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7 Reports

Subject Areas

51	Highway Safety
52	Road User Characteristics

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Foreword

This RECORD includes papers on a wide range of subjects related to seeing and driving. Some papers deal with the judgment of drivers, their eye movements, and their interactions with other vehicles on freeways, while others deal with vehicle and intersection lighting and suggest improvements in operations and safety.

Safford, Rockwell, and Banasik present results of several studies of driving performance as affected by automotive rear-signal system characteristics. They looked at characteristics such as color, size, and location and concluded that almost any change from the current systems would result in improvement.

Drivers' judgments and decisions at nonsignalized intersections in a dark rural setting under differing glare exposures are evaluated by Tsongos and Schwab. Glare was produced with both conventional and polarized headlighting, and the more glaring conditions were found to adversely affect gap-acceptance times. Other conclusions include a finding of superiority for the polarized lighting under the conditions studied.

Lipinski and a team of researchers in Illinois review the status of knowledge in roadway illumination of rural at-grade intersections and and summarize current practices. The summary data were gathered in a broadly circulated questionnaire.

Richards has again provided an in-depth review of research related to a specific area of visibility. This review pertains to vision at levels of night road illumination and covers the literature during the period from 1967 to 1969. Nearly 200 references were reviewed.

Gordon describes a study of individual driver behavior as influenced by an experimental car moving at relatively slower than normal freeway speeds. Photographs were made from the experimental car and from a stationary, high-elevation platform. They were analyzed to show positional relationships and to show changes in lead distances as a function of time.

Kaluger and Smith tell of investigations of driver eye movements under conditions of prolonged driving (9 hours) and of sleep deprivation (24 hours before the 9-hour driving task). The authors use a new index, pursuit eye movements, in drawing conclusions about drivers' ability to perform under such conditions.

Heathington, Worrall, and Hoff tell of their attempt to determine drivers' priority preference for scheduling improvements in the Chicago area highway system. They were especially concerned with the desire for real-time traffic information, and this was deemed reasonably important to freeway drivers.

Contents

The Effects of Automotive Rear-Signal System Characteristics on Driving Performance

R. R. SAFFORD, T. H. ROCKWELL, and R. C. BANASIK,
Systems Research Group, Ohio State University

This paper presents the results of several research projects concerned with the evaluation of the effects of automotive rear-signal system characteristics on driving performance. Variables considered in the evaluation included color, size, placement, location, and informational content of the signal systems. Experimental results indicate that almost any change from the current conventional system results in an improvement.

• EXTENSIVE RESEARCH INVESTIGATIONS on the effects of automotive rear-signal system characteristics on driving performance conducted by the Systems Research Group of the Department of Industrial Engineering at the Ohio State University are described and summarized. Sponsors of the research projects that are reported include the National Cooperative Highway Research Program, the Ohio Department of Highways, and the Federal Highway Administration and the National Highway Safety Bureau of the U. S. Department of Transportation. This research spanned a period of 5 years and not only was concerned with signal system design configurations and the conceptual basis for such designs but also included the problem of determining performance measures for evaluating alternative systems.

One of the areas of the traffic safety problem that rank high in accident frequency is the rear-end collision. Various studies claim that rear-end collisions account for 20 to 40 percent of all accidents. Although not adequately documented, it is believed that many of these collisions result from inadequate communication from the lead car to the following driver. The only method currently available for communicating between 2 vehicles is that of using the signal lights on the back of the lead vehicle. At the present time this communication system is capable of displaying very limited amounts of information. A list of the functions that the system can perform, or rather types of information that can be displayed with the current taillight configuration, includes only the following items: (a) braking information, on-off; (b) running information (absence of braking), on-off; (c) turning information, left-off-right; and (d) backing information, on-off.

Of these 4 functions it can be argued that the presentation of information concerning the braking behavior of the lead vehicle is the most important. Failure of the taillight system to transmit braking information might be a factor in the large number of rear-end accidents.

