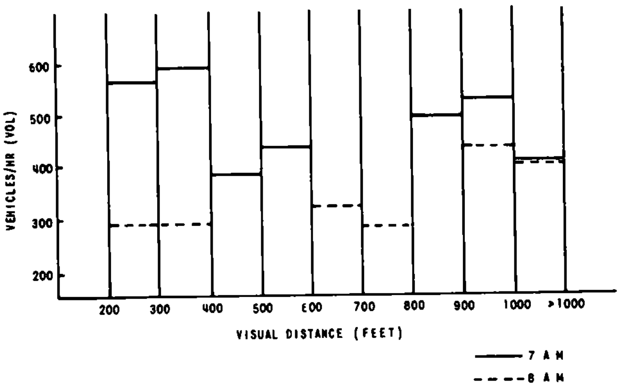


Figure F-1. Computed traffic volumes for each visual distance interval.

collections and average volumes were computed for each visual distance interval. The results are plotted in Figure F-1. The pattern of volumes for each hour can be compared to patterns of the various traffic measures. By so doing, it can be seen that the only variable which appears to correlate with volume is time headway, a fact which is to be expected. With regard to the other traffic measurements, a contaminating effect of volume is not found. It should be noted that the volume range for the 7 AM data is approximately 400 to 600 vph; for 8 AM, 300 to 450 vph.

The number of observations used in the various analyses is given in Table F-4. These numbers are given for the researcher who wishes to know something of the reliability associated with the data points. Small deviations from these frequencies occur in some of the analyses due to incomplete information for some vehicles. For example, in a few instances there were sufficient data to determine speed but not lateral location.

TABLE F-4

NUMBER OF OBSERVATIONS

	NUMBER OF OBSERVATIONS			
	7–8 AM		8–9 AM	
VISUAL DISTANCE (FT)	ALL VEHICLES	ISOLATED VEHICLES	ALL VEHICLES	ISOLATED VEHICLES
201–300	141	7	185	28
301–400	155	10	230	26
401–500	202	24	—	—
501–600	210	16	—	—
601–700	—	—	135	15
701–800	—	—	109	15
801–900	170	16	—	—
901–1,000	310	21	99	11
>1,000	660	66	161	18

APPENDIX G

SUPPLEMENTARY TRAFFIC MEASUREMENTS

LATERAL PLACEMENT

It was hypothesized that the use of the passing lane would decrease as fog became more dense. This was based on the premise that, in reduced visibility conditions, drivers would be satisfied to stay in the right-hand lane in order to minimize interactions with other vehicles. This was thought to be a valid hypothesis, even though the opposing traffic was separated by a grass median. The results of the analysis are given in Table G-1.

Although some decreased use of the passing lane was observed for the 8 AM data, there appears to be no important relationship between lane usage and visual distance. With regard to the 8 AM data, any decrease in passing lane

TABLE G-1

PROBABILITY OF DRIVING IN THE PASSING LANE

VISUAL DISTANCE (FT)	PROBABILITY	
	7–8 AM	8–9 AM
201–300	0 26	0 09
301–400	0 24	0.10
401–500	0 10	—
501–600	0 20	—
601–700	—	0.09
701–800	—	0.08
801–900	0 16	—
901–1,000	0 23	0 15
>1,000	0 17	0 13

usage occurred before visual distance became critical; recall that a similar effect was noted in the speed data.

A separate study was made of lateral placement of the right-hand side of vehicles in the right-hand lane to see if fog changed the amount of clearance from the edge of the road. The results are given in Table G-2. No consistent trend in terms of a monotonic relationship with visual distance was observed.

Although mean lateral placement showed no important change due to fog level, it was thought that perhaps certain drivers might differentially respond to decreased visibility Therefore, the probability of driving quite close to the edge of the road was studied; Table G-3 shows the results. Again, no important trend was found.

