NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **40**

MEANS OF LOCATING DISABLED OR STOPPED VEHICLES

HIGHWAY RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

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REPORT 40

MEANS OF LOCATING DISABLED OR STOPPED VEHICLES

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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.

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

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

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

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

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 final report will be of special interest to highway administrators, highway patrol officers, and traffic engineers responsible for locating and aiding stranded motorists on the national system of limited-access highways. The results of a development program to design, demonstrate, and field test a feasible and economical automatic stopped-vehicle detection system are presented. This system would instantly detect, locate, and inform a central control of the presence of stopped vehicles on the freeway and within the adjacent sholder areas. If desired, speed limit violators could also be detected for law enforcement purposes.

This report stems from NCHRP Project 3-4. Only the final phases of this research pertaining to the development of a stopped-vehicle detector system are reported herein. The initial phase of this investigation describing the nature and extent of the disabled and stopped-vehicle problem has been published in an interim report (*NCHRP Report 6*).

The constantly increasing mileage of limited-access-type highways has been an asset to the highway user. However, by the very nature of the design of these facilities problems are introduced not heretofore encountered to any significant degree. On limited-access highways, in particular, the driver of a disabled vehicle may become stranded many miles from the nearest point from which he can summon assistance.

If suitable means could be provided to assist the stranded motorists in relaying information regarding their location and the nature of their difficulties to a central dispatching facility, the resultant benefit to the motoring public in terms of time and lives saved would be considerable.

In the interest of increased highway safety and convenience to the motoring public, improved methods for the detection of and dispatch of assistance to the stranded motorist are needed. It was with these thoughts in mind that this project was initiated.

As the traffic demand grows and as the highway death toll increases the need for the quick detection of stopped vehicles continues to become more urgent. In too many instances severe traffic congestion has developed and lives have been lost due to present limitations involving the detection of stopped vehicles. One approach that seems likely to reduce this problem is through the use of an automatic detection system, not directly involving the motorist, that is capable of immediately communicating stopped-vehicle information to a central location.

Due to recent technological advancements in solid-state electronic equipment, a detection system using a laser diode, previously prohibited by cost considerations, is now a realistic and practical possibility.

Airborne Instruments Laboratory in this thorough and well-documented study has investigated the feasibility of using a light source in conjunction with roadside detectors for locating disabled vehicles. On the basis of the experimental and analytical work performed, it is concluded that the concept of an optical infrared system of detection is technically feasible. A prototype roadside receiver and mobile transmitter has been designed, built, and tested on the highway.

Future research efforts could involve a full-scale test of the disabled motorist detection system in conjunction with an economic evaluation of the benefits obtained by the motorists. It is envisioned that a section of a toll road could serve as the test facility; roadside receivers would be installed and transmitters would be placed on all vehicles using the facility. It seems quite likely that the savings obtained by the motorists would considerably exceed the costs of installing and maintaining the control system.

Among other suggested future research areas are: (1) an application and cost analysis program to obtain current data on the frequency and nature of disabled vehicles on various types of roads, in order to develop criteria for the best type of disabled-vehicle detection system to use on different classes of roads with different traffic densities; (2) an investigation of the application of infrared techniques to other motorist aid devices, including a tailgate warning device and communication from a central station to the moving vehicle concerning roadway conditions ahead.

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MEANS OF LOCATING DISABLED OR STOPPED VEHICLES

SUMMARY

Initial Phase

The main subject of this study was the "Methods and Means of Communicating with Disabled Vehicles from a Central Location." The problem was approached in four reasonably distinct, but highly interrelated stages: (1) the problem of the disabled vehicle was defined in terms of its frequency of occurrence, reason for stop, traffic level, and road type; (2) the importance of defining an objective as a basis of system design was analyzed and some relationships of the objectives to the system concepts were developed; (3) the generic types of equipment applicable to the detection of and communication with disabled vehicles were examined and a number of novel approaches discussed; and (4) several representative roads or road complexes were hypothesized and a sequence of logical steps followed toward a workable solution of the disabled-vehicle problem. The details of the initial phase of this research are presented in NCHRP Report 6.

Problems are defined by using data pertaining to stop distributions from whatever facilities such data could be obtained. Some of the pertinent variables, such as average daily traffic, average trip length, and the expected stop rate, are shown to be sufficiently related to allow a statistical prediction of the stop rate, given the other two variables. Distribution in stop types for the various types of facilities are found. An analysis of the patrol effort that forms the chief source of the stopped-vehicle data is made. Patrol characteristics must be known before reliance can be placed on the quantitative validity of the data collected by these patrols.

Also analyzed are the many possible objectives that may serve as the basis for the eventual solution of the disabled vehicle problem; for example, (1) to increase safety, (2) to maintain or increase the capacity of the facility, (3) to offer service to the motorist, and (4) to aid in law enforcement. The fact that the objective is dictated by road type, traffic volumes, and the desires of the cognizant authorities is discussed and the unsuitability of the same objective for different road types is shown.

The basic types of sensors are examined as to their capabilities and limitations, costs, and ease of maintenance. A number of novel ways of detection, communications, and servicing are discussed. Some that are considered worthy of further investigation are (1) specialized patrols, (2) signaling devices, (3) means for the distressed motorist to call for aid, and (4) devices to render services in a manner consistent with some specific objectives. It is concluded that only one basic communication from the driver is required—a request for aid.

Several representative problems are hypothesized and realistic objectives for each are formulated. A logical procedure is then followed in choosing elements of detection, communications, and service so that the objectives can be met. The cost of implementing the complete system is assessed in terms of dollars per assist.

The road types examined are (1) an urban expressway; (2) an urban bridge or tunnel; (3) a cross-country turnpike or toll facility; and (4) a network of unlimited access roads consisting of a mix of major, intermediate, and small rural

roads. The four examples are intended to serve as guides for dealing with most road types; they point out the close interrelationship between the elements of detection, communications, and service.

The first solution sought for the examples chosen was in systems achievable either immediately or in the future at reasonable costs. It is concluded that when police patrols are available, they should stand ready to render the basic services required by the disabled vehicles. It is cheaper to expand existing law-enforcement agencies than to form and equip new agencies devoted to detection or service exclusively.

In all cases, the manpower costs were greater than equipment costs; therefore, automatic devices should be used when they can perform as well as a man. However, the increased cost of automatic equipment without removing men is usually out of proportion with the improvement achieved in fulfilling the objectives.

Technically, communications to the motorist are much more easily achieved than communications from the motorist. However, it is shown that most problems can be solved without such complications.

A solution that does not require a motorist to invest in equipment is believed superior to one that requires compulsory investment. The degree to which the system relies on the motorist to help actively in his detection should likewise be kept to a minimum, or altogether avoided.

Final Phase

Based on the conclusions of the initial phase of research, the final phase as reported herein is a development program to investigate and demonstrate the technical feasibility of an automatic surveillance system that will instantly detect and locate all stopped vehicles on the freeway and adjacent shoulder areas.

This development program proceeded through the following phases:

1. Investigation of solid-state infrared light-emitting diodes and detector diodes.
2. Investigation of the system optical requirements.
3. Design and construction of an experimental laboratory test model.
4. Design and construction of an engineering model of a completely solid-state vehicle-detection system.
5. Field test evaluation.

The results of this development program demonstrate that an infrared disabled-vehicle detection system is technically feasible. This system operates reliably to a range of 750 ft and covers a field 60-ft wide. This would ensure adequate coverage of three lanes plus the shoulder of a road.

This system operates with pulsed signals. Therefore, pulse coding techniques may be employed to transmit a variety of discrete messages. This capability could extend utilization of the system to uses other than just detecting disabled vehicles.

The solid-state infrared devices used in the equipment are relatively new developments. It is reasonable to assume that with further technological advances their performance will surpass that of present day devices, and their cost will decrease with increased production.

The approximate cost of implementing the proposed detection system amortized over a ten-year period is $1,627 per year per mile.

Some suggestions for needed future research are contained in an appendix. Another appendix gives additional sources of information and data on pertinent material.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

The first report on this project (*NCHRP Report 6,* entitled "Means of Locating and Communicating with Disabled Vehicles—Interim Report") described the nature, extent, and characteristics of the stopped-vehicle problem. It indicated that existing equipments and systems did not adequately solve the problems of detection and communication with stopped vehicles.

The present report describes the feasibility aspects of a disabled-vehicle location system using a modulated light source and roadside-mounted detectors. On the basis of experimental and analytical work performed, it was concluded that the concept of an optical infrared system for the detection of disabled vehicles was technically feasible. The technical information which forms the basis for this conclusion is contained in Appendixes A, B, C, and D.

The work discussed in this report deals with the design and development of an optical infrared detection system as a study model. This model uses solid-state components and the transmitter and receiver are completely self-contained units, requiring no external power supplies.

Figure 1 shows the tripod-mounted roadside receiver and the mobile transmitter. Figure 2 shows the internal arrangement of both the receiver and the transmitter.

RESEARCH APPROACH

The basic task was to develop an infrared optical system for the detection and location of disabled vehicles. This system must fulfill the following basic functional requirements:

1. To maintain surveillance over the active lanes of a highway, plus the shoulder area where a disabled vehicle might park, a wide receiver aperture is necessary.
2. Similarly, the transmitted beam must be wide enough to illuminate the receiver from any of the active lanes or the shoulder without requiring any optical realignment.
3. The system must be able to operate reliably over a reasonable range.

In addition to these functional requirements the system should be small, lightweight, simple to operate, and economically feasible.

A system concept of a vehicle-mounted transmitter and a roadside receiver was adopted. This approach yielded the greatest range, positive vehicle detection, and greater discrete message flexibility.

Solid-state components were used because their small size, low power drain, and high reliability, permitted the design of efficient, self-contained units.

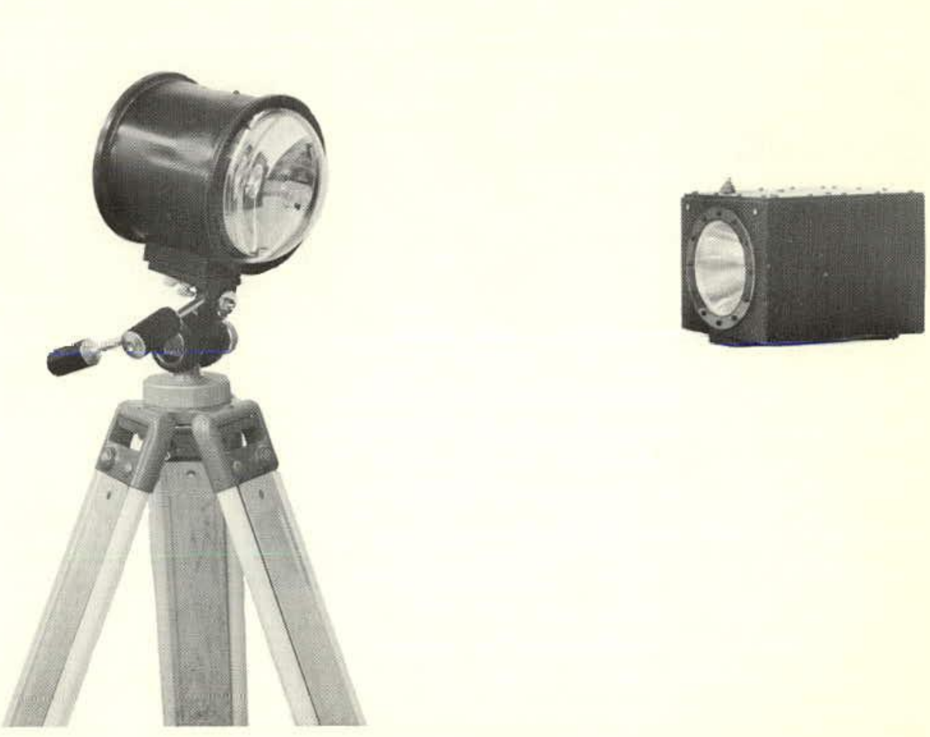

Figure 1. Tripod-mounted roadside receiver (left) and mobile transmitter (right).

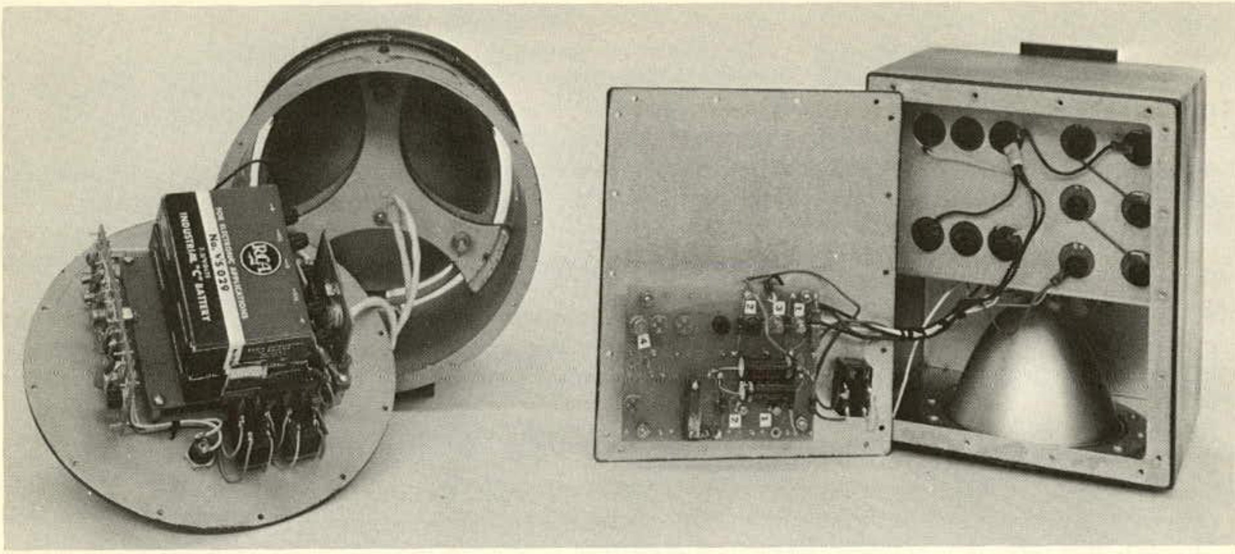

Figure 2. Internal arrangement of receiver (left) and transmitter (right).

The development program included the following phases:

1. Investigation of solid-state infrared light-emitting diodes and detector diodes.
2. Investigation of system optics.
3. Design and construction of an experimental laboratory test model.
4. Design and construction of an engineering model.
5. Field test evaluation.

Laboratory tests and evaluations were performed as required throughout the various developmental phases.

CHAPTER TWO

SUMMARY OF FINDINGS

The current project was concerned with the design and development of an optical infrared vehicle-detection system as a study model. Both experimental and analytical work has been accomplished and is reported in detail in the appendixes.

The infrared optical system that has been developed is based on the concept of a vehicle-mounted transmitter and a roadside receiver. The transmitter emits pulses of infrared light, which are detected and amplified by the receiver unit; emitted infrared energy is at a low level and is not injurious to living tissue. The transmitted pulse frequency may be varied, so that discrete messages may be transmitted.

Solid-state components are used because their small size, low power drain, and high reliability permit the design of efficient, self-contained units. The fast "turn-on" and "turn-off" time of the solid-state infrared emitting diode permits the use of an electronic pulse modulation device, rather than the bulky mechanical chopper required by incandescant infrared sources.

An optical system is necessary for both the transmitting and receiving units in order to fulfill the field of coverage and range requirements.

Each unit is packaged, complete with batteries, in a weatherproof housing. For demonstration purposes, the roadside receiver is mounted on a tripod. The mobile unit is equipped with magnets on its base, so that it may be set on the hood of a vehicle.

Field tests of the system have been made under the varied conditions of rain, drizzle, haze, and bright sunlight with no deterioration of performance noted. Outside stimuli, such as flashing headlights and reflected sunlight, have been introduced into the system with no effect on over-all performance. The system operates reliably to a range of 750 ft and covers a field 60 ft wide. This ensures coverage of three lanes plus the shoulder of a road.

CHAPTER THREE

APPLICATION OF FINDINGS

The results of this development program demonstrate that an infrared disabled-vehicle detection system is technically feasible. The engineering model has operated reliably to a range of 750 ft and covers a field 60 ft wide. By increasing the mirror diameter in the receiver optical system, the range could be increased to 1,500 ft. This means a minimum of five receivers per mile would be required to give continuous road and shoulder surveillance along a highway.

This system operates with pulsed signals, therefore pulse coding techniques may be employed to transmit a variety of discrete messages. This capability could extend utilization of the system to uses other than just detecting disabled vehicles.

A descriptive outline for a vehicle detection system follows: Assume a system range of 1,500 ft and five receivers per mile on a controlled highway. The receiver outputs are connected by telephone line to a central control post. The central control post has an electronic display board that shows the highway in map form and the individual surveillance zones covered by each receiver. The control post has radio communication with patrol and service vehicles to facilitate dispatching them where needed.

Each vehicle using the highway is equipped with an infrared transmitting unit. The transmitter is actuated by the driveshaft of the vehicle (via the speedometer cable) so that motion of the vehicle may be monitored. If the vehicle stops, the transmitter is automatically turned on and transmits code A (stopped vehicle). If the stopped vehicle is disabled, the operator may signal for the type of aid required by closing the proper switch on his selector panel; for example, switch No. 1, medical aid—code B; switch No. 2, mechanical aid—code C; switch No. 3, need fuel—code D; and switch No. 4, other (?)—code E.

The various codes would be determined by the frequency of the transmitted pulse. If it were desirable to transmit more than one code, it would be done on a time-sharing basis, possibly alternating between the two codes at 1-sec intervals.

The roadside receiver monitoring this particular zone would detect and decode the transmitted signals. The receiver would then transmit the decoded message, via telephone lines, to the central control post. The message would be automatically displayed on the electronic control board, showing the location and the type of aid requested. The controller would then dispatch, via radio, his nearest service vehicle to aid the disabled motorist.

The location of service vehicles could be monitored by assigning each vehicle a distinct code which would be transmitted at given intervals. In this manner, the controller could determine which service vehicle was nearest to the distress call.

If it is desirable to monitor vehicle speed, this can be accomplished via the speedometer cable. A predetermined maximum speed may be set into the transmitter. When it is exceeded, a specific speeding code would be transmitted. The central control post could monitor the speeder's progress on the electronic display board and alert patrol cars on the road ahead to the speeder's approach. If a minimum speed must also be maintained, this too can be monitored in the same manner.

If a traffic jam occurs, the controller can detect it and identify its point of origin by monitoring the electronic display panel. He can then dispatch the nearest patrol vehicle to unsnarl the traffic. If a collision caused the traffic problem, the controller might be able to bypass the traffic around the trouble spot via another route.

An approximation of the cost of the system described is outlined in Table 1. It is assumed that the central control station will monitor the traffic in both directions for 25 miles on either side of it, giving a total coverage of 50 miles

TABLE 1

COST BREAKDOWN FOR SYSTEM COVERAGE OF 50 MILES

EQUIPMENT COST FACTOR	NO. OF UNITS	COST ($)				COST PER YEAR ($)			COST PER DAY[a] ($)
		PER UNIT	INSTALLATION	OTHER	TOTAL	EQUIP.[a]	MAINT.	TOTAL	
Patrol vehicles	5	4,000[b]	—	—	20,000	20,000	6,000[c]	26,000	
Service vehicles	3	8,000[d]	—	—	24,000	12,000	6,000[e]	18,000	
Mobile I.R. trans.	2,500	35	—	—	87,500	8,750	8,750[f]	17,500	
Roadside I.R. recvr.	600	50	12,000[g]	—	42,000	4,200	3,000[f]	7,200	
Phone line rental	4[h]	4[i]	9,000[j]	—	14,400[k]	5,760	—	5,760	
Central control equip.	1	30,000	3,000	20,000[l]	53,000	5,300	1,590	6,890	
All					250,000[m]			81,350[n]	223[o]

[a] Over 10 years. [b] Life of 1 year. [c] 100,000 mi @ $0.06. [d] Life of 2 years. [e] 50,000 mi @ $0.12. [f] 10 percent replacement. [g] 600 @ $20. [h] Each 25 mi long. [i] Per mile per month. [j] Twice rental per year. [k] For first year; $4,800 per year thereafter. [l] Central control building. [m] = $5,000 per mile. [n] = $1,627 per year per mile. [o] = $4.46 per day per mile.

of two-way highway traffic. It is also assumed that the mobile transmitter is owned by the facility and is issued to the motorist only when he is using the facility. The number of mobile transmitters required is based on an ADT of 36,000. This requires 1,500 units plus 1,000 units for peaks and spares, giving a total of 2,500 units.

Table 1 gives an initial equipment cost of $250,000, or $5,000 per mile. The approximate cost per year amortized over a 10-year period, including maintenance, is $81,350, or $1,627 per year per mile. These approximate costs are for an entirely new facility and do not take into account that such items as patrol and service vehicles and suitable buildings may already be available in existing facilities.

Variations in the utilization of such a system are manifold and are best determined by the expert highway engineer. Serious consideration should be given to the use of pulsed infrared light as a communication medium for this type of application. It is invisible to the human eye and cannot distract or hamper a vehicle operator's driving ability. By virtue of its directivity it offers a high degree of security from outside interference. It is highly unlikely that pulsed infrared light will become a popular communications medium with amateur users, and thus become cluttered to the extent that the radio frequencies have become cluttered. In addition, scientific development in the field of infrared solid-state devices promises to make such a system economically feasible in the near future.

Additional suggestions for needed future research are given in Appendix J, and additional bibliographic material in Appendix K.

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APPENDIX A

EXPERIMENTAL INVESTIGATION OF SIGNAL ENVIRONMENT

The theoretical work reported elsewhere in this report was supplemented by some experimental efforts. A small part thereof is mentioned where applicable; for example, the response of some simple light sources that was measured is described in Appendix C. The remaining effort was devoted to experiments designed to investigate the signal environment. The detector previously developed was used.