The type of taillight system currently used on automobiles is not an ideal communication system and often leads to confusion. Two types of errors can be identified with the present taillight system. The first kind of error occurs in the car-following situation where the separation distance between vehicles is less than 500 ft when the driver of the following vehicle fails to notice a change in the taillight signal of a lead vehicle.

Paper sponsored by Committee on Visibility and presented at the 48th Annual Meeting.

The second kind of error occurs in the approach or overtaking situation where the headway and relative velocity between the 2 vehicles are usually large. Here the driver of a vehicle suddenly encounters a vehicle in front of him and errs in judging whether the car is braking or maintaining speed. The first type of error can be considered an error in signal change detection, while the second type of error can be considered an error in signal magnitude estimation (because braking in the current system is signalled by an increase in intensity of the running light).

Brightness change for encoding information in a taillight system, which is currently used today, is a very poor choice. Doubling the absolute intensity of sound does not mean that the human subject will be able to perceive a doubling. In the case of brightness, J. C. Stevens and S. S. Stevens (12) and others have shown that the human requires large changes in brightness intensity to perceive differences. A tenfold increase in brightness yields about a twofold increase in perceived brightness for most individuals. In addition to using a coding mechanism to which the human is insensitive, the present system has many other faults. A red signal that means "stop" and also "running" causes confusion. Red signal lights also usually appear farther away than other colors viewed at the same distance (1). The major question, therefore, appears to be not whether a better rear-end signal system can be designed but which of the many available alternative systems is best. The Systems Research Group at the Ohio State University has conducted several research studies to find the answer to this problem.

Before describing the results of these studies, this paper will explore some of the problems that are inherent in research of this nature.

PROBLEMS ASSOCIATED WITH HUMAN FACTORS RESEARCH IN DRIVING

One problem associated with research on automobile taillights (or on any aspect of automobile driving) is that there exists an overabundance of experts in the field. Approximately 100 million critics subjectively judge the results of any research (at least those results that are implemented).

Another problem associated with this type of research is the selection of the methodological approach that is to be used in the research. Several approaches are available and include laboratory simulation, part task simulations, and studies conducted in the real world. All of the experiments performed by the Systems Research Group have been done in instrumented vehicles on actual Interstate highways and secondary roads. This approach does not allow the precise control over variables that might be available in a laboratory situation or in a partially simulated driving task. The results that are obtained on the highway do, however, have the distinct advantage of being readily interpreted into meaningful conclusions. The philosophical problems and stark practical uncertainties, which are present when extrapolations are attempted from laboratory simulation results into real-world contexts, are minimized when studies are conducted in the setting in which they are to be interpreted.

Another problem associated with research in vehicle rear-signal systems is the determination of a criterion. Given an alternate to the current system, how should it be evaluated in terms of the present or conventional system. It is clear that this question depends to some extent on measurement capabilities. Measurement problems include determining when the following-car driver detects the presence of a lead car and determining when the driver detects a mode change, for example, a change from running to braking. Two questions that point to other measurement problems are as follows:

1. How does a driver ascertain the rate of closure between his vehicle and the vehicle in front of him?
2. How can the confusability of a signal system be measured?

RESEARCH PHILOSOPHY

The research philosophy used by the Systems Research Group in conducting its investigations into the design of vehicle rear-light systems is a multifaceted philosophy. The complexity of this philosophy is dictated by the complexity of the rear-end signal system design problems. Figure 1 shows a schematic diagram of some of the factors that must be considered in research into the design of automobile signal systems. Using the notation of the schematic, we might state the research objective as follows:

> Compare possible display configurations using the stated performance measures to determine which configuration is "best" suited to achieve the system functions in the different visual environments, and under different given situation variables and different human and component reliability factors.

Ideally all possible combinations of these factors would be examined in determining the best signal system display. At the present time, however, such an effort is not possible. It is, therefore, not currently possible to design the optimum or ultimate system. For that reason the Systems Research Group has adopted the principle of guided evolution in its research. This principle presumes that there should be logical order in the evolution of rear-end signal systems from the current conventional system to advanced optimum systems. The evaluation would be characterized by small, mutually