RELATIONSHIPS WITH OTHER VEHICLES

Measurements were made of time headways; these observations were used along with vehicle speed to estimate distance headways, or vehicle spacing. Mean time headway, because it is completely dependent on volume, is not likely to be directly responsive to fog effects. (Because the driver population was thought to consist primarily of drivers going to work, there was no reason to expect volume to be influenced by fog; indeed, no consistent relationship was found between volume and fog level.) Because the "California rule" for following (i.e., one car length for every 10 mph) reduces to a recommended headway of approximately 2 sec, the probability of headways less than 2 sec was determined for each fog level, no trend was found. The results are given in Table G-4.

Vehicle spacing, front to rear, was not thought to require extensive analysis, because evaluation without reference to speeds gives little information regarding hazards involved. Analyses were performed, however, to see if anything unusual would be found. Nothing was; spacing bore no consistent relationship with visual distance.

Another measure, which has frequently occurred in the literature concerning following behavior, is spacing divided by the difference between the subject vehicle's speed and that of the lead vehicle. This formulation, spacing divided by relative speed, is referred to herein as collision course time (CCT), because for positive relative speeds it is the time that could elapse before two vehicles in the same lane collide. In other words, CCT measures the time available for a following vehicle to slow down or change lanes to avoid a collision. Because of the inherent mathematical difficulty in using CCT (viz, as relative speed approaches zero, CCT becomes infinite), its reciprocal was used in the analysis. Results are shown in Table G-5. Cutoffs for 1/CCT were 0.02 and 0.06 per sec; hence, cutoffs for CCT were 50 and approximately 17 sec.

Again, it is apparent that virtually no monotonic relationship existed between visual distance and CCT. It is of interest to note that although a CCT of 50 sec might be thought to be quite ordinary, the data show that a CCT of that length or less occurs only about 10% of the time.

VARIABILITY OF DRIVER BEHAVIOR

The remainder of the analyses were related to measures of variability. The general area of inquiry had to do with drivers behaving in dissimilar ways due to decreased communication. No monotonic relationships were found between visual distance and the variance of the driver performance measures.

TABLE G-2

LATERAL PLACEMENT IN THE RIGHT-HAND LANE

VISUAL DISTANCE (FT)	LATERAL PLACEMENT (FT)	
	7–8 AM	8–9 AM
201–300	3 0	3.2
301–400	3 3	3 1
401–500	3.3	—
501–600	3.6	—
601–700	—	3 0
701–800	—	3.1
801–900	3 2	—
901–1,000	3 2	2 9
>1,000	3.3	3 0

TABLE G-3

PROBABILITY OF BEING LESS THAN 1 FT FROM THE RIGHT-HAND ROAD EDGE

VISUAL DISTANCE (FT)	PROBABILITY	
	7–8 AM	8–9 AM
201–300	0.05	0.04
301–400	0.03	0 03
401–500	0.02	—
501–600	0 02	—
601–700	—	0.04
701–800	—	0.04
801–900	0 02	—
901–1,000	0 04	0.02
>1,000	0 03	0 03

TABLE G-4

PROBABILITY THAT HEADWAYS WERE LESS THAN 2 SEC

VISUAL DISTANCE (FT)	PROBABILITY 7–8 AM	8–9 AM
201–300	0.16	0.10
301–400	0.20	0.08
401–500	0.17	—
501–600	0.19	—
601–700	—	0.15
701–800	—	0.09
801–900	0.16	—
901–1,000	0 18	0.14
> 1,000	0.18	0.12

TABLE G-5

PROBABILITY THAT CCT IS LESS THAN 50 SEC AND LESS THAN 17 SEC

VISUAL DISTANCE (FT)	PROBABILITY 7–8 AM		8–9 AM	
	50 SEC	17 SEC	50 SEC	17 SEC
201–300	0.09	0.03	0.12	0.04
301–400	0.05	0.01	0.12	0.04
401–500	0.07	0.02	—	—
501–600	0.06	0.02	—	—
601–700	—	—	0 09	0.02
701–800	—	—	0.07	0.04
801–900	0.06	0.03	—	—
901–1,000	0.07	0.02	0.10	0.05
> 1,000	0.07	0.02	0.14	0.02

APPENDIX H

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