EQUIPMENT DEPLOYMENT

Figure A-1 shows schematically the manner in which the equipment was used. The signal source was at various times (a) the ambient environment alone, (b) a specific light source in that environment, or (c) a light source in a controlled or dark environment. The detector utilized a lead-sulfide photo-resistive cell for all work except that with the flash tube, for which a cadmium selenide (CdSe) cell was found to be more expedient. The chopper was nothing more than a slotted wheel (much like that shown in Fig. C-1) interposed between the signal source and the detector. The chopping rate was about 500 cps. Its purpose was to permit detection of relatively slow changes in the light amplitude level, and to permit the recording of the detector output by the magnetic tape recorder, which by its nature is an alternating-current device. The oscilloscope was used chiefly in the laboratory to display and record

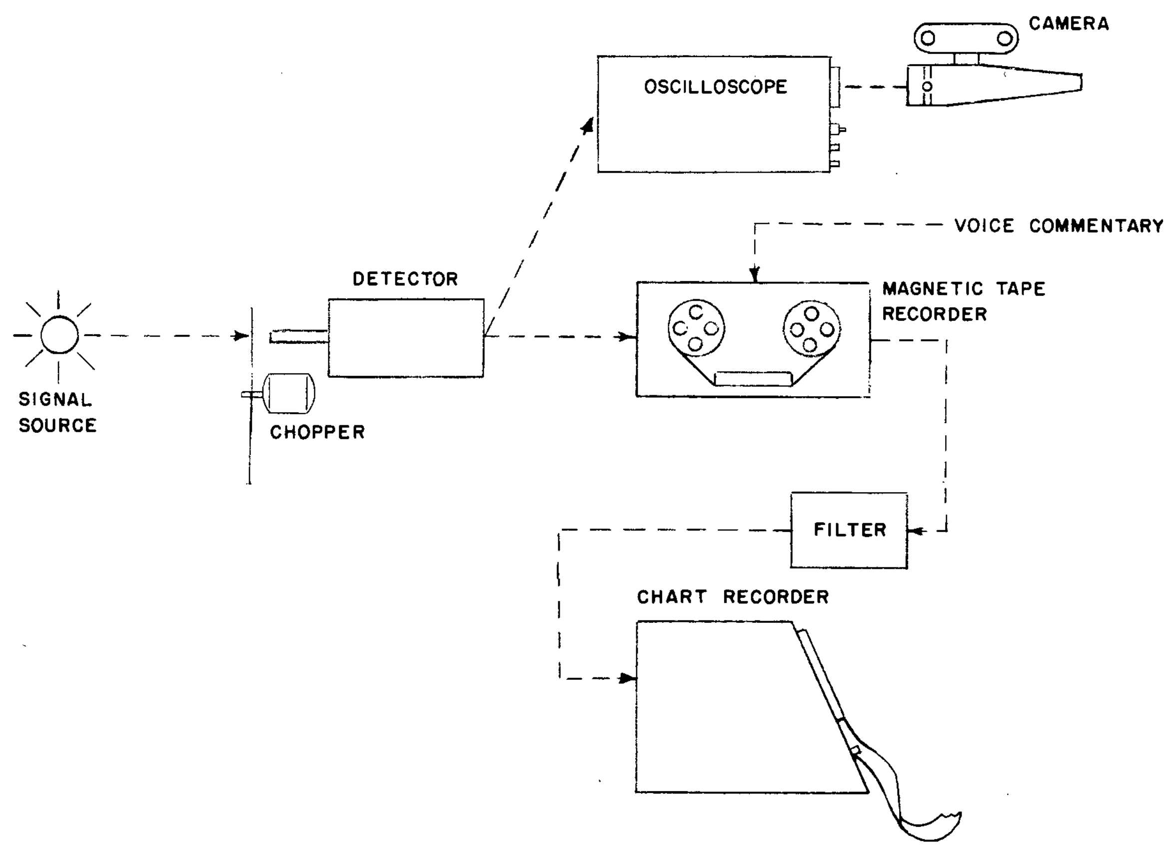


Figure A-1. Schematic representation of equipment use.

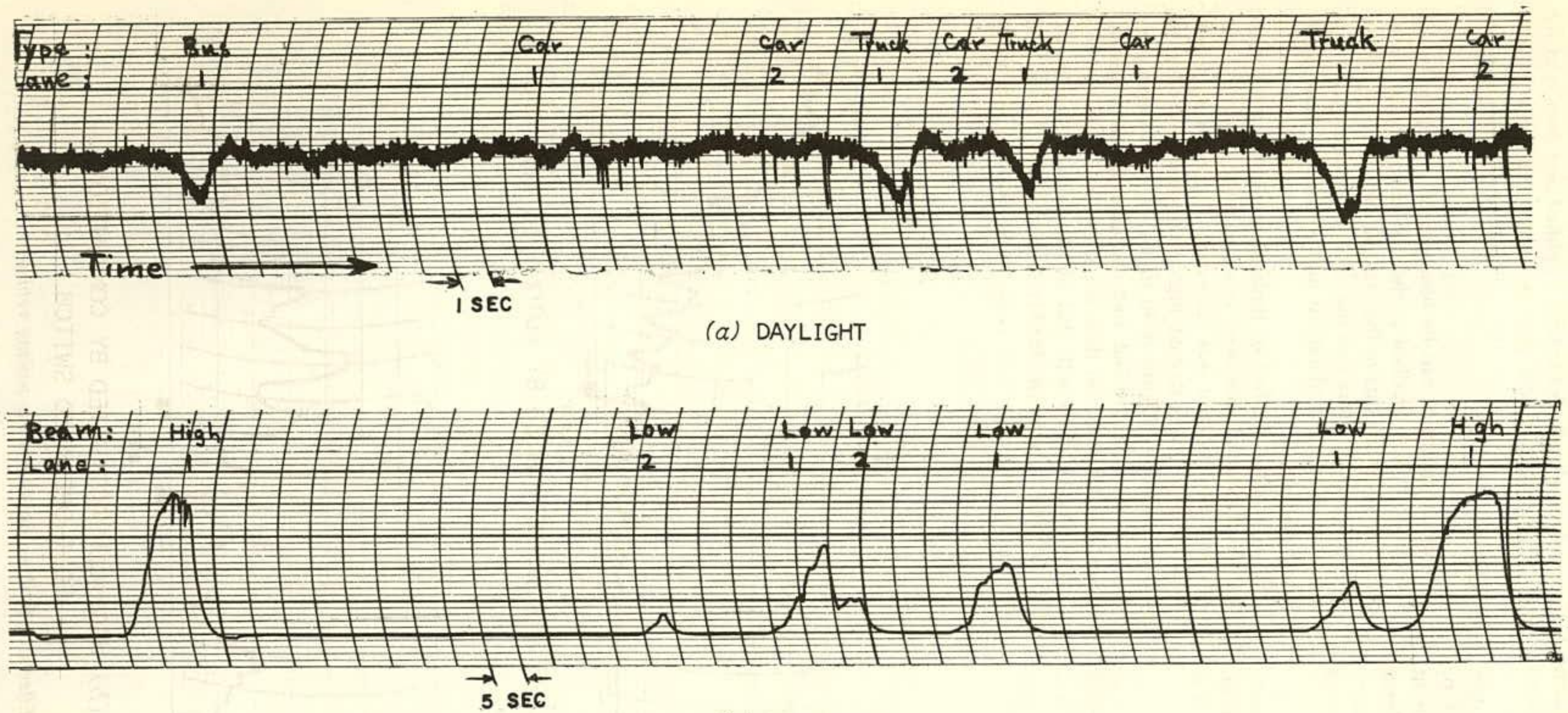
(with a scope camera) some waveforms of interest. For example, the turn-on, turn-off characteristics of some signal sources were thus displayed and recorded (Appendix C). The magnetic tape recorder served a dual purpose; first, to record data in the field, and second, as an intermediate amplifier to display the same data graphically on a chart recorder. The filter was a simple low-pass filter/detector such that the 500-cps signal (as induced by the chopper) was blocked and the amplitude variations produced by the signal were passed and traced on the chart recorder.

It is seen, therefore, that the artificially introduced 500-cps carrier was introduced solely as a convenience because of the relatively greater ease of handling, amplifying, recording, and storing the same. The light intensity "seen" by the detector appears as amplitude modulation superimposed on this carrier, which is effectively removed when no longer needed.

AMBIENT ENVIRONMENT

An experimental survey of the ambient environment was conducted as follows. The detector was located on the shoulder of a busy suburban highway, looking upstream; the chopper was immediately in front of the detector. The recorders were in a car parked well off the shoulder. The observer could record simultaneously on a parallel track of the magnetic tape recorder whatever signals were generated by the detector and his voice analysis of everything that transpired within the field of view of the detector. Comments such as . . . "large truck entering field of view about now . . . in lane 1 . . . and leaving field of view about now . . ." can be later correlated with the detector output record. The daylight survey was conducted at about midday, on a bright but hazy day. Figure A-2a is a sample of the chart record of that survey, extending over a period of about 45 sec. (About an hour of data was taken under these conditions.) Generally the largest vehicles produced the largest signal, because the magnitude of the signal was caused by the partial obstruction of the basic light source (the sky) in the detector's field of view. Similarly, vehicles in lane 1 caused a larger change than those in lane 2 for the same reason. The sense of the change was negative—that is, the net illumination level decreased as each vehicle passed through the detector's field of view. The "quiet" level, that part of the trace when no vehicles were passing, tended to fluctuate slightly due to slowly changing atmospheric conditions, such as the sun being partially obscured by clouds and then exposed again. This trace does not contain any signal proper; it is only the prevalent noise spectrum, on which any superimposed signal would have to be detected.

Figure A-2b shows a comparable trace taken during hours of darkness. In this trace the detector sees substantially only the passing of headlights; the amplitude of the



(a) DAYLIGHT

(b) DARKNESS

Figure A-2. Chart record of day and night survey.

deviation from the "quiet" level depends on the brightness of the headlights and their alignment relative to the detector. Thus, a low beam passing in lane 1 produced a considerably stronger signal than a low beam passing in lane 2. This is due largely to the directionality of the headlights in azimuth.* It should be noted that the excursion denoting the passage of a vehicle is in the positive direction; this is because the net illumination on the detector is increased by the vehicle's headlights. As in daylight, this represents the ambient noise against the background of which the signal will eventually have to be detected. About an hour of nighttime recording of this nature also was done.

The rather apparent difference in the day and night traces, the former jittery and the latter relatively clean, is caused by two factors, as follows:

1. The magnitude of the signal † in the daytime is much smaller than at night relative to the "quiet" light level. Hence, the signal-to-noise ratio is smaller by day than it is by night.

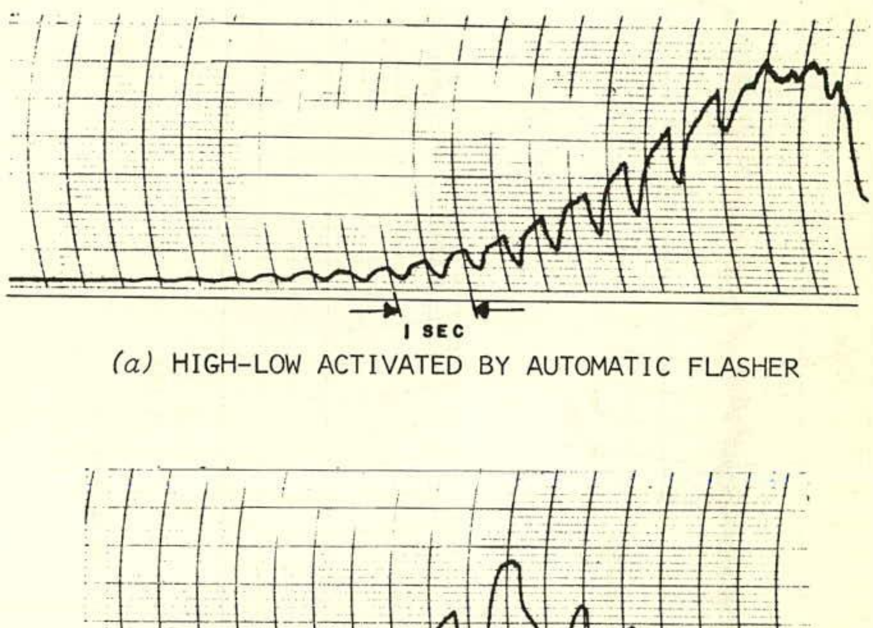
2. In view of item 1, higher gain (in the recording system) must be used to adequately record and display the signal by day, but the chopper introduces a certain amount of jitter, not all of which is attenuated by the filter. Hence, in achieving respectable signal-over-quiet level amplitudes, the jitter amplitude is likewise amplified and displayed by day. But at night, less gain is required because of the favorable signal-to-noise ratio; hence, a smoother signal results.

Slight irregularities can be observed at very high signal levels only; that is ascribed to the fluctuation in the signal level at the detector due to the extreme directionality of the headlights, and the fact that the vehicles producing the signals were passing at about 50 mph on a less than glass-smooth surface.

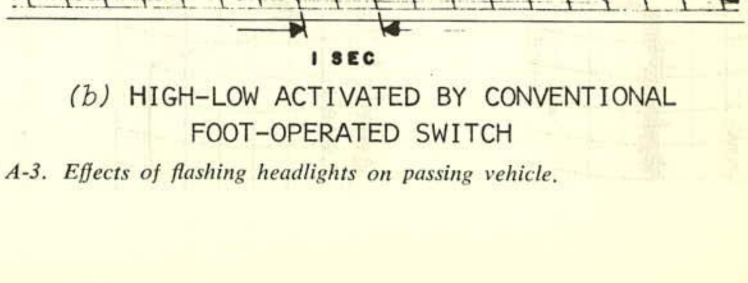
To ascertain the effect of flashing headlights on a passing vehicle, several runs were made past the detector location, and the response was recorded. Figure A-3a shows the headlights being flashed high beam-low beam by an automatic flasher. Figure A-3b shows high-low being activated by the conventional foot-operated dimmer switch. Noting the difference in time scale, one can compare the trace of Figure A-2b with that of Figure A-3a and A-3b. The difference between steadily burning high beams and flashing high-low beams is quite unmistakable. The slight

* A graph defining this directionality has been extracted from the *SAE Handbook* (1947) page 702, and is reproduced in *Traffic Engineering* by T. Matson, W. Smith, and F. Hurd (1955) McGraw-Hill, p. 42, as Fig. 3-13. On page 41, Fig. 3-12 shows contours of equal intensity of a sealed-beam lamp versus distance in front of the vehicle.

† "Signal" in the sense of "the effect of passing vehicle," not any kind of signal such as will have to be superimposed on the ambient noise.



(a) HIGH-LOW ACTIVATED BY AUTOMATIC FLASHER

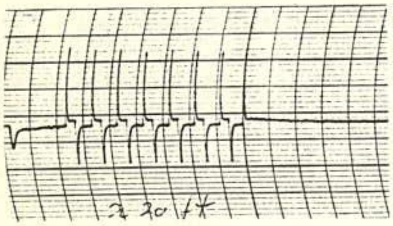


(b) HIGH-LOW ACTIVATED BY CONVENTIONAL FOOT-OPERATED SWITCH

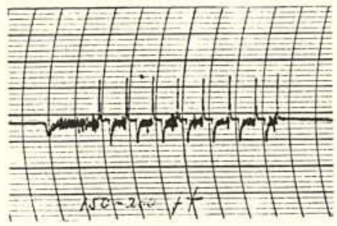
Figure A-3. Effects of flashing headlights on passing vehicle.

rise at the beginning of the trace of Figure A-3b is due to a vehicle preceding the test vehicle.

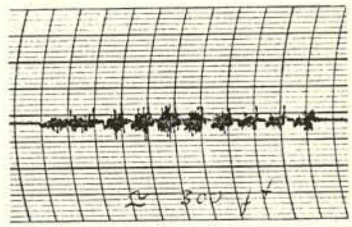
In all of these recordings a number of additional, though relatively minor, effects were observed. First, the color of the vehicle during daytime recording had a small effect, because it tended to reflect much of the diffused light, thereby canceling part of the effect of obscuring the sky. Thus, a clean white passenger vehicle has a smaller effect than a dark vehicle of similar size, passing in the same lane. Second, during nighttime recording it was noted that headlight alignment on the passing vehicles tended to vary considerably, the brightness being further affected by apparently dirty lenses and, in some cases, overloading and single headlights.



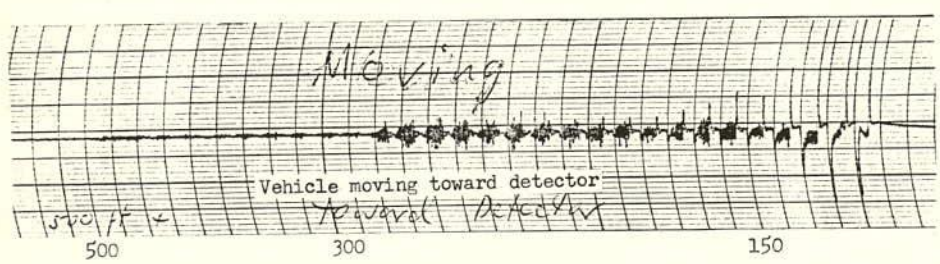
(a) HEADLIGHTS FLASHED AT 20 FEET



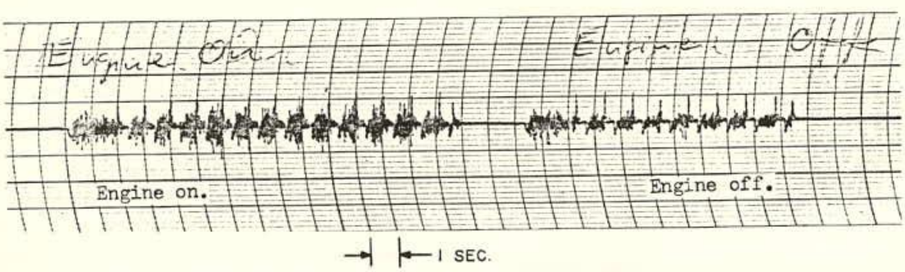
(b) HEADLIGHTS FLASHED AT 150-200 FEET



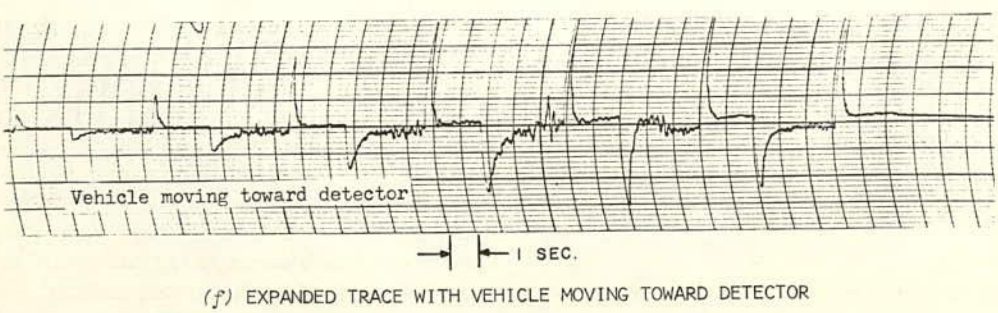
(c) HEADLIGHTS FLASHED AT 300 FEET



(d) VEHICLE MOVING TOWARD DETECTOR



(e) ENGINE ON (LEFT) AND OFF (RIGHT)



(f) EXPANDED TRACE WITH VEHICLE MOVING TOWARD DETECTOR

Figure A-4. Samples of traces in daylight experiment.

Some additional experimentation was performed in daylight to determine at what distances flashing headlights and taillights could be detected. A bright sunny day was chosen, and the tests were performed in AIL's parking lot. Headlights were flashed at varying distances, the effect of vehicle motion toward the detector recorded, and the effect of the engine being run versus shut off was examined. No chopper was used for these tests, so that the signal could be expected to show a spike when the light was turned on, and a spike of opposite polarity when it was turned off. The magnitude of the spike should be proportional to the rate of change of the light intensity. Thus, for a light turning on or off in infinitely short time, theoretically an infinite spike would result.

Figure A-4 shows samples of traces obtained. Specifically, Figures A-4a, A-4b, and A-4c show headlights being flashed at 20, 150, and 300 ft, respectively, from the detector. Figure A-4d shows the trace obtained with the vehicle moving toward the detector from about 400 ft. Figure A-4e shows a comparison between the signals received with the lights being flashed while the engine was running and then with the engine shut off, at about 180 ft.

The nature of the apparent oscillation during the on phase of the flashing operation at greater distances from the detector is not entirely understood. It begins to show up at about 150 to 200 ft. Figure A-4f is an expanded trace recorded under conditions identical to those of Figure A-4d in order to get a better look at this oscillation; it appears to be about 30 cps. Inasmuch as this effect is apparently independent of whether the engine is on or off and whether the flashing is done by hand or with an automatic flasher—in fact, the only variable appears to be distance—it is suspected that this may be some scintillation effect of the atmosphere.

Some additional data were obtained in looking at the nature of the incandescent light source—specifically the headlight and taillight, and are reported on briefly in Appendix C (mechanical modulators). One conclusion drawn bears repeating: the response time of such a light source precludes any modulation in excess of about 100 cps. The rise time of a taillight can be seen particularly well in Figure C-2a to be about 0.1 sec.

APPENDIX B

DETECTORS

This appendix discusses the principal types of light sensors. Three basic types are considered in terms of their principles of operation, size, per unit cost, life, reliability, efficiency, frequency response, additional equipment requirements, voltage requirements, and any limitations.

It must be kept in mind that the suitability of any given detector is considered in the light of its intended use in the application under consideration in the current project.

PHOTOMULTIPLIERS

There are two diverse physical effects governing the operation of the photomultiplier—primary and secondary electron emission. Primary electron emission or photoemission occurs when light impinges on a cathode. In the case of monochromatic light, the number of electrons emitted is proportional to the incoming light flux. This effect generally obeys Einstein's law that states

$$e(V + \phi) = h\,c/\lambda \qquad \text{(B-1)}$$

in which

e = electronic charge = 1.6×10^{-19} coulomb = 4.8×10^{-10} esu;

V = energy, in volts;

ϕ = work function of metal comprising the cathode, in ergs;

h = Planck's constant = 6.6×10^{-34} joule-seconds;

c = velocity of light = 3×10^{10} centimeters per second;

λ = wavelength of impinging radiation.

The term $h\,c/\lambda$ is more frequently referred to as $h\nu$ and is equal to the energy of a photon of incident radiation moving through space with velocity c. The quantity eV can also be expressed as $\frac{1}{2}\,mv^2$ and is equal to the kinetic energy of the ejected electron; this quantity is directly proportional to frequency, V, of the impinging radiation and is independent of the intensity of radiation. This means that the kinetic energy of the photoelectrons depends on the energy and not the number of incident photons.

An important aspect of any sensing element operation is that of its spectral sensitivity. Thus, for a given sensor, the sensitivity may be stated as so many amperes per unit of illumination—but at a particular frequency. That frequency is usually that of the maximum response of the sensor. Actually, the frequency is usually stated implicitly in terms of wavelength in angstrom (Å) units or microns. Thus, the most "popular" phototubes and photomultipliers achieve their maximum response at wavelengths between 3,300 and about 8,000 Å, although some units respond to 12,000 Å. The wavelength of maximum spectral sensitivity is determined by the cathode material. The previously mentioned cathode work function, ϕ, is a measure of the

amount of energy which an incident photon must have to liberate an electron, and is proportional to V or the frequency of the incident radiation. Hence, there exists for each metal, for example, a threshold frequency (or alternatively, wavelength) for radiations below which (or wavelengths above which) no electrons shall be dislodged. Specifically, the amount of energy necessary to overcome the surface attractive forces on the cathode is given by

$$W = h\,\nu_0 = h\,c/\lambda_0 = e\phi \qquad \text{(B-2)}$$

Hence, the lowest work function will result in emission of electrons at the lowest frequencies (or longest wavelengths). Some of the lowest work functions are found in double-metal films, such as silver-cesium ($Ag\text{-}Cs_2O\text{-}Cs$) ($\phi = 0.75eV$) with spectral limit of approximately 10,000 Å. Table B-1 gives a number of such combinations, their work functions, and the corresponding threshold wavelengths, together with some comparative single-element work functions and one compound, bismuth sulfide, with an exceedingly low work function.

It should be noted that all of the cathode materials listed will respond to wavelengths equal to or shorter than the threshold values given; this threshold value is sometimes referred to as the "long-wave limit". Most cathodes are made of double-metal films, or single-metal multiple films. The individual tube's spectral response is generally given in terms of a particular (standard) type cathode surface: these are designated, respectively, as S1, S3, S5, S6, and S8. The relative response characteristics of S1, S3, and S8 surfaces are shown in Figure B-1. The response of any particular tube at a particular frequency can be found by multiplying the value of the ordinate at that frequency by the absolute sensitivity as stated for that tube. The simplest of phototubes consists of an evacuated glass envelope and two elements—the cathode, which is exposed to the incoming radiation, and the anode, which is kept at a suitable potential above that of the cathode by external means. The liberated electrons can flow to the anode, resulting in a current in an external circuit proportional to the light flux impinging on the cathode.

A photomultiplier tube is basically a phototube as described previously, but with a number of additional elements, called dynodes, within the envelope. Potential differences between the cathode and the first dynode, first dynode and second dynode, etc., are such that electrons liberated at each stage are accelerated toward the next. This electron bombardment results in what is known as secondary electron emission. If the ratio of secondary to the primary emission is greater than unity, effective amplification results. This ratio, usually referred to as K, is called the secondary emission factor and depends on the nature of the metal or alloy forming the dynode. The last element is, of course, the anode or collector. If all the dynodes have the same secondary emission factor, K, and there are n such dynodes, the total amplification factor is K^n.

If the cathode is illuminated by L lumens of radiant energy and as a result emits S amperes of current flow to the first dynode, the over-all current flow from the collector (through the external circuit) is LSK^n amperes. Figure B-2 shows a simple representation of the phototube and photomultiplier tube circuits; the electron flow between elements is indicated by dotted lines.

The secondary emission factor, K, may have values up to about 10, and the number of stages (intermediate or secondary emitters—that is, dynodes) may be as great as 10 or 12. Thus, very high multiplication factors, K^n, are theoretically possible.

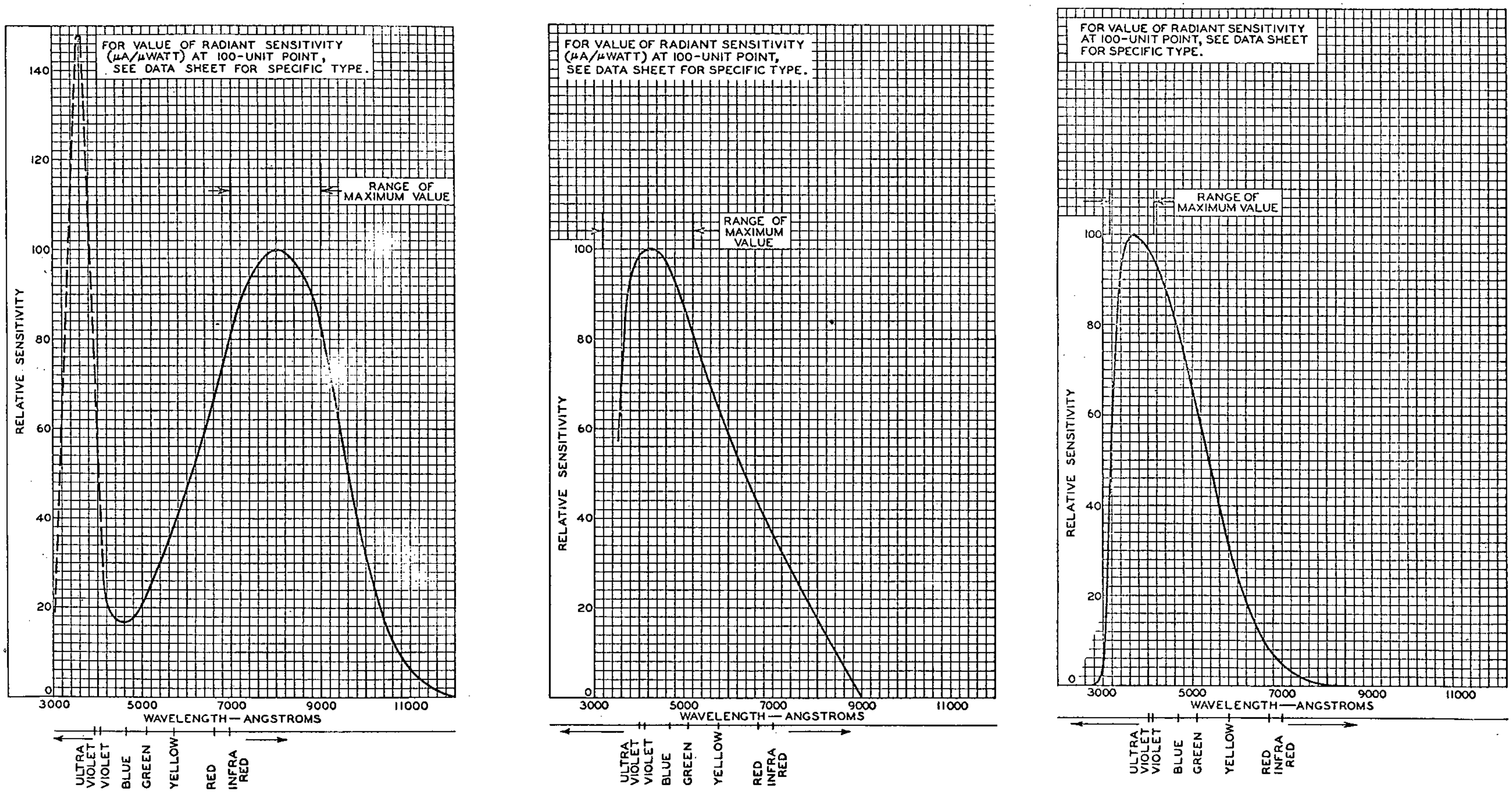
Another version of a phototube is much like the vacuum phototube described, except that the glass envelope is filled with an inert gas. As the emitted electrons proceed from the cathode to the anode accelerated by the electric potential imposed, at some point they acquire sufficient energy to ionize any gas molecules with which they collide. The photoelectrons, plus any electrons produced by these collisions proceed to the anode. The positive gas ions move toward the cathode with sufficient energy to impact on the cathode, causing more electrons to be emitted. Thus, amplification (by a factor as high as 10) occurs. The operating principle of the tube, therefore, is similar to that of the photomultiplier in that primary and secondary emission is involved, and to the vacuum phototube in construction and element configuration.

In size, the photomultiplier tubes are generally larger than the phototubes—whether of the vacuum or the gas type—simply because of the large number of secondary elements contained within the envelope. Photomultiplier tubes range in size from 2 to 3 in. in length to more than 5 in. in length, and 1 to 2 in. in diameter. Phototubes are generally shorter; 1½ in. long and less than 1 in. in diam-

TABLE B-1

WORK FUNCTIONS AND CORRESPONDING THRESHOLD WAVELENGTHS OF SOME TYPICAL DOUBLE-METAL AND SINGLE-ELEMENT FILMS

FILM			
TYPE	CHEM. SYMBOL	WORK FUNCTION (eV)	THRESHOLD WAVE-LENGTH (Å)
Double-metal films:			
Sodium-platinum	Na-Pt	2.08	5,900
Potassium-platinum	K-Pt	1.60	7,700
Rubidium-platinum	Rb-Pt	1.56	7,950
Cesium-platinum	Cs-Pt	1.38	8,900
Barium oxide-platinum	BaO-Pt	1.34	9,200
Lithium-tungsten	Li-W	1.83	6,700
Thorium-tungsten	Th-W	2.52	4,900
Barium-silver	Ba-Ag	1.56	7,900
Silver-cesium	$Ag\text{-}Cs_2O\text{-}Cs$	0.75	10,000+
Single-element films:			
Lithium	Li	2.2	5,580
Sodium	Na	1.9	6,470
Potassium	K	1.8	6,820
Iron	Fe	4.7	2,620
Silver	Ag	4.61	2,680
Cesium	Cs	1.54	8,000
Tungsten	W	4.56	2,700
Low work function compound:			
Bismuth sulfide	Bi_2S_3	0.0206	70,000



(a) S-1 RESPONSE

(b) S-3 RESPONSE

(c) S-8 RESPONSE

Figure B-1. Spectral-sensitivity characteristics of phototubes.

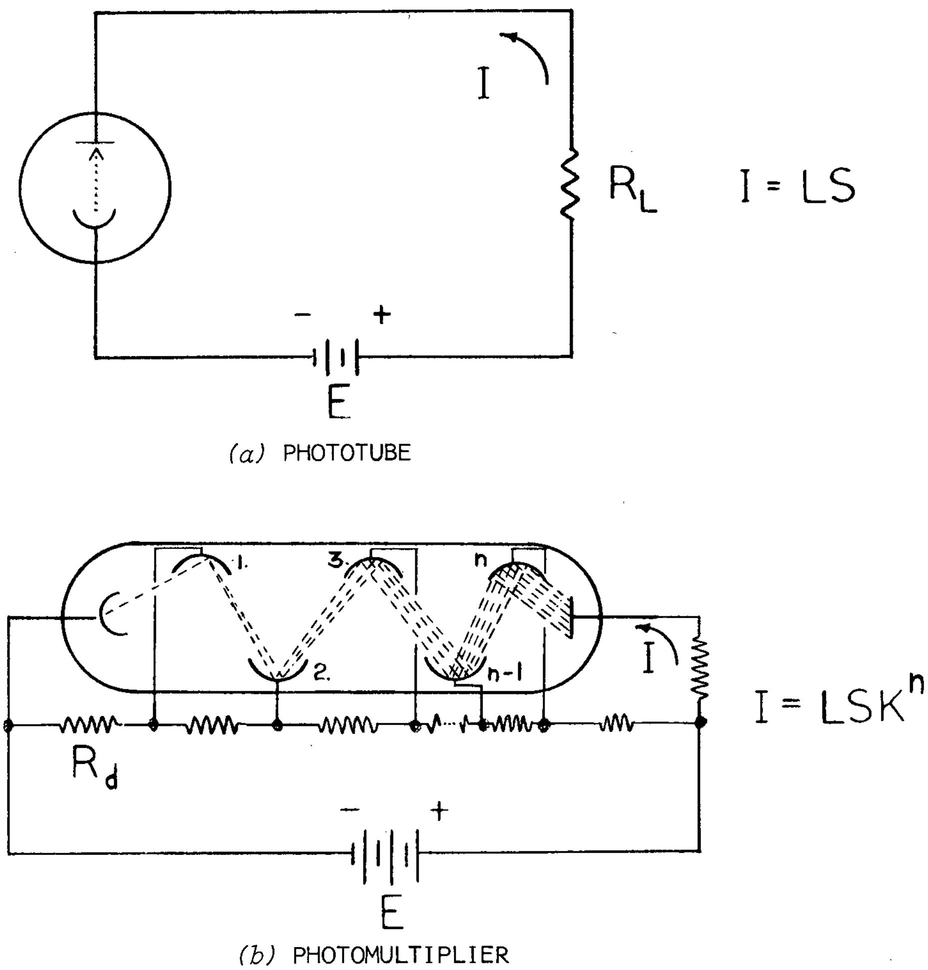


Figure B-2. Phototube and photomultiplier operating circuits.

eter is typical, although various special purpose tubes may vary from these dimensions. The retail cost of the least expensive photomultiplier tubes (such as those used in automatic headlight dimmers in automobiles, for example) is somewhat less than $10, and goes up to hundreds of dollars for special purpose (for example, low contrast) tubes.

The expected trouble-free life of these tubes is comparable with that of most electronic tubes, though obviously no breakdowns due to filament burnout will occur. Degradation in performance with time is due largely to electrode erosion and "gassing."

Typical current amplification factors in readily available photomultipliers range up to 16×10^6. With the multiple electrode arrangement the current flow increases from dynode to dynode so that the current gain is the ratio between the anode (or collector) and cathode currents; this is easily seen by reference to the circuit of Figure B-2b.

There is considerable disparity in frequency response of gas-filled phototubes as opposed to vacuum phototubes and photomultipliers. The former are generally limited to about 1,000 cps (1 kHz) due to the low gas-ion mobility; but of the latter, photomultipliers respond to up to 100 MHz, and phototubes are even faster.

Anode supply voltages that could be considered typical for the three types are 100 v for gas phototubes, 250 v for vacuum phototubes, and 1,000 v for photomultipliers.

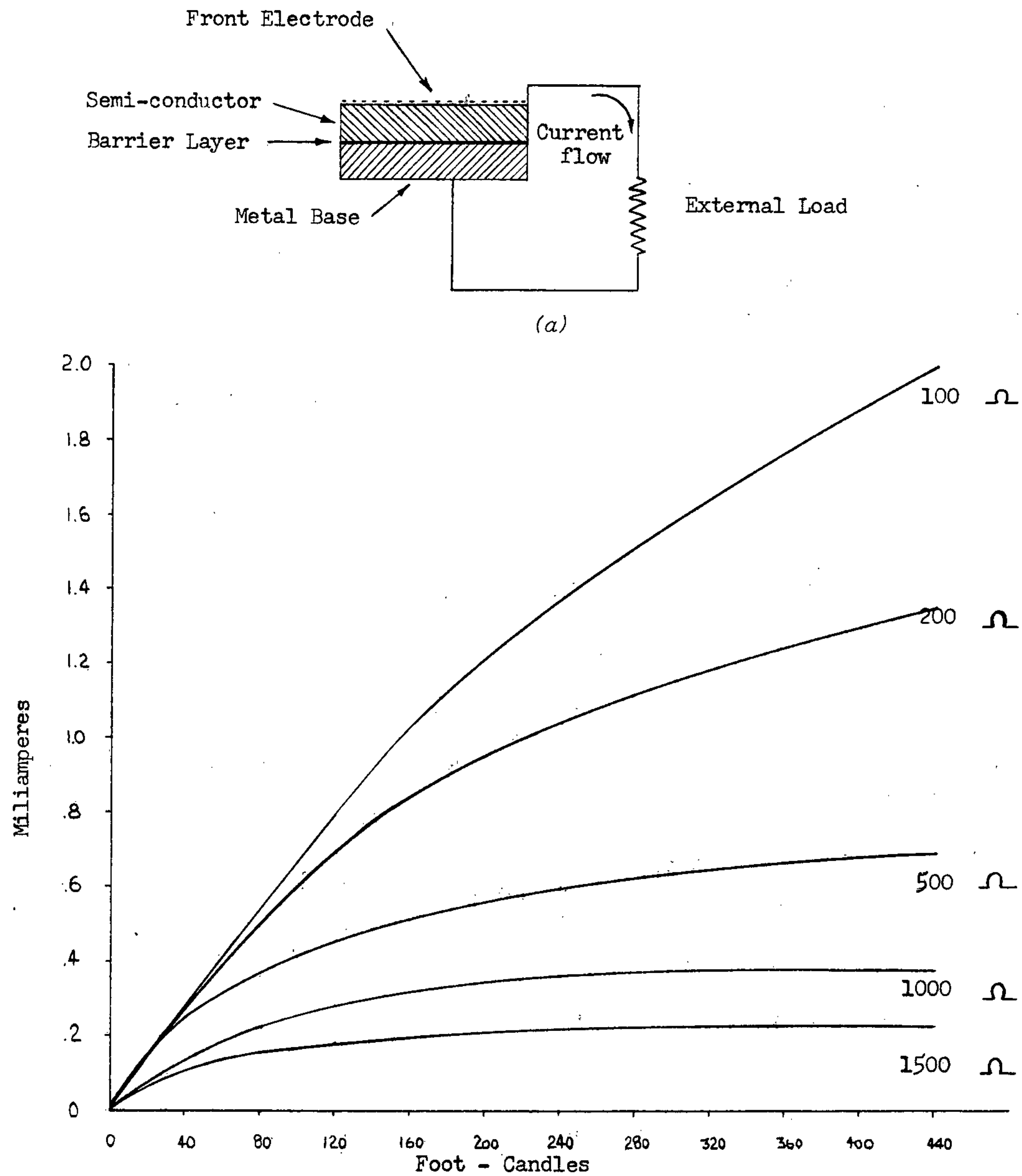
All three types are subject to thermal noise, which effectively limits the minimum detectable signal. Thermal noise effects can be reduced by physically cooling the device.

In attempting to judge the suitability of a device for a particular application, care must be exercised to fully use the device's capabilities. Thus, for example, the high-frequency response of the vacuum phototube is hardly required if the signal to be received is not likely to exceed several hundred cycles; alternatively, the very high amplification of the photomultiplier is hardly required if the signal is sufficiently strong to be detected by a simpler device.

The high-voltage requirement for the photomultiplier would tend to make its suitability for frequency roadside applications less desirable than a device of lesser voltage requirements.

VOLTAIC CELLS

Variously referred to as voltaic, photo-EMF, or self-generating cells, the chief characteristic of these elements lies in the property that illumination of the cell results in the transfer of electrons between the electrodes of the cell and, thus, current flow in an external circuit. The best example is the "solar battery" array of such cells, which have functioned and are functioning very successfully on some space vehicles, converting solar energy to useful electrical power. Each individual cell is capable of producing only minute amounts of power, but many thousands are used to achieve useful powers—ranging to several kilowatts. Figure B-3a shows a schematic representation of the various constituent layers of a photo-EMF cell. In this figure, the "front electrode" is generally an exceedingly thin metal film, usually gold or platinum, which is transparent. This film is generally vapor deposited or "sputtered" on; its thickness may be measured in molecular thicknesses. Next comes a semiconductor layer. Some of the materials used for N-type semiconductors are cadmium sulfide, cadmium telluride, or gallium arsenide; copper oxide, copper telluride, or copper sulfide are used for P-type semiconductors. To create the required junction, thin layers of one of each must be used. Since the mid-1950's the silicon cell has come into its own in the process of development of lightweight power supplies for spaceborn hardware. These cells are somewhat



(b) OUTPUT CURRENT CURVES

Figure B-3. Photo-EMF cell, schematic and output current curves.

simpler in that they consist of the silicon wafer suitably bonded to some substrate (which is load bearing, the crystal being rather weak) that forms one electrode, and a suitable transparent electrode bonded to the other side. The P-N junction is created by diffusion of phosphorus to a limited depth (0.5 micron) into the silicon wafer; this junction corresponds to the "barrier layer" or semiconductor-conductor junction of the older photo-EMF cells.

The following is a simplified explanation of the mechanics of operation of a photo-EMF cell. On one side of the junction the semiconductor is electron rich (N-type); on the other side the semiconductor is electron poor (P-type). Incident light in the form of photons tends to dislodge some electrons to higher energy levels. In so doing, these electrons tend to become separated from their original sites and, given a convenient path, will return to their original (lower) energy levels, doing some useful work in the process—that is, traversing the load.

Because the cell is self generating, it follows that no external voltage is required for the cell's operation. However, the current produced by a single cell is usually quite low; hence, suitable amplification is necessary before a useful function can be performed. In the process of making the cell a part of a working circuit care must be taken to isolate the cell electrically from the rest of the circuit, so that no undesirable externally applied potential appears across the cell. In some special cases, however, a carefully controlled small external potential can be used to advantage to increase the output of the cell. Any alternating voltage can be expected to destroy the cell.

Whereas earlier cells had efficiencies ranging to about 6 percent, recent developments (particularly in silicon cells) have resulted in conversion efficiencies as high as 10 to 12 percent. Because of manufacturing limitations, the individual cells are quite small; about 1 by 2 cm is typical. Thus, about 10 percent of incident energy is converted; the remaining 90 percent is converted to heat, which if allowed to build up, will ruin the cell. Furthermore, the generated EMF is reduced by temperature increases. Hence, provisions must be made to dispose of this heat by radiation, convection, or otherwise (this is a major problem in space applications, not so much in earthbound ambient environments where air effectively acts as a convector/absorber). Further considerations are (a) the differential expansion of the various elements of the cell, with the possible attendant separation of layers; and (b) the humidity prevalent in the atmosphere of the earth tends to gradually degrade the spectral response characteristics of the cell. This latter effect can be avoided by suitable encapsulation, but this in turn leads to the question of transmissivity of the encapsulating material.

Figure B-3b shows a representative output current of a photo-EMF cell in terms of the incident illumination and load resistance. It should be noted that the total power available from a single cell is quite small.

The spectral response of most photo-EMF cells corresponds roughly to the normal visibility curve, but extends somewhat to either side thereof into the ultraviolet and the infrared areas, principally the former. Selective response within the basic envelope can be achieved by use of filters, though with some attendant attenuation due to the filter material.

TABLE B-2

CURRENT RATIO OF ALTERNATING COMPONENT TO MAXIMUM VALUE

FREQUENCY (Hz)	CURRENT RATIO FOR 100 OHMS	500 OHMS
50	1.00	1.00
100	1.00	0.98
500	0.99	0.79
1000	0.95	0.54

The frequency response of the photo-EMF cell is generally greater for smaller cells than for larger cells; this is caused by the internal capacitance effects of the cell. Furthermore, the values of the load resistance limit the modulation frequency that the cell can respond to for a given loss of efficiency. Table B-2 gives the current ratio of the alternating component of the current to the maximum value of the current for two values of load resistance for several frequencies. This maximum value is attained when the shunting effect of the cell (internal) capacitance is zero. Hence, this ratio indicates the efficiency of the cell in responding to modulation at specific frequencies. Therefore, it can be seen that the frequency response required must be traded off against the desired output level, or vice versa, keeping also in mind the effect of load resistance on the modulation frequency.

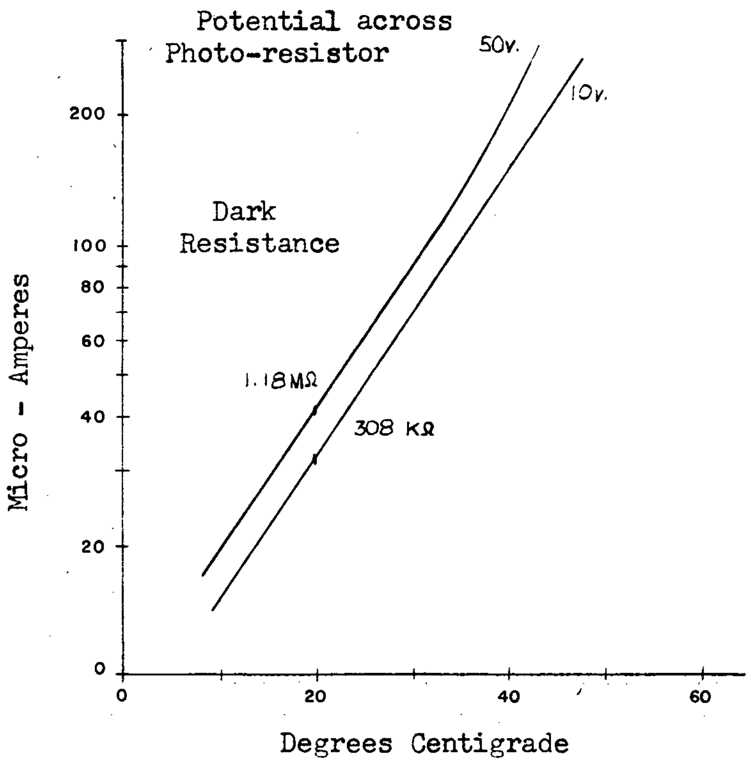
Some causes for cell degradation have been mentioned previously; specifically, humidity and elevated temperatures (50 C and higher). Other causes are excessive shock and, depending on cell type, some types of radiation. For example, if Mylar is used as covering material, ultraviolet will tend to decrease the transmissivity of Mylar in time and thus decrease the cell's effective output.

The internal dark impedance of the photo-EMF cell may be anywhere between several hundred to several thousand ohms. It is to be noted that its response is largely that of a current rather than a voltage change. Hence, they are eminently suitable for use with transistor circuits.

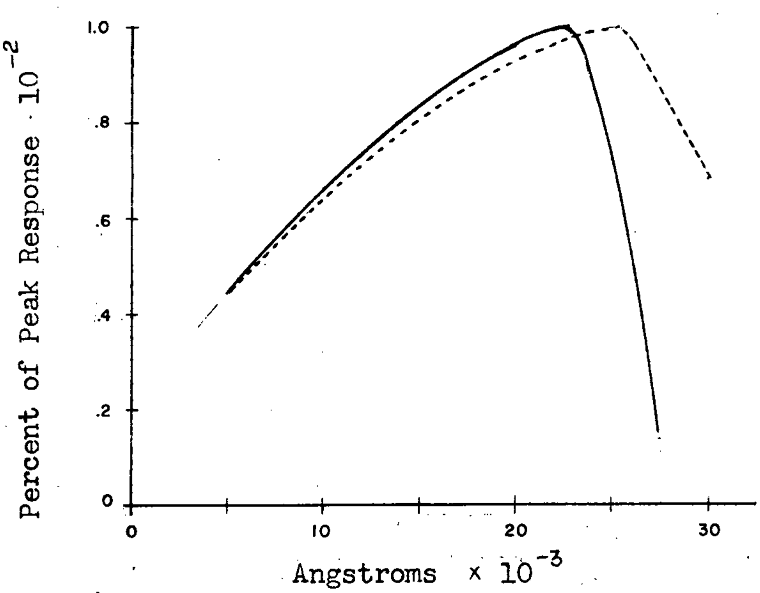
The cost of photo-EMF cells is generally quite low; some selenium photocells can be bought for less than $1 each, retail.

RESISTIVE CELLS

As the name implies, resistive cells change their internal resistance when exposed to radiation. The basis for this effect is the so-called "inner photoelectric effect," wherein the energy of an incident photon, h_ν, is sufficient to raise an electron to a vacant conductivity level. This is distinct from the "outer photoelectric effect," such as that found in phototubes, photomultipliers, and the like, where the electron is emitted from the cathode. In the inner photoelectric effect, the conductance of the substance is increased by the



(a) DARK CURRENT AS FUNCTION OF CELL TEMPERATURE



(b) SPECTRAL-SENSITIVITY OF LEAD SULFIDE CELL

Figure B-4. Photocell characteristics.

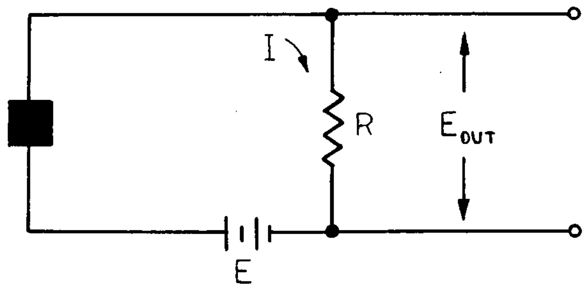
presence of the "free" electrons; hence, if a suitable potential is applied to the cell, the amount of current flowing through the cell is inversely proportional to its resistance (or, conversely, directly proportional to its conductance). No implication is made here of linearity between the irradiation level and the resulting resistance change; in fact, the relationship is in fact nonlinear for most resistive photocells. (Specifically, the output current is proportional to the square root of the incident radiation level.)

Structurally, photoresistive cells are considerably simpler than the tubes or photo-EMF cells. They consist basically of the active element between two electrodes. In some cases, it is necessary to enclose the cell between layers of glass or other protective film to prevent corrosion and hence degradation of performance.

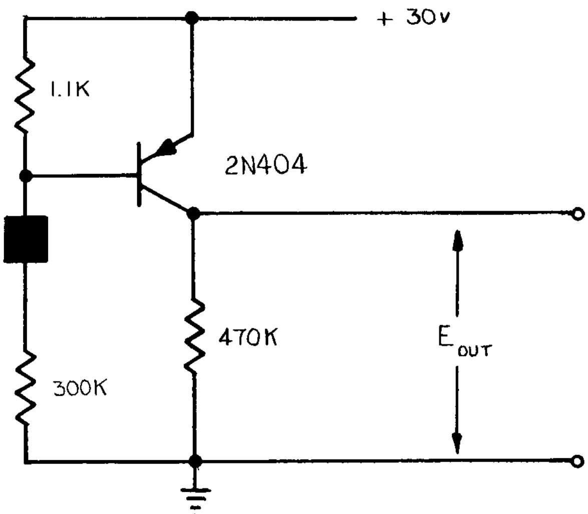
The resistance of the photocell is strongly affected by the cell's temperature. Thus, for a given voltage across the cell, the current through the cell (for the same illumination level) increases significantly if the temperature increases. For example, for a germanium photocell, the change in the cell's dark current as a function of cell temperature is shown for two cell voltages in Figure B-4a. Because the ordinate is logarithmic, the relationship is seen to be exponential. The "dark current" is the current flowing through the cell with no irradiation and is dictated by the cell's "dark resistance," which is finite. Also, the dark resistance is not independent of the potential applied across the cell; for the example of Figure B-4, the "dark resistance" values at 20 C are easily seen to be, respectively, 308 k-ohms for 10 v, and 1.18 meg-ohms for 50 v. Thus, when specifying the characteristics of a photoresistor, it is important to note the dark resistance at the value of the applied d-c potential.

The photoresistive cell can be sensitive to long wavelengths; that is, red and infrared radiation. For example, selenium cells peak generally around 7,000 Å, thallium sulfide at 10,000 Å, lead sulfide at about 20,000 Å, bismuth sulfide at 7,000 Å, and bismuth telluride at 10,000 Å. Their effective ranges are, by and large, quite extensive: for example, the latter two types respond to about 40,000 Å, as does lead sulfide. Their response does fall off, however, for shorter wavelengths (toward the blue-violet), and becomes negligible in ultraviolet. Figure B-4b shows the spectral sensitivity of a lead sulfide cell at 20 C to its peak response (that is, ordinate = 1.0). It can be seen that the response of the cell reaches only about 50 percent of its peak response at the onset of infrared, and goes up for longer wavelengths; following a peak, it drops fairly rapidly. It should be noted that the long-wave limit can be extended by cooling. Thus, the same cell, if cooled to − 183 C (temperature of liquid oxygen), peaks at about 25,000 Å and drops off less rapidly; it is shown as a dotted curve in Figure B-4b. Of course, this property is only of academic interest in relation to the cell's intended application. By and large, there are no strict limitations on the value of the d-c voltage that can be impressed on the photoresistor; voltages from 10 to 1,000 volts can and have been used for various applications.

The simplest possible circuit that could be used with a photoresistor is shown in Figure B-5a. Here, the cell is in



(a) SIMPLE CIRCUIT



(b) MORE COMPLEX CIRCUIT

Figure B-5. Basic photocell circuits.

series with a d-c voltage source (battery, E) and a resistor. Because the current flow in the circuit, *I*, changes in accordance with the resistivity of the photoresistor, which is determined by the irradiation intensity and frequency, the voltage drop across the resistor, R, is proportional to that current; hence, if the characteristics of the cell are known, this voltage, E_{out}, can be used as a measure of the irradiation. Note that if the frequency of the radiation is known, a measure of intensity is available; conversely, if the intensity is fixed and the frequency varies, the latter provides some measure of frequency. (Note that here ambiguity is possible because the cell responds equally to at least two frequencies on either side of the peak response frequency.) But no unequivocal measure of both is possible. It is suggested that in its intended application the frequency (color) will be fixed, and the intensity modulation used as the information-carrying device.

A somewhat more complex circuit is shown in Figure B-5b. Here, the 2N404 transistor acts as an amplification stage; at low signal levels (that is, near "dark" conditions) the current flow through the photocell is at a minimum. Any changes in this flow as a result of even small changes of the radiation will manifest themselves in a change in this current and thus in the base bias of the transistor. Hence, the voltage as seen across the 470-k resistor corresponds to the irradiation (the same restrictions as to intensity and frequency hold here, of course) on the face of the photoresistor. Thus, this circuit forms a d-c device.

In size and weight, as well as exterior configuration, the photoresistor is much like the self-generating photocell. Generally, it is much more tolerant of ambient conditions—with the exception of heat, the effects of which have been discussed previously and must be taken into account. Prices per unit are likewise quite low, in some units being obtainable at retail for well under $1.

The frequency of the photoresistor response must be considered next. Until several years ago, the photoresistor was the slowest responding of the three basic sensor types considered; response times in the order of 0.05 sec to as high as 0.1 sec were quoted, thus limiting the modulation frequency to under 20 Hz. Since then, photoresistors have been developed which respond comfortably to more than 1,000 Hz. An example is the lead sulfide cell (KODAK, Q-2, 10 × 20 mm) used in the circuit of Figure B-5b, which is readily available commercially. Whereas such response is much inferior to that of phototubes and the photo-EMF cells, it appears quite adequate for the application at hand.

In summary, having considered the three basic elemental detector types as to their characteristics, availability, cost, probable longevity, simplicity of use, and applicability, it is concluded that the photoresistor is the most suitable for use in frequent roadside detectors for the purpose of receiving suitably coded messages from moving or stationary vehicles.

SOME NEW SOLID-STATE DEVICES

Recently, the increase in solid-state knowledge has lead to the development of many new types of light detectors. These detectors are generally of the junction type, whereas a newer variety are of the laser type.

In the junction types there are many varieties, the simplest being the single junction or photodiode. In this device, light shining on the P-N junction of a conventional diode structure causes excitation of the charge carriers at the junction. If no external power source is used, these excited carriers produce a voltage across the diode. It is also possible to back-bias the junction by an external power source so that the excited carriers effectively cause a modulation of the conductivity of the diode. Thus, a photodiode combines the principles of photovoltaic and photoconductive devices. These devices have a wide spectral response, fast response time, high sensitivity and linearity, and simplicity of circuit design. For example, EG&G's SD-100 photodiode covers the spectrum from 0.35 to 1.13 microns; it has a quantum efficiency of almost twice the maximum efficiency of an S-4 phototube. The rise and fall times are 4 and 15 nanoseconds, respectively; this gives a frequency response of 50 MHz.

Other junction devices are constructed by use of the multijunction techniques; by addition of a second junction a transistor configuration is obtained. In this configuration a much higher gain is obtained. Some such devices have gains considerably greater than that of a photomulti-

plier tube and all such devices are more or less subject to temperature variations. Some of the silicon devices are sufficiently insensitive so that the base lead is not brought out of the case. In some other devices, the base lead is brought out so that a temperature-compensating bias may be applied.

Additional junctions can be added so that the devices become a four-layer structure. In this form, they resemble the SCR or switch configuration. The power gains are generally higher in such devices, but the gain is not linear. They usually have turn-off problems similar to those of the SCR's (see General Electric *SCR Manual*).

Another new type is the field-effect device. It has a very high impedance, which in some instances is advantageous. These are newer devices and more expensive, so that the technology is not as well advanced in these areas.

All of these solid-state devices are new and at present somewhat expensive as individual components. The prices are falling rapidly, and the simplicity of construction and similarity to other such semiconductors indicate that the ultimate price could be quite reasonable in the near future. One of the major advantages of these devices is that they operate at low voltages and require considerably less peripheral equipment. Therefore, the over-all cost is less even if the actual device cost is a little more.

Another type of detector mentioned is the laser. This type is really a light amplifier rather than a detector. Light energy coming into the device stimulates the emission of more light of the same frequency, so that the total light out is greater than that received. These devices are probably the newest in concept and as yet have the least operational experience. All the preceding classes of devices would likely be sufficient for the needs of this system.

APPENDIX C

MODULATED LIGHT SOURCES AND MODULATORS

The system considered is basically a one-way communications system in which the roadside detectors are the receivers, and the vehicle-mounted modulated light source is the transmitter. The suitability of a given transmitter is predicated on its conformance to the following requirements:

1. The motorist must be willing to buy, install, and use the device; to do this, he must believe in the effectiveness of the device.
2. The device must be inexpensive (relative to the cost of the car).
3. It must be simple to install, maintain, and use.
4. It must have a demonstrated high reliability to function when needed.

The last requirement requires some comment: specifically, the "when needed" concept is subject to discussion. The system can be:

1. In operation at all times the car is in operation; the vehicle's velocity may be used as the modulating variable.
2. In operation only under conditions other than normal; for example, if speed falls below some predetermined level.
3. In operation only if the vehicle stops, automatically.
4. In operation only if the vehicle stops, by driver command action.
5. In operation at any time, by driver command action.

Of the foregoing, items 1 and 5 appear by far the most practical. Hence, for item 1 the system is needed and must be operable at all times, and for item 5 the system must be ready to operate for use at all times.

These are rather stringent requirements. Consider a hypothetical system which derives its operating power from the battery of the vehicle. For a vehicle with battery failure, or generator and hence subsequent battery failure, the system would not do its job. Next, consider directionality. A highly directional light source would require very extensive roadside instrumentation to assure its being "seen." These are important system characteristics which must be taken into account, leading to the following reasonably detailed study of several modulated light sources.

MECHANICAL MODULATION

One of the simplest means of modulating a light source is mechanically, with a shutter arrangement. By alternately opening and closing the shutter, messages can be transmitted. The form of modulation may be either the rate at which the light is flashed on and off or the duration of the on period—that is, pulse rate or pulse duration. A great number of physical configurations are possible. Some of the basic types of shutters might be worth mentioning, such as the iris type, the linearly moving slot type, the slotted disk type, or the slotted cylinder type. It is also possible to use a rotating mirror, or a plane reflector, or to rotate a complete directional light source. Light sources of the latter types are usually found on top of emergency vehicles, police vehicles, fire apparatus, and the like. Their objective is to attract attention by virtue of the fact that the light amplitude apparently rises and falls. Thus, they are effectively transmitters and the public, whom they alert to their presence, is the receiver. One might also add that they are quite effective.

Whereas the mechanically modulated light source is conceptually and physically quite simple, it does require a mechanism to accomplish the shutter operation, which requires power in addition to that required by the light source itself. The simplest form of signal is a constant source that can be turned on by the driver with no need for further modulation. However, this allows but one message (for example, HELP!).

If the light source is switched on and off in accordance with a coded pattern, a more sophisticated system is created. However, it requires that the driver be physically and mentally able to send the code. The next step in sophistication is achieved by controlling the rate at which the light is switched on and off. Mechanical modulation occurs through the actuation of a switch, or electrically through a relay, or by interruption of the light beam itself.

The advantages of the mechanically modulated system are its inherent simplicity and relatively low cost. On the other hand, for the case where the light source is turned on and off, the resulting thermal cycling will tend to reduce the life of the bulb and for the mechanical shutter, a moving mechanical device, rotating or reciprocating, must be maintained, lubricated, and actuated via a shaft, a motor, or manually. Any of these subordinate parts is subject to wear, and hence failure.

The frequency of modulation for a mechanical system is somewhat limited. Consider, for example, a spinning cylinder with slots, with the source inside as shown in Figure C-1a. Suppose there were 10 slots; at 1,000 rpm there would be approximately 167 pulses per second. To get 1,000 pps, the cylinder would have to spin at about 6,000 rpm. Simple, inexpensive assembly, and casual maintenance would not do. Of course, doubling the number of slots in the cylinder would require only one-half the rotational speed, but then considerations of size and masses would be involved. Analogous considerations hold for a spinning disk, as shown in Figure C-1b.

Directionality is achieved by introducing a stationary slot so that light will pass only when the source, the stationary slot, and the moving slot are in alignment. For a cylinder without a stationary slot, the modulation will be seen from any direction. Plan views of Figures C-1a and C-1b show the directionality of the modulated light signal. In both arrangements, the source is assumed to be constantly on. Directivity depends on the geometry of the construction, including the size of the light source, the distance of the source from the slot, the size of the slot, and the distance between slots.

The properties of an incandescent light source which is

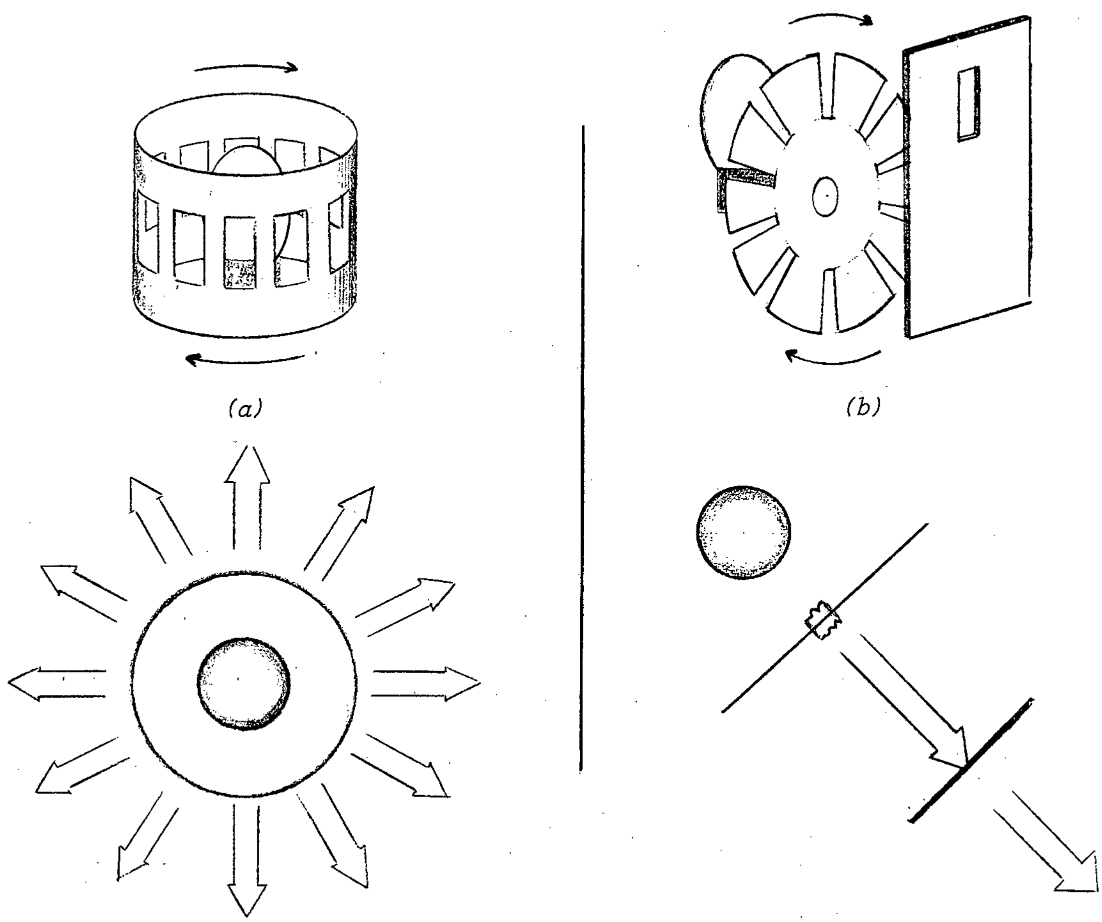
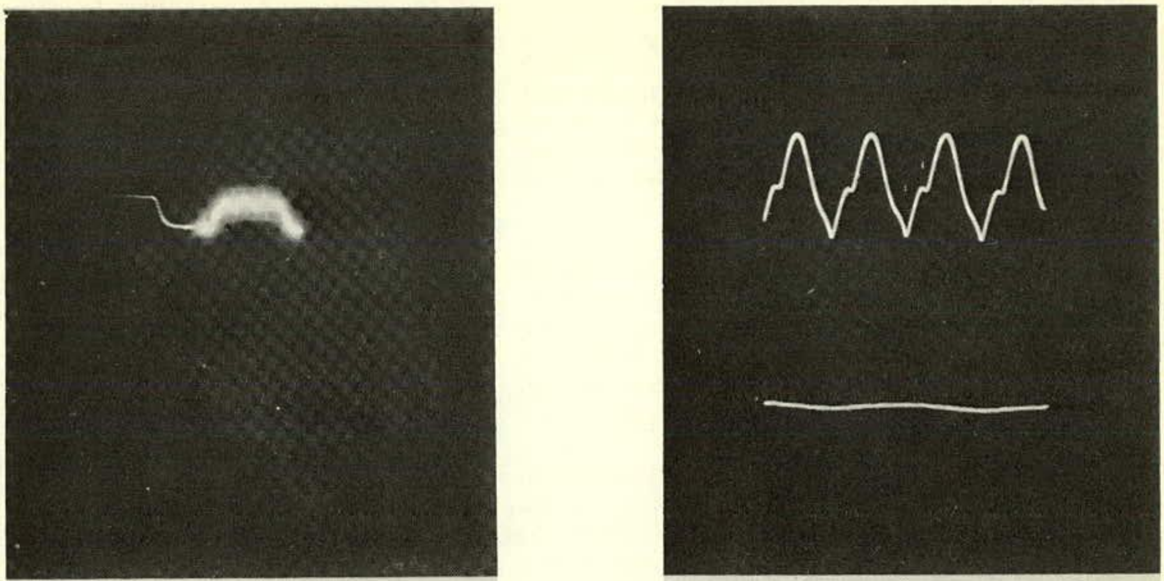


Figure C-1. Examples of simple mechanical modulation (a) by slotted cylinder and (b) by slotted disk.



(a) DETECTOR RESPONSE TO TAILLIGHT

(b) DETECTOR RESPONSE TO FLUORESCENT LIGHT

Figure C-2. Oscilloscope photo of detector response.

cycled on and off alternately have been investigated, because this is a simple and readily available signaling means. The filament appears to no longer turn off (that is, cool off beyond incandescence) at modulation frequencies higher than 25 to 30 Hz; no visually detectable flicker is present at frequencies higher than about 30 cycles. However, a detector employing a lead sulfide cell (which is most sensitive to red and infrared radiation) can detect modulation up to about 1,000 cps. For the experiments, a readily available 6- to 8-v, 0.25-amp bulb was used. In addition, some tests were performed to ascertain the possibility of auto headlights or taillights being seen in broad daylight (Appendix A). Figure C-2a shows a scope photograph of the detector response to a taillight being turned on and off at about 50 ft on a bright sunny day. Flashing of headlights at about 250 ft produced a similar response. Figure C-2b shows for comparison the same detector response to the interior fluorescent light environment.

GAS TUBE

There are many kinds of gas tubes. Some examples are tubes in various lengths and forms used in advertising and signing, gas discharge tubes or flash tubes (such as those used in photography), and indicator or pilot lights (such as the familiar neon bulbs). Not all of these are suitable for signaling purposes, and not all function in exactly the same manner. The neon bulb mentioned produces only a faint glow. Some tubes, such as the familiar fluorescent light tubes, employ heated cathodes, whereas others, such as the neon bulb, do not. Some have auxiliary elements between the cathode and the anode for discharge control purposes (such as the flash tubes), and others do not. The common factor lies in the presence of some selected gas at a predetermined pressure in the envelope containing the electrodes. Both the type of gas and its pressure influence the discharge characteristics of the tube. The gas type and any coatings on the envelope are used to produce light of various colors. Further distinction must be made between a glow discharge and an arc discharge. The neon bulb under normal discharge exhibits glow discharge, whereas the photoflash tube conducts in an arc. It must be noted that if sufficiently high potential is applied to a glow discharge tube, arc discharge will take place, usually resulting in the ultimate destruction of the tube. Glow discharge usually has current measured in milliamperes, whereas arc discharge has current usually measured in amperes.

Figure C-3a shows the qualitative current-voltage relationships for the glow and arc discharges. No attempt to describe the mechanics of the two types of discharges is made here. It should be mentioned, however, that usually the gas discharge tubes operate at reduced pressures, and that ionization potentials of the gases involved, as well as the pressure, the potential applied, and the external resistance (that is, current limiting factors), are some of the most important factors in determining whether or not a discharge is initiated and/or maintained.

One characteristic common to all gas discharge tubes is the fact that they require relatively high potentials to conduct. Because of the wide availability of the popular NE-51 neon bulb, this tube lends itself to investigation of its basic characteristics. For example, the bulb requires about 80 v to "fire" initially, but will continue to conduct down to about 60 v. When this bulb is excited with sinusoidal voltage (oscillating about a value midway between the turn-on

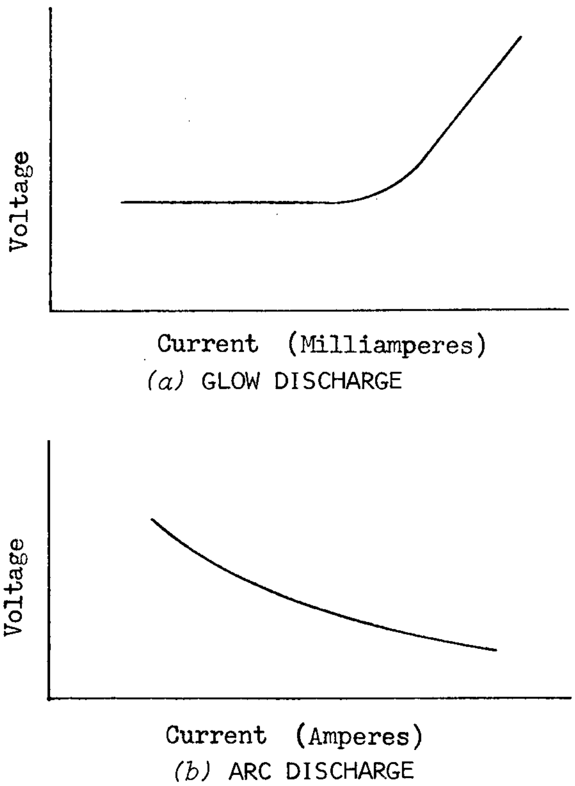


Figure C-3. Generalized current vs voltage relationship for (a) glow and (b) arc discharge.

and turn-off potentials of the particular bulb), the glow fails to extinguish completely for frequencies in excess of about 300 Hz. Figure C-4a shows the lead sulfide detector intensity-time response of the NE-51 bulb being excited at 5 Hz. Figure C-4b shows an oscilloscope plot of intensity versus voltage (Lissajous patterns or plots) across the bulb for the same and other frequencies. Figure C-4c is a composite showing a plot of the current (abscissa) versus intensity (ordinate) for excitations of 5, 10, 50, 100, 200, and 500 Hz. It can be seen that the current does not show a step discontinuity for frequencies of somewhat over 200 Hz. Finally, Figure C-4d shows the bulb response to excitation by a square wave (rather than sinusoidal) at 180 and 360 Hz. It can be seen that the bulb responds quite well at 360 Hz.

Because the light output of the glow discharge bulb is relatively faint, its usefulness as a signal source is at best limited. An arc discharge, on the other hand, can produce a signal of great brilliance. Photoflash tubes, and flash tubes such as those found in strobe lights and the like, are examples of discharge tubes. These generally produce a pulse of only a few microseconds duration but of considerable magnitude. This results in the average power required being of reasonable magnitude.

The voltages required to fire most flash tubes are of the order of several hundred volts. Most employ one or more intermediate electrodes (that is, between the anode and the cathode) which are used for control purposes—that is, to initiate or terminate the discharge.

An example of such a flash tube is the EG&G FX-6B. The duration of its light pulse is of the order of 10 microsec and the required anode-to-cathode potential at least 500 v. It can be fired at up to about 1,000 Hz. The peak light output of this bulb is about 200,000 candlepower (peak output obtainable only at reduced firing rates; at high rates output is correspondingly lower); however, because the pulse duration is so short, the average input power requirement is only 7 watts. The gas used is xenon, and the peak intensity of the flash is in the blue-violet part of the visible spectrum.

Figure C-5 shows the response of the detector to the bulb mentioned as being flashed at the rate of slightly more than 100 Hz. It is worth noting that since the spectral characteristics of this flash tube are much different from those of the neon gas bulb (which glows in the yellow-red part of the visible spectrum), a different basic sensing element was used. More is said of this in the section dealing with basic detectors and in the description of the experimental program (Appendixes A and B).

In price, there is a considerable disparity between glow discharge tubes such as the NE-51 and the flash tubes such as the one previously described. The former are available at a few cents per unit, but the latter cost $10 to $20 each. In addition, both require high-voltage power supplies. The flash tube requires the higher voltage and comparatively more power than the glow discharge tube.

Frequency modulation of either device can be accomplished by various means. An example of a simple way of modulating the gas discharge lamp is a simple relaxation oscillator circuit where the flashing rate is controlled by varying the magnitude of the R and/or C components (Figure C-6a).

Another possible way is to externally vary the voltage across the tube between the turn-on and turn-off potentials of the tube, possibly by mechanical means.

The flash tube is somewhat more complex in that, in addition to the high-voltage supply, it requires a control signal and some additional circuitry to suitably bias the intermediate electrodes. For the tube previously discussed (EG&G FX-6B), this additional circuitry can be had in an integrated form, all components being encapsulated and called a "Lite-pac" by the manufacturer. The components of this trigger circuitry are shown schematically in Figure C-6b. There are four terminals: two for the high-voltage supply (500 v minimum) and the remaining two for the trigger signal, which must be generated externally at a level of about 20 v. Again, any of a number of external means may be used to produce the trigger signal, from mechanical to electronic devices.

In summary, it can be seen that the flash tube may well be useful as a modulated signaling device because of its ability to produce a powerful signal in a considerable range of frequencies. Care must be taken to try to match the emission spectral characteristics of the tube to the sensitivity characteristics of the basic detector element. Thus, for example, the lead sulfide detector is suitable for signals in the red and infrared, but a cadmium selenide is more suit-

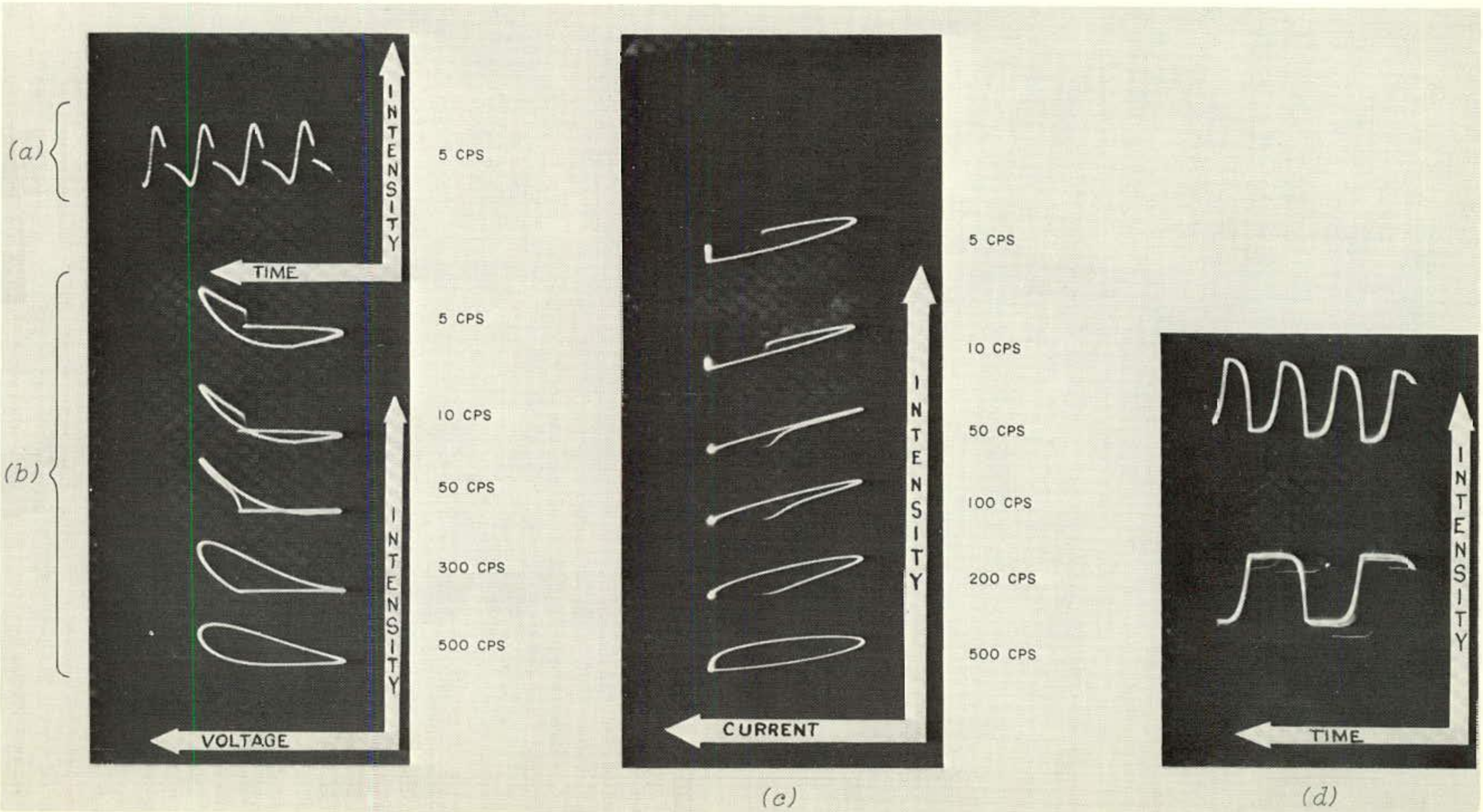


Figure C-4. Response of NE-51 gas bulb (see text for explanation).

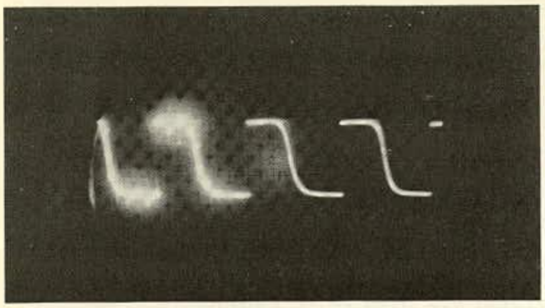


Figure C-5. Response of xenon flash tube.

able for the blue-violet emissions of the xenon tube. On the debit side is the requirement for the rather high voltages, hence the associated power supplies, in addition to the modulating equipment. It must be remembered that in its application as a vehicular signaling device, any electrical or electronic equipment would have to rely either on the auto battery, or on an internal (battery) power supply. The former is 12 v, hence must be stepped up to the required working voltages; the latter runs the risk of faring much like the flashlights carried by many motorists—that is, in the event of an emergency the flashlights turn out to have very "tired" batteries. Extra-long-life batteries are available, of course, but they are quite costly.

It is concluded that the flash tube, though useful as a research or special purpose tool, would not be suitable to widespread application as a simple, reliable, and inexpensive emergency signaling device.

LASERS

A laser is a device performing Light Amplification by Stimulated Emission (of) Radiation and usually is thought of in conjunction with laboratory experimentation, an exotic communications device for space, and sophisticated welding, cutting, and weapons applications. Indeed, much of the research being done on lasers to date has been classified. However, enough information is available pertaining to laser characteristics and capabilities to warrant its consideration for the problem at hand.

Lasers are generally classified into three categories by their "lasing" element—solid state, gas, or junction. The first two types are not believed applicable to the current problem, because of the complexity of the associated equipment necessary and the low-power conversion efficiencies (generally less than 1 percent). They are also required to operate under very low (cryogenic) temperatures.

The junction laser, on the other hand, does warrant consideration. It operates satisfactorily at ambient temperatures—the gallium arsenide injection laser emits radiation of about 9,000Å at about 80 F (about 8450Å at 77 K, or the temperature of liquid nitrogen). It is basically a diode —a P-N junction. It requires no complex "pumping" light (the flash tubes discussed previously are frequently used as "pumping" or excitation lights for gas and solid-state lasers), the primary excitation being accomplished by pulsing the current through the diode. Its power conversion efficiency is quite high, in some cases being as high as 70 percent. The radiation emitted is coherent, but not quite as collimated as that of the two laser types. This is due largely to the small size of the emitting surface. Lenses can be employed for beam shaping. Amplitude modulation at very high frequencies (as high as 200 MHz) has been employed experimentally. Some measurements with pulses of very short duration and short rise times have yielded an apparent cutoff frequency of the laser of about 3 GHz, though the measurements were limited by the silicon photodiode and other electronics equipment used.

The junction laser is compact and rugged; Figure C-7 shows a gallium arsenide laser diode manufactured by Maser Optics, Inc. As far as is known, the device has not been used operationally to date. No quantity production was indicated and the per unit price is still high ($365). However, bearing in mind the phenomenal drop in prices of some transistors of three to five years ago, it is speculated that a price reduction by an order of magnitude may be possible, or if a mass application were found necessitating production in the millions, then maybe even by two orders of magnitude.

The laser's radiation is coherent*—that is, of one frequency—which makes it possible to carefully examine the transmission properties of the transmission medium at that frequency and hence anticipate the attenuation to be expected under any anticipated conditions. Conversely, because temperature plus the elements making up the junction affect the emission frequency, it may be possible to choose these variables so as to correspond to the peak sensitivity of the detector, the attenuation "window" of the atmosphere, and the like. Furthermore, knowledge of this emission band allows for a judicious choice of filters and other associated equipment in a way such as to increase the probability of signal detection and decrease the probability of false alarms—that is, to optimize over-all system performance.

Additional equipment consists of a suitable pulse generator, several of which are also manufactured by Maser Optics, Inc. These pulse generators are special purpose units (pulse widths of 1 microsec, 5 or 10 nanosec; peak current output ratings of 100, 300, and 5,000 amp), and as such are rather expensive as long as they remain substantially laboratory equipment units. However, as in the case of the junction diode, production should allow for considerable price decreases, though no absolute estimate as to the possible ultimate cost can be made at this time.

SOME GENERAL OBSERVATIONS ON MODULATORS

Although the discussed modulated light sources by no means make an exhaustive list of such sources, it is felt that these are the most likely prospects for the signaling application from the automobile to the roadside.

A passing reference has been made to the coherence of laser-emitted radiation. This has been explained as light of

* Ideally, all lasers are supposed to emit coherent radiation. In reality, the injection lasers emit radiation within a narrow band (for the particular junction laser considered here, about 15A), hence are still amenable to all but the most critical applications.

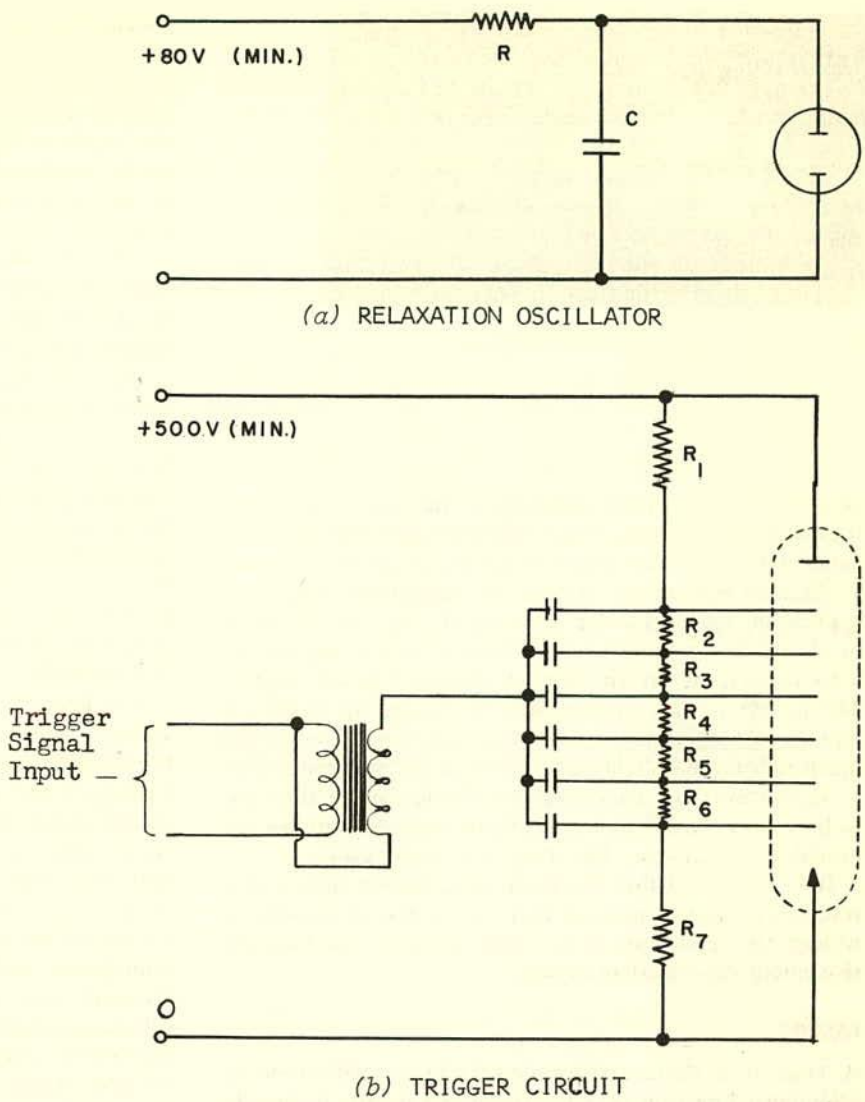


Figure C-6. Frequency modulation techniques.

a single frequency (or in the range of the visual spectrum as of a single color). This should not be confused with the term "monochromatic," because though coherence necessitates monochromatic properties, the reverse is *not* true.

A great deal can be accomplished with filters, lenses, masks, hoods, reflectors, and other passive means, on both the source and the detector. All of these can be applied as necessary to enhance the operating characteristics of a particular system. Care must be taken, however, not to negate the intended improvement by a concurrent negative effect. For example, a baffle or hood tends to restrict the field of view of the device (transmitter or receiver); it also makes the device more directional, hence more difficult to align, place, and the like. A filter may enhance the signal-to-noise ratio of a system by attenuating unwanted frequencies more than the signal frequency, but the latter will also be attenuated. Likewise, a lens will increase or decrease the field of view, magnify or reduce as necessary,

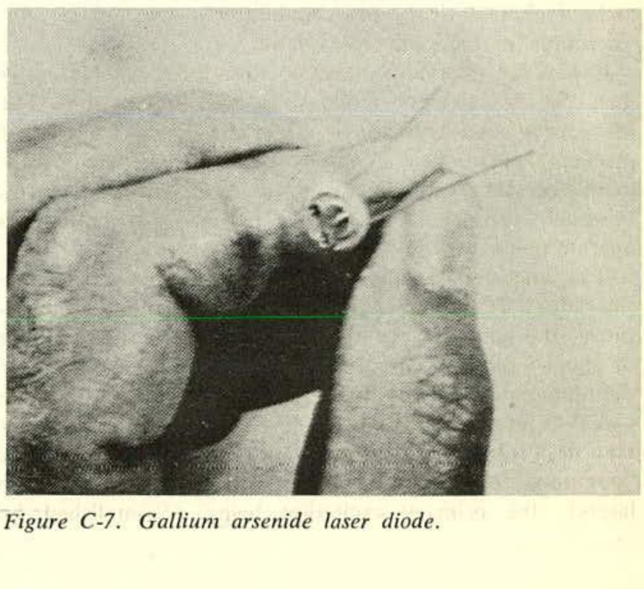


Figure C-7. Gallium arsenide laser diode.

but also offer some signal-level attenuation. Whereas a highly directional device is desirable where the direction of the transmission is predictable and subtends but a small angle, an omnidirectional device is indicated for situations where this is not true.

At the beginning of this appendix the basic requirements for any potential system were stated as being explicitly dependent on the driver's willingness to acquire the system on the basis of the implicit criteria of cost, simplicity, and reliability. It must be kept in mind that the system reliability must include not only elements of the signaling device itself, its associated equipments, power supply, and the like, but also those elements of the detection devices and their operational characteristics, and ultimately the aid rendering effort. The driver who signals for aid cares little how his signal is received and processed. All he wants to know is that the requested aid is forthcoming. If he can count on receiving such aid in a reasonable time, he will consider the system reliable and worthwhile. If not, then obviously the detection system has no future.

The cost and simplicity aspects pertain to the modulator and its associated equipments because the driver must pay for and maintain the same. The same criteria must be applied to the detection hardware, but not for the same reason.

APPENDIX D

REDUCED VISIBILITY—FOG

In the preceding appendixes, the various aspects of the proposed system concept have been discussed in general, and some specifically possible system elements have been discussed in particular. It becomes apparent that there are numerous means of achieving a working system concept. Because the concept itself is in a rather embryonic stage, an effort should be made to find what the optimum configuration might be for the accomplishment of the desired objectives.

These objectives have not as yet been specifically outlined; however, some partial objectives or problem areas become apparent almost immediately. One of these is the effect of adverse atmospheric conditions. This appendix outlines some of the groundwork for the effects of such atmospheric conditions, and in particular, that of fog.

A rather broad spectrum of operating frequencies is available with the equipments described earlier. Within this spectrum, numerous different phenomena occur according to the exact frequency at which the equipment is operating. The new laser devices permit the selection of virtually a single frequency rather than a broad band of frequencies as with conventional devices. This characteristic alone makes all the old concepts obsolete and forces a new analysis of the problem.

It is quite apparent that one objective of the system is for reliable operation regardless of atmospheric conditions. Therefore, the available spectrum must be studied and its characteristics examined. First, it is necessary to resolve any misunderstandings that may arise as a result of the terminology used.

TERMINOLOGY

In describing the effects of a medium upon radiation, there are a host of related terms that are used to designate the same phenomenon. In optics, the electric field vector and the intensity are related by

$$I \propto \epsilon^2 \qquad \text{(D-1)}$$

Thus, it is possible to refer either to the intensity or to the electric field vector and describe the same phenomenon.

Figure D-1 shows a representation of the problem under discussion. Assume there is a block of atmosphere perpendicular to the incident radiation, ϵ_i. A portion of this radiation will be reflected, ϵ_r, a portion absorbed, ϵ_a, a portion scattered, ϵ_s, and the remainder transmitted, ϵ_t. By Eq. D-1, a similar representation can be achieved by means of the intensities. Thus, the following relationships can be formed between the various quantities:

Reflectance or reflectivity $= I_r/I_i$
Transmittance or transmissivity $= I_t/I_i$
Absorptance or absorptivity $= I_a/I_i$
Reflection coef. $= \epsilon_r/\epsilon_i$
Transmission coef. $= \epsilon_t/\epsilon_i$

It is apparent that the larger the volume of the medium in the x direction, the greater the absorption and scattering. Therefore, the length of path must be taken into account. If the energy or intensity is incident upon a unit of area, it is referred to as "irradiance." The loss of irradiance in passing through the block of atmosphere is

$$dI = I_i - I_t \qquad \text{(D-2)}$$

There is a constant, σ, that relates the amount of loss per unit length; that is, σ is the attenuation or extinction coefficient or optical density per unit length. Thus,

$$\frac{dI}{I} = -\sigma\, dx \qquad \text{(D-3)}$$

which is known as Beer's Law. From Figure D-1, it is

apparent that σ is caused by two phenomena—absorption and scattering. Therefore,

$$\sigma = \alpha + \beta \qquad \text{(D-4)}$$

in which α is the absorption coefficient and β is the scattering coefficient.

Integration of Eq. D-3 gives

$$I_t = I_i \, e^{-\sigma x} \qquad \text{(D-5)}$$

If a similar approach is taken for the ϵ vector, an analogous factor to σ is K, which is the absorption constant.

It should not be assumed by this description that the terminology of the field is at all solidified. The terms used are merely a general concensus of most authors. Authors will, in general, be talking about one of the previous relations. It may seem at this point that the scientist has taken every combination of variables available to him, but this is unfortunately not true.

The rather innocent looking factors of σ and e in Eq. D-5 can be further manipulated by

$$\log_{10}(e) = 0.43429 \qquad \text{(D-6}a\text{)}$$

or

$$e = 10^{0.43429} \qquad \text{(D-6}b\text{)}$$

Substitution of Eq. D-6 in Eq. D-5 gives

$$I_t = I_i \, 10^{-0.43429} \qquad \text{(D-7)}$$

Many people define optical density per unit length as equal to 0.43429σ. Finally, results may be normalized to some value or designated as relative. Here, care must be taken as to what value has been chosen as reference.

GENERAL FACTORS OF ATMOSPHERIC ATTENUATION

The problem of electromagnetic penetration of the atmosphere is dependent on factors of both the atmosphere and the radiation. The primary means of attenuation for light under normal atmospheric conditions is by absorption. The particular gases that absorb this radiation depend on the spectrum that is of current interest. For this particular work, interest is in the visible and infrared (IR) range. The visible spectrum extends from about 0.3 to 0.7 microns. The IR spectrum is divided into two regions—the near IR (0.7 to about 15 microns) and the far IR (15 to about 100 microns). None of these limits is rigorously defined, but these general ranges are quite common.

For the range of interest, the primary gases for absorption of radiation are ozone, O_3, carbon dioxide, CO_2, and water vapor, H_2O. The absorption spectra are shown in Figure D-2. It might be best to clarify at this point the difference between precipitable H_2O, or water vapor, and precipitated H_2O. Precipitable H_2O is that water in the atmosphere that could be precipitated. Its concentration is commonly measured in terms of relative humidity at fixed temperature. This is the component of H_2O in the atmosphere that leads to absorption. The water that does precipitate creates the mist or fog and generates what is known as Mie scattering.

Water enters into both of the major components of attenuation in the atmosphere, absorption and scattering.

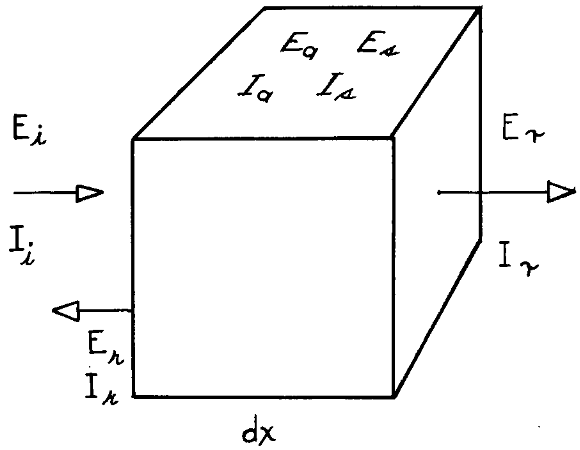


Figure D-1. Elemental volume of transmitting medium.

Until H_2O precipitates the absorption phenomenon dominates as the means of attenuation. As the precipitated H_2O increases, the scattering phenomenon dominates. The characteristics of the scattering depend on the size of the scattering particles and the wavelengths of the radiation. Water is not the only precipitate that will cause scattering. In many industrial areas particles of dust from the industrial processes will cause atmospheric scattering (and absorption). These particles, in general, are smaller than the precipitated H_2O particles.

The preceding discussion has been qualitative. In the following, an attempt is made to be more quantitative, dealing first with scattering.

VISIBILITY IN FOGS

Visibility generally refers to the ability of a human to perceive an object. This in general depends on many factors, as explained by Middleton (*1*). Therefore, the numerous ways of expressing visibility and its parameters are examined to see what they mean in relation to the problem under study.

Spencer (*2*) has investigated the problem of fogs on turnpikes. In his analysis, he uses the attenuation coefficient as the definition of fog severity. He maintains that this is possible due to an earlier article (*3*), in which he shows that fogs all have a similar scattering function. Implied in this argument is the fact that the predominant means of attenuation is scattering and not absorption. This is true for fogs of sufficiently large particle size and densities. One point that is not brought out is the dependence of Mie scattering upon frequency.

Apparently his results are for an effective attenuation factor for white light, which covers the entire visible spectrum. This does not say what the results would be for a narrow spectrum system. His results are, however, indicative of human sight.

According to Spencer, the definition of visual range is the distance at which transmissivity decreases to 0.05. This definition does not permit an increase of source intensity to

increase visual range. He apparently draws his definition from a meteorological one wherein this factor reduces the contrast sufficiently so that detection is not possible. This definition of visible range as it relates to optical density is shown in Figure D-3, together with Spencer's definition of thick, moderate, and light fog.

It is obvious from experience that the denser the fog, the greater the amount of water in the fog. Houghton and Radford (*4*) have shown the experimental relationship of visibility and water content. Their results are shown in Figure D-4a. It is not possible to exactly relate the visible range definition of Figures D-3 and D-4a because of their

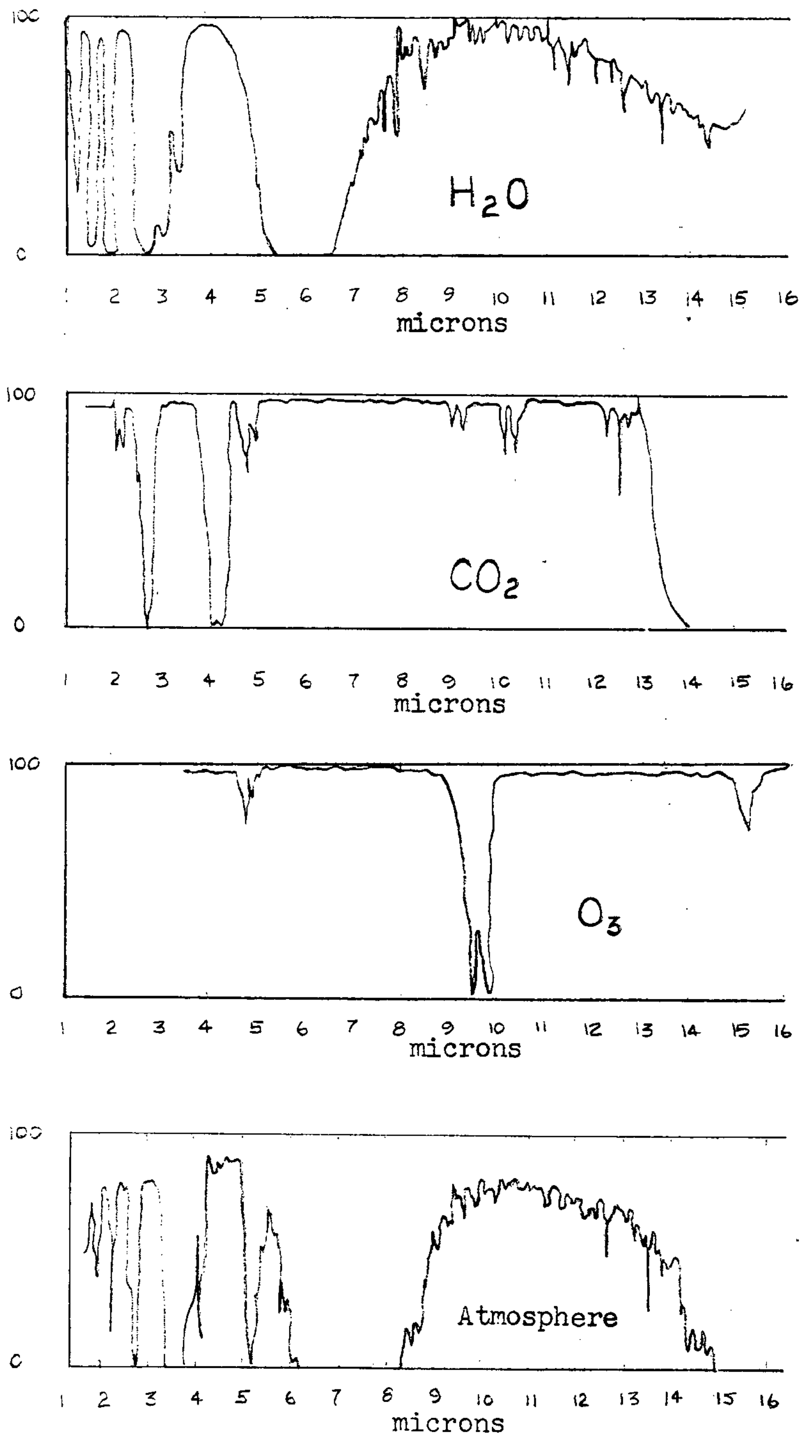


Figure D-2. Absorption spectra.

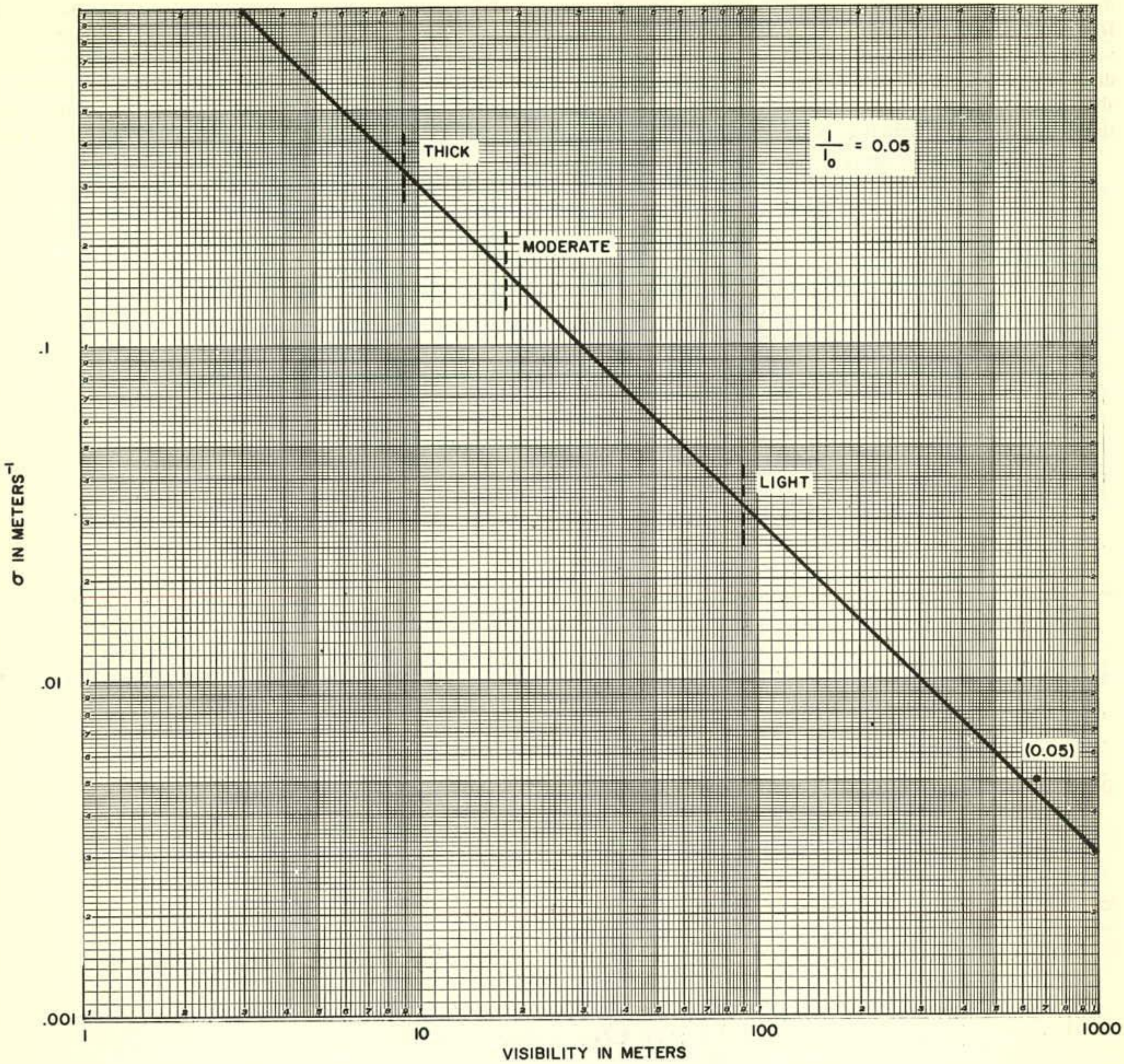


Figure D-3. Visible range related to optical density.

dissimilar bases. The foregoing has presented the variation of visibility with two parameters—σ and the volume of precipitated water, w. Work has been done by Kurnick et al. (*5*) that relates these parameters in an apparently good theory. This work is based on a theory of particle size distribution, derived by Junge (*6*), which appears to be quite reliable for most purposes and states that the number of particles of radius r is

$$n(r) = Cr^{-p} \qquad \text{(D-8)}$$

in which C and p are constants.

Following the work of Kurnick et al., it can be said that if $r_0 << r_1$, where r_0 is the smallest value of r in Eq. D-8 and r_1 is the largest,

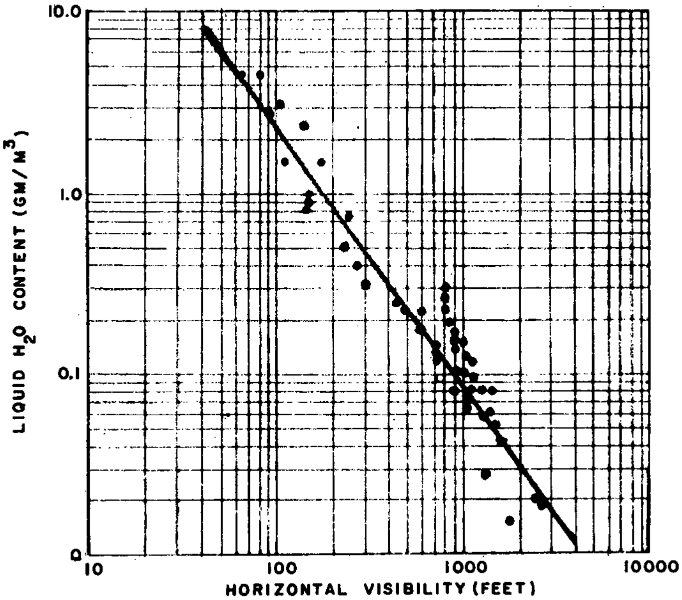
$$w = \frac{4\pi\, C\, r_1^{(4-p)}}{3\,(4-p)} \qquad \text{(D-9)}$$

The same paper goes on to show that

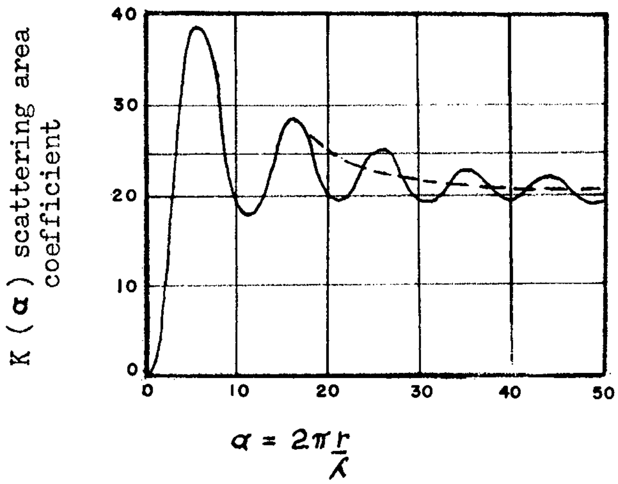
$$\sigma = C\,\pi\,\lambda^{(3-p)} \int_{r_0/\lambda}^{r_1/\lambda} a^{(2-p)}\, K\,(a)\; da \qquad \text{(D-10)}$$

in which

$a = r/\lambda$; and
$K =$ scattering ratio.



(a)



(b)

Figure D-4. Visibility vs H_2O content of atmosphere (left) and variation of scattering coefficient (right).

Eqs. D-9 and D-10 show that the distribution of particle size determines both w and σ. There are two variables (C and p) in the distribution function; therefore, if w and σ are known, C and p can be determined from Eqs. D-9 and D-10.

The data from Figures D-3 and D-4a can be used to define w and σ as functions of visibility. Thus, solving Eq. D-9 for C gives

$$C = \frac{3\, w\, (4-p)}{4\, \pi\, r_i\, (4-p)} \qquad \text{(D-11)}$$

Substituting this in Eq. D-10 gives

$$\sigma(\lambda) = \frac{3\, w\, (4-p)}{4\, r_i\, (4-p)} \int_{r_o}^{r_i} r^{(2-p)}\, K\left(\frac{r}{\lambda}\right) dr \qquad \text{(D-12)}$$

Eq. D-12 is in terms of $\sigma(\lambda)$, because the scattering coefficient is a function of λ, the wavelength of the radiation. The σ's given in the visibility data are averages over the visible spectrum; therefore,

$$\bar{\sigma} = A \int_{\lambda_0}^{\lambda_1} \sigma(\lambda)\, d\lambda = A \int_{\lambda_0}^{\lambda_1} \int_{r_0}^{r_1} r^{(2-p)}\, K\left(\frac{r}{\lambda}\right) dr\, d\lambda \qquad \text{(D-13)}$$

in which

$$A = \frac{3\, w\, (4-p)}{4 r_i^{(4-p)}\, (\lambda_1 - \lambda_0)} \qquad \text{(D-14)}$$

The remaining problem is to define $K(r/\lambda)$. This function is extremely complex in form; however, the interest is in its general, smoothed shape. Houghton and Chalker (*7*) have shown some of the fine structure of K for the range of interest here, and a smoothed approximation is given by Van de Halst (*7*). The smoother function is shown in Figure D-4b. This function can be approximated by

$$K(a) = 3.9\, \frac{a}{\sigma}\, [u_{-1}(a-6)] + u_{-1}(a-6) \left\{ 2 + e^{(a-6)/12.7} \left[0.9 + \cos \frac{\pi(a-6)}{5} \right] \right\} \qquad \text{(D-15)}$$

Substituting Eq. D-10 in Eq. D-9 and dividing through by w gives

$$\frac{\bar{\sigma}}{w} = A^1(p)\, I(p) \qquad \text{(D-16)}$$

in which $A^1(p) = A/w$; and $I(p)$ represents the double integral in the right-hand side of Eq. D-13.

By using the definition of horizontal visibility and Beer's Law, $\bar{\sigma}$ can be obtained as a function of visibility. The work of Radford (*4*) gives w as a function of horizontal visibility. Therefore, inserting these definitions and experimental results in Eq. D-16 indicates how the parameter p in Junge's distribution (*6*) varies with visibility. A computer program was written to evaluate $A^1(p)\, I(p)$ from the foregoing equations. The results are shown in Figure D-5.

From Radford's work (*4*), the following is derived:

$$w\, v^{1.431} = 8.84 \times 10^4 \qquad \text{(D-17)}$$

in which

w = liquid H_2O content, in gm/m^3; and
v = visibility, in meters.

Spencer's definition and Beer's law give the relationship

$$0.05 = e^{-\bar{\sigma} v} \qquad \text{(D-18)}$$

or

$$\bar{\sigma} v = 3 \qquad \text{(D-19)}$$

Combining Eqs. D-16, D-17, and D-19 gives

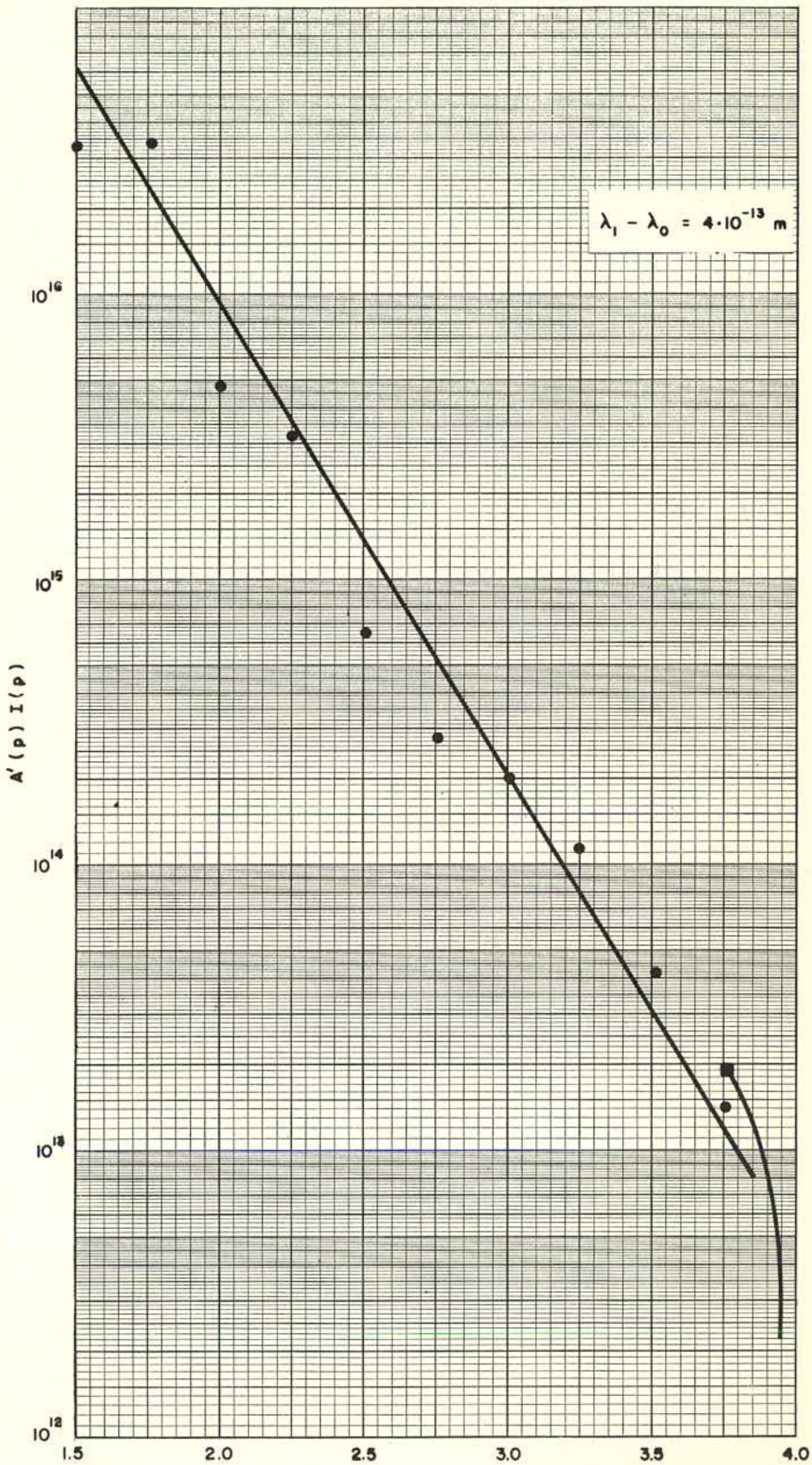


Figure D-5. Parameter P *of Junge distribution vs* A′(p) I(p).

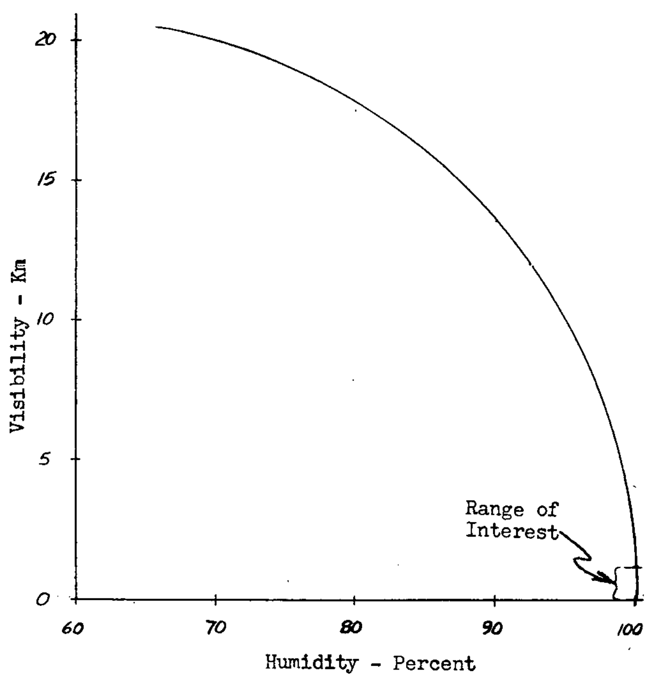


Figure D-6. Visibility in kilometers vs percent humidity.

$$\frac{\bar{\sigma}}{w} = 3.39 \times 10^{-5}\, v^{0.431} = A(p)\, I(p) \qquad \text{(D-20)}$$

Eq. D-20 and Figure D-5 indicate that the parameter, p, is for all practical purposes for the type of visibility problems under consideration here. Therefore, one of the parameters of the Junge distribution has been determined.

The indications are that C is the parameter that produces the fog characteristics of interest.

Insertion of the value $p = 4$ in Eq. D-9 gives an indeterminate value. By L'Hopital's rule, in the limit as p goes to 4,

$$w = \frac{4\pi}{3} \log (r_1)\, C \qquad \text{(D-21)}$$

These results do not appear to be unlikely in comparison with other researchers' data. Figure D-6, showing the relationship of visibility and percent humidity, indicates that the range of interest corresponds to a very small change in humidity.

The parameter of visibility is much more meaningful than is liquid water content. Therefore, Eq. D-21 is modified by Radford's results (Eq. D-17) to obtain

$$C = \frac{2.09 \times 10^{3}}{v^{1.431} \log (r_1)} \qquad \text{(D-22)}$$

Now the variation of σ with v can be found by substituting Eq. D-18 in Eq. D-3, or

$$\sigma(\lambda) = \frac{6.56 \times 10^{3}}{v^{1.431} \log (r_1) \lambda} \int_{r_0/\lambda}^{r_1/\lambda} \frac{K(a)}{a^2}\, da \qquad \text{(D-23)}$$

which shows the advantages of a longer wavelength for fog penetration. Assume that r_0 is sufficiently small so that the lower limit can be assumed to be zero. The upper limit varies inversely as λ, and because the integral is monotonically decreasing with λ, as λ increases σ decreases due to the $1/\lambda$ factor as well as a decreased value of the integral.

It can be shown that σ varies inversely as λ^2 for large values of r_1. This means that increasing the wavelength from 0.3 to 3 microns would give a decrease in optical density by a factor of 100. This is an upper limit to the amount of improvement that can be obtained; however, practical values should come close to this limit.

APPENDIX E

DESCRIPTION OF SYSTEM

TRANSMITTER

The purpose of the transmitter is to radiate a pulse of infrared energy each time it is triggered. The infrared source is a pair of General Electric LED-11 gallium arsenide infrared light-emitting diodes. The diodes are operated at ambient temperature and emit 250 mw of power each at a peak wavelength of 0.897 micron when driven by a 1-μsec, 70-amp pulse at 200 pps.

The transmitter unit (Fig. E-1) consists of an oscillator, a modulator, and two infrared emitter diodes. The oscillator determines the frequency of the radiated infrared pulses by supplying the basic system timing. The modulator consists of a trigger circuit and a reset circuit.

The oscillator fires the trigger circuit and reset circuit simultaneously. The reset circuit generates a pulse which prevents the B+ voltage from charging storage capacitors C2 and C5 for a period of 200 μsec. The trigger circuit generates a 0.5-μsec trigger pulse, which fires SCR CR2 and CR7. The SCR's act as switches, which allow the charge stored on capacitors C2 and C5 to discharge through the infrared

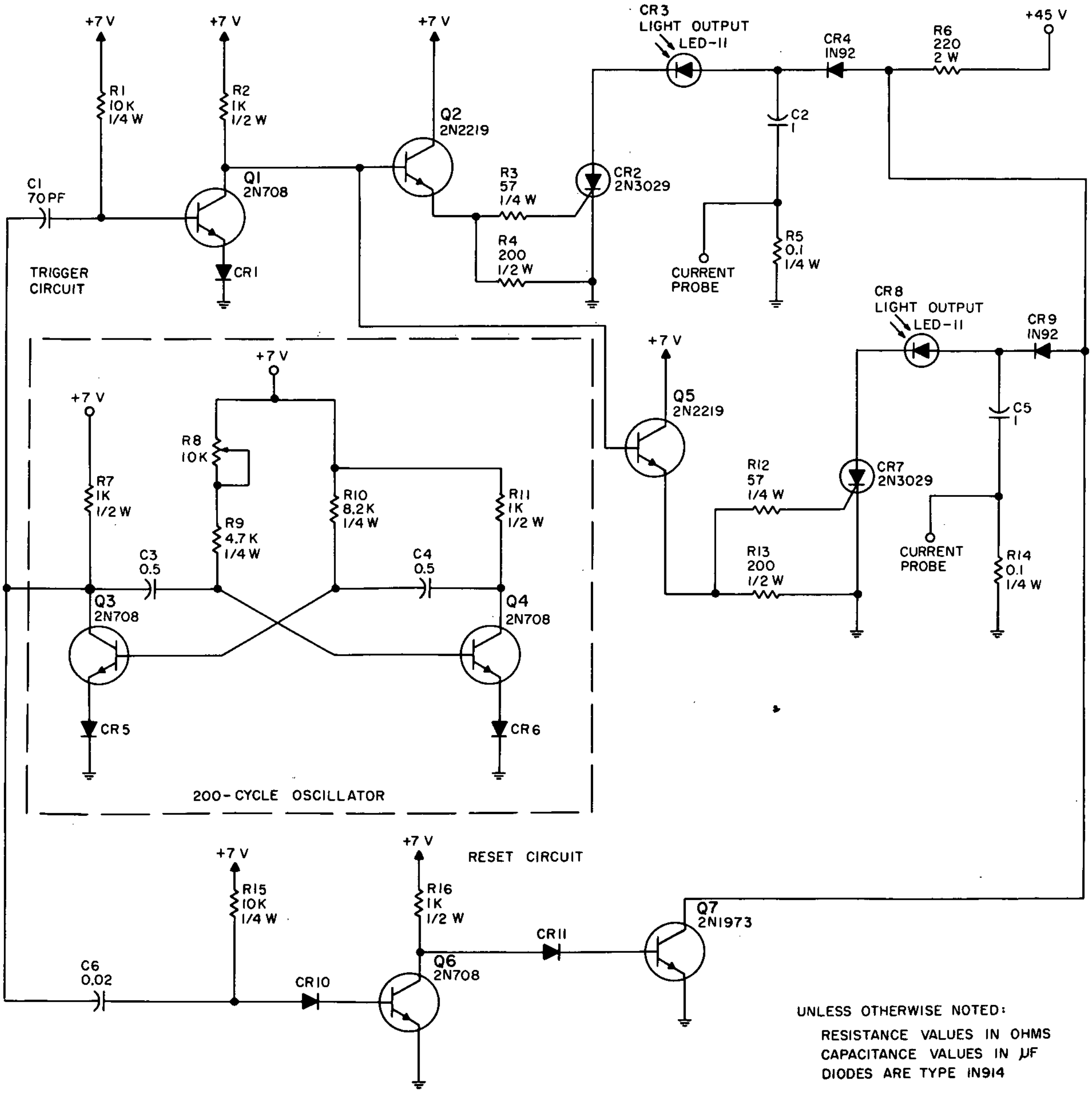


Figure E-1. Infrared transmitter, schematic diagram.

emitting diodes CR3 and CR8 to ground. This takes approximately 1 μsec, and causes CR3 and CR8 to emit a pulse of infrared light. Because the reset circuit prevents any more current from being supplied to capacitors C2 and C5 for 200 μsec, the charge on C2 and C5 drops to zero, causing switches CR2 and CR7 to open. At the end of the 200-μsec reset pulse, the B+ voltage is allowed to recharge the capacitors in preparation for the next cycle. This procedure is repeated at the oscillator frequency.

RECEIVER

The function of the receiver is to detect, amplify, and generate a usable signal for each of the infrared pulses received from the transmitter. The infrared detector diode is an Electro-Nuclear Laboratory Type 601-10D photovoltaic silicon optical detector. The silicon surface is completely passivated, permitting wide-angle operation in air without any intervening windows. The spectral response of the detector is 0.85 micron peak and the active area is 10 mm in diameter.

The receiver unit, shown schematically in Figures E-2 and E-3, consists of the infrared detector diode, an amplifier, and a signal indicator circuit. A Texas Instruments SN777 solid circuit semiconductor low-level audio amplifier is used. The frequency response of this amplifier is from 20 Hz to 10 kHz and the voltage gain is 72 db. The signal indicator is an auxiliary circuit used for monitoring or demonstration purposes. It consists of a monostable multivibrator and a light driver circuit.

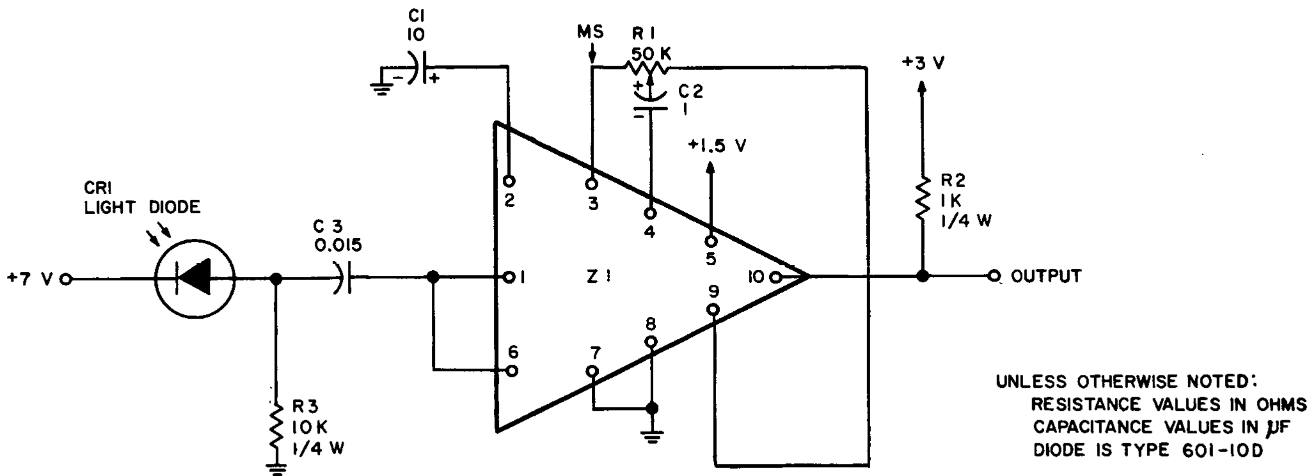


Figure E-2. Infrared receiver, schematic diagram.

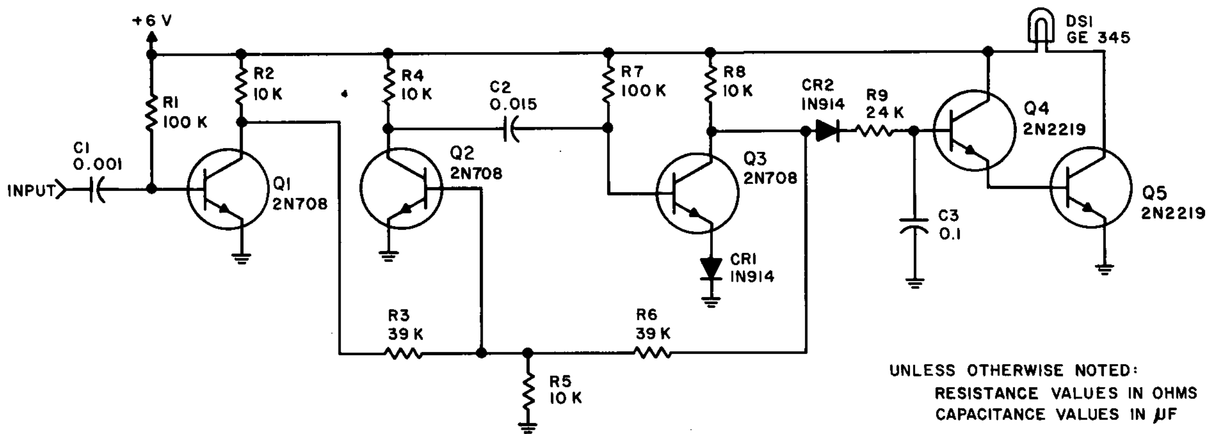


Figure E-3. Signal indicator, schematic diagram.

The pulses of infrared energy impinging on the active area of the detector diode cause current to flow through the diode. The resulting current pulse is amplified and coupled to the signal light indicator, causing the bulb to be energized. The bulb will remain energized as long as pulses are received. When no more pulses are received, the bulb is extinguished.

OPTICS

Optical devices are required in both the transmitter and the receiver in order to obtain both range and field of coverage. The transmitter uses an AR-400 beam shaping reflector manufactured by the Amglo Corporation. This reflector is designed to give a 40° total beamwidth. The infrared emitter diodes mounted in the reflector are operated with their focusing lenses removed, which results in a 6-db increase in available power from the diodes and also permits the reflector to shape the beam properly.

The receiver uses a 6-in. diameter radius-type mirror, which reflects the light that impinges on it to its focal point 1⅞ in. out on its axis. A Schott infrared filter and the receiving diode are mounted at this point. The Schott filter is Type RG-10, has a ⅝-in. diameter, and is 3 mm thick. The internal transmittance is 99 percent between 0.87 and 1.60 microns, which brackets the transmitter peak wavelength of 0.897 micron. The infrared filter is effective in eliminating spurious signal indications due to light pulses at other wavelengths. Figure E-4 shows how the spectral response of the system is narrowed down to the desired pass band.

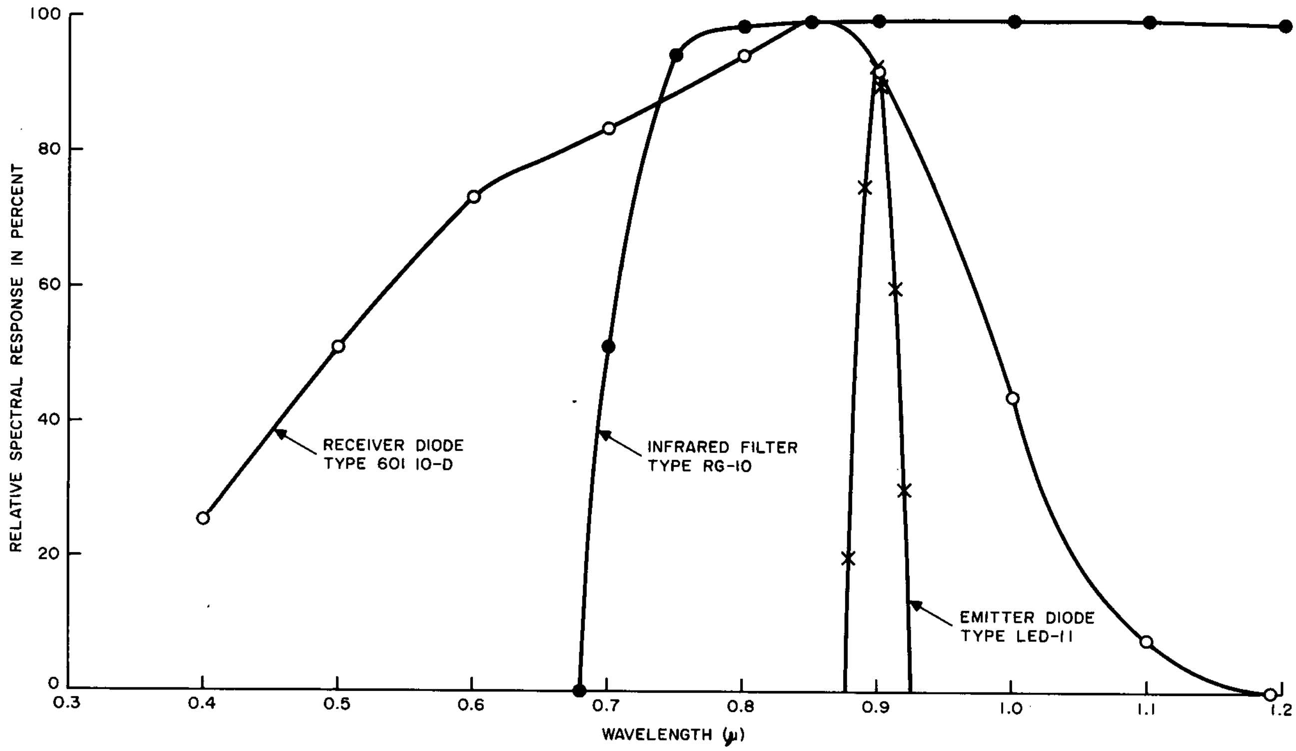


Figure E-4. Spectral response of system.

APPENDIX F

LIGHT-EMITTING DIODES

This appendix discusses the investigation of solid-state infrared light-emitting devices and pertinent aspects to be considered for the application studied in the current project.

The family of light-emitting diodes, LED-9, 10, and 11, manufactured by General Electric, were investigated. These are gallium arsenide light-emitting diodes designed to produce noncoherent radiation at 300 K(25 C). The LED-11 is the same as the LED-10 except that the lens cap is removable. The ratings on the LED-11 are based on the cap removed.

These diodes emit infrared light, peaked at a wavelength of 0.8975 micron, when current is passed through the diode. If the current is applied in pulses (in this case a 1-μsec pulse width, 200 pps), the output will be pulses of infrared light. The higher the input current pulse, the higher the output power of the light pulse will be. This is limited by the maximum power dissipation of the device.

The output of the LED-9, with a maximum allowable 10-amp pulse input at 25 C ambient temperature, is 8 mw. This output is too low for the application studied. The output of the LED-10, with a maximum allowable 70-amp pulse input at 25 C ambient, is 125 mw. The output of the LED-11, under the same conditions but with the lens cap removed, is 250 mw. The difference in output levels is due to lens cap attenuation. The function of the lens cap is to concentrate the infrared energy into a beam of approximately 16° total width. Without the lens cap, the infrared energy is spread over a beam width of approximately 160°.

To obtain maximum efficiency, the LED-11 with lens cap removed was selected for use in the system. For beam shaping, a 40° total beam width reflector is employed.

APPENDIX G

LIGHT-DETECTOR DIODES

This appendix discusses the investigation of light-sensing devices and pertinent aspects to be considered for the application under study.

SD-100 PHOTODIODE

The SD-100 silicon photodiode is manufactured by Edgerton, Germeshausen and Grier, Inc. Relative spectral response is from 0.35 to 1.13 microns, peaked at 0.94 micron. The relative spectral response at 0.8975 micron (transmitter wavelength) is 95 percent, which is quite acceptable. This diode is packaged in a TO-5 case, which has a lens aperture of 0.12-in. diameter and uses Corning 7052 glass. The diode active area is 0.011 sq in. Maximum angular coverage of the diode is 44° to either side of centerline. This coverage is determined by the geometry formed by the lens diameter opening and the distance between the diode and the lens. The importance of the angular aperture of the diode is shown in Figure G-1.

601-5D AND 601-10D PHOTODIODES

The 601-5D and 601-10D photodiodes are manufactured by Electro-Nuclear Laboratories, Inc. Their relative spectral response is from 0.4 to 1.4 microns, peaked at 0.85 micron. The relative spectral response at 0.8975 micron is 92 percent, which is acceptable. The active area of the 601-5D diode is 5-mm diameter and for the 601-10D diode is 10-mm diameter. The diode surface is passivated, permitting wide-angle operation in air without intervening windows. The angular aperture of the 601-5D diode is 70° and of the 601-10D diode is 76°.

Figure G-1 shows the effect of the diode aperture angle on the optical system. For clarity, only the SD-100 and 601-10D diodes are compared. The relatively narrow aperture of the SD-100 reduces the effective diameter of the mirror to 3⅛ in., or 7.75 sq in. of reflecting surface. The 601-10D diode uses the full 6-in. mirror diameter, or 28.4 sq in. of reflecting surface. The coverage improvement factor of the wide-angle aperture diode versus the narrower-angle aperture is approximately three times in width and two times in range.

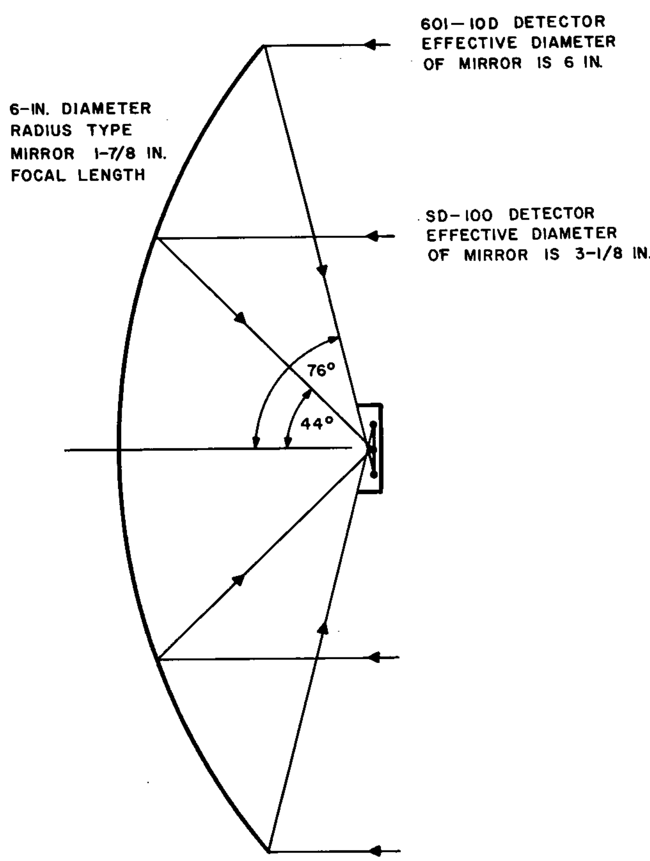


Figure G-1. Effects of diode aperture angle on optical system.

APPENDIX H

FIELD TEST EVALUATION

The design and development work discussed elsewhere in this report was supplemented by experimental tests both in the laboratory and in the field. Many of these tests were to investigate and verify theories and their practical application to the vehicle detection system. Tests pertaining to over-all system performance are discussed here.

The purpose of pattern tests is to determine the coverage pattern of the system. The test conditions are that the

receiver will remain fixed while the transmitter is moved at right angles across the field of view of the receiver at various ranges. The optical axis of the transmitter is maintained parallel to the optical axis of the receiver as the pattern cross-cuts are made. The point at which reliable signal reception ceases is marked and the distance to the receiver centerline is measured and recorded. This procedure is repeated at various ranges on both sides of the receiver centerline. The recorded data are then plotted and coverage patterns similar to those shown in Figure H-1 result. These patterns are repeatable and have been made under the varied conditions of rain, drizzle, haze, and bright sunlight with no apparent deterioration of system performance.

Figure H-1 is a composite plot of the coverage patterns using three different receiver diodes. Pattern 1 was made using the SD-100 photodiode, which has a total aperture of 88°. Pattern 2 was made using the 601-5D photodiode, which has a total aperture of 140°. Pattern 3 was made using the 601-10D photodiode, which has a total aperture of 152°. These patterns illustrate the improvement in coverage patterns obtained by using a diode whose aperture is capable of utilizing the full reflective surface of the mirror in the receiver (Fig. G-1).

The patterns also illustrate the theorem that system range will vary directly with mirror diameter. This is because doubling the range will reduce the received power by a factor of 4. However, doubling the mirror diameter increases the reflective area by a factor of 4, which makes up for the signal loss due to doubling the range. This means that if the receiver mirror in this system was increased to 12-in. diameter and the focal length was increased to 3¾ in., the range of the system using a 601-10D photodiode would be increased to approximately 1,500 ft. This increased range would be realized without any changes in the system electronics.

APPENDIX I

RECEIVER LOCATION

This appendix discusses the optimum roadside location of the receiver in order to achieve maximum coverage of the roadway and shoulder using the least number of receivers per mile.

The coverage pattern of the engineering model using the 601-10D diode detector shown in Figure H-1 shows an over-all range of 750 ft and a beam width of 9°. The maximum pattern width is 60 ft, which is attained at 400-ft range. Examination of the pattern shows that it can be fully utilized if the receiver is mounted on the shoulder of the road and skewed toward the road.

Figure I-1a shows the coverage pattern superimposed

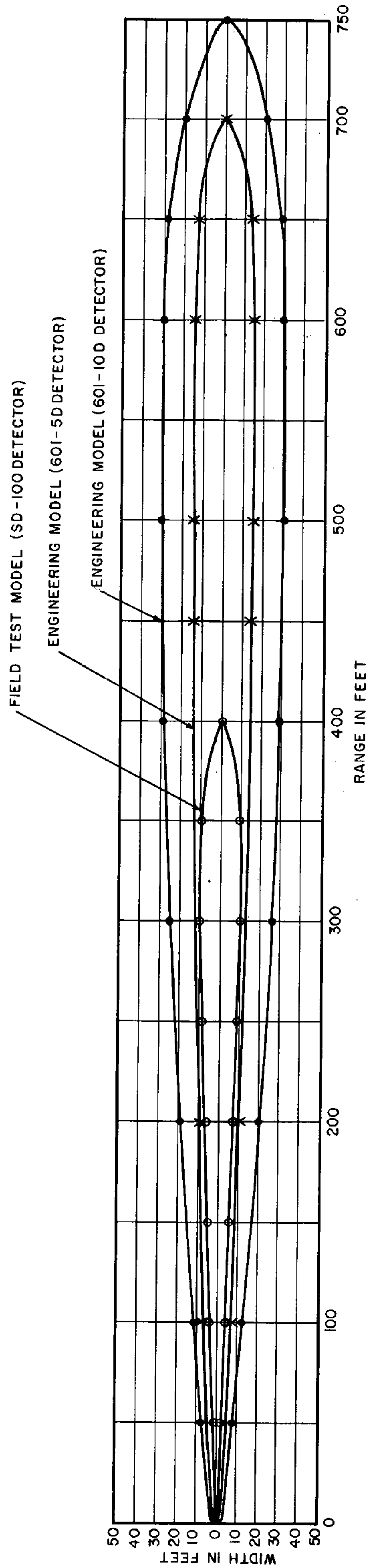


Figure H-1. System coverage patterns composite.

over a 35-ft wide roadway and a 15-ft shoulder. The receiver is located on the shoulder, 10 ft from the edge of the road. The receiver centerline is then skewed 3° toward the roadway, from a sighting parallel to the roadway. This arrangement leaves a triangular area from 0 to 300 ft, and a second triangular area from 500 to 750 ft without coverage. These areas will be covered by the location of successive receivers.

Figure I-1b shows the location of successive receivers, and how they complete the coverage requirements. This arrangement uses a 500-ft separation between receivers; there is a small area of overlap of receiver pattern, which is unavoidable. A stopped vehicle in this area would activate both receivers; however, it would still be located to within 500 ft.

This arrangement covers the case of a straight section of roadway, but the same analysis would apply to curved sections. In the case of curved roadway sections, it might be necessary to vary the receiver separation to obtain proper system coverage.

Elevation of the receiver is related to elevation of the transmitter. Ideally, both should be at the same elevation. However, a ± 5-ft differential can be tolerated at 5-ft range. If the receiver is mounted at an elevation of 6 ft, it can receive signals from a transmitter whose elevation can range between 1 ft and 11 ft. This allows for a broad scope of transmitter heights to accommodate both cars and trucks. However, the transmitter should also be mounted at an elevation as close to 6 ft as possible. The elevation angle of the transmitter should be 0°. The elevation angle of the receiver should be parallel to the roadway surface.

This arrangement will satisfy the coverage requirements imposed by the various grades on a road, because the receiver is fixed parallel to the road grade and the mobile transmitter is adjusted to the road grade by the vehicle. Thus, the transmitter will illuminate the receiver despite the grade.

APPENDIX J

SUGGESTED FUTURE RESEARCH

Several potential research areas have become evident as a result of this study. These are outlined as follows:

1. Application and Cost Analysis Program. This study would obtain current data on the frequency and nature of disabled vehicles on various types of roads, and the extent of the motorist inconvenience involved. From these data, criteria would be developed for the intelligent determination of the best type of disabled-vehicle detection system to use on different classes of roads with different traffic densities.

This determination would be made on an economic and motorist derived benefit basis. It could indicate that a patrol vehicle, at a given patrol frequency, is quite adequate for a rural road with a low ADT. A rural road with a moderate ADT might best be served using the "cooperative motorist" technique to compliment the patrol vehicles. An urban road with a high ADT might require the more sophisticated infrared detection system outlined in this report.

The study could also serve as an evaluation yardstick to help determine how much money the individual motorist might be willing to invest in motorist aid devices, considering the benefits derived.

2. Motorist Aids Using Infrared Techniques. This program would investigate the application of infrared techniques to other motorist aid devices. One phase of the program would study the feasibility of incorporating into the infrared disabled-vehicle detection system a tailgate warning device that would measure headway and closing rate and initiate a warning to the driver when a dangerous situation is impending.

Another phase of the program would investigate the possibility of establishing an infrared communication link between the roadside and the vehicle. A central control station, receiving information from patrol cars concerning road and traffic conditions ahead, could advise approaching vehicles, via roadside transmitting units, of these conditions and the recommended maximum safe speed. It could also transmit lane clearance messages to facilitate the movement of emergency vehicles or service vehicles. These messages would be pulse coded, and when received would actuate appropriate message indicators in the vehicle. The message could be projected onto a portion of the windshield so that the driver would not have to divert his eyes from the road in order to read it. The message would be displayed continuously until it is changed or erased by the central control station. This gives maximum assurance that the driver will be aware of, and understand, the message.

3. Field Tests. The results of the infrared disabled-vehicle detector development program indicate that the system is technically feasible. The next phase of the program would be a full-scale test under actual operating conditions. A section of toll road could be an appropriate test facility. Roadside receivers would be installed, and mobile transmitters issued to vehicles at a toll booth when

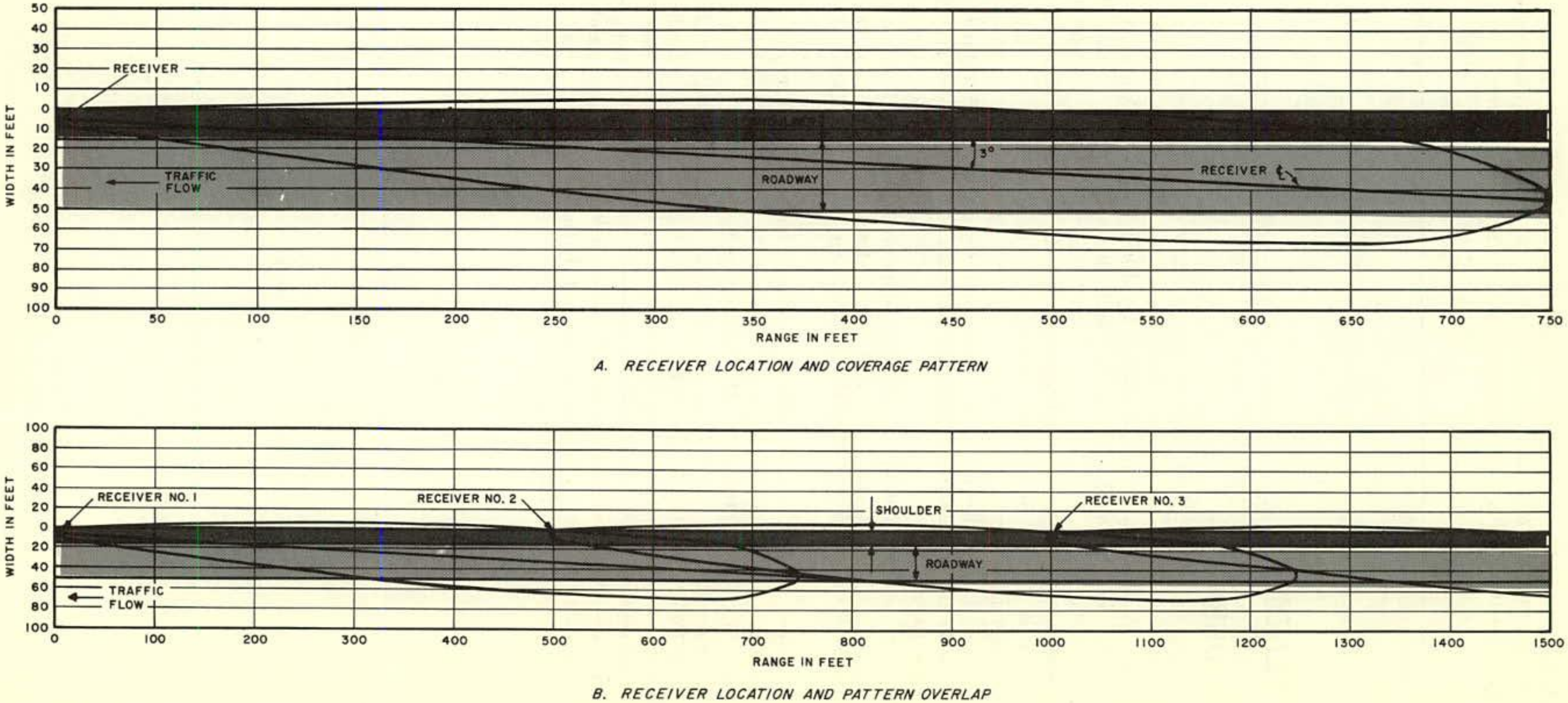


Figure 1-1. Receiver location geometry.

entering the test section. The mobile transmitters would be retrieved from the vehicles at a toll booth at the end of the test section. These transmitters would then be issued to vehicles traveling in the opposite direction.

Data would be collected over an extended period, pertaining to system reliability, effectiveness, motorist response, and road operators evaluation.

A test facility of this type could also be used to evaluate future developments in motorist aid devices under actual operating conditions.

APPENDIX K

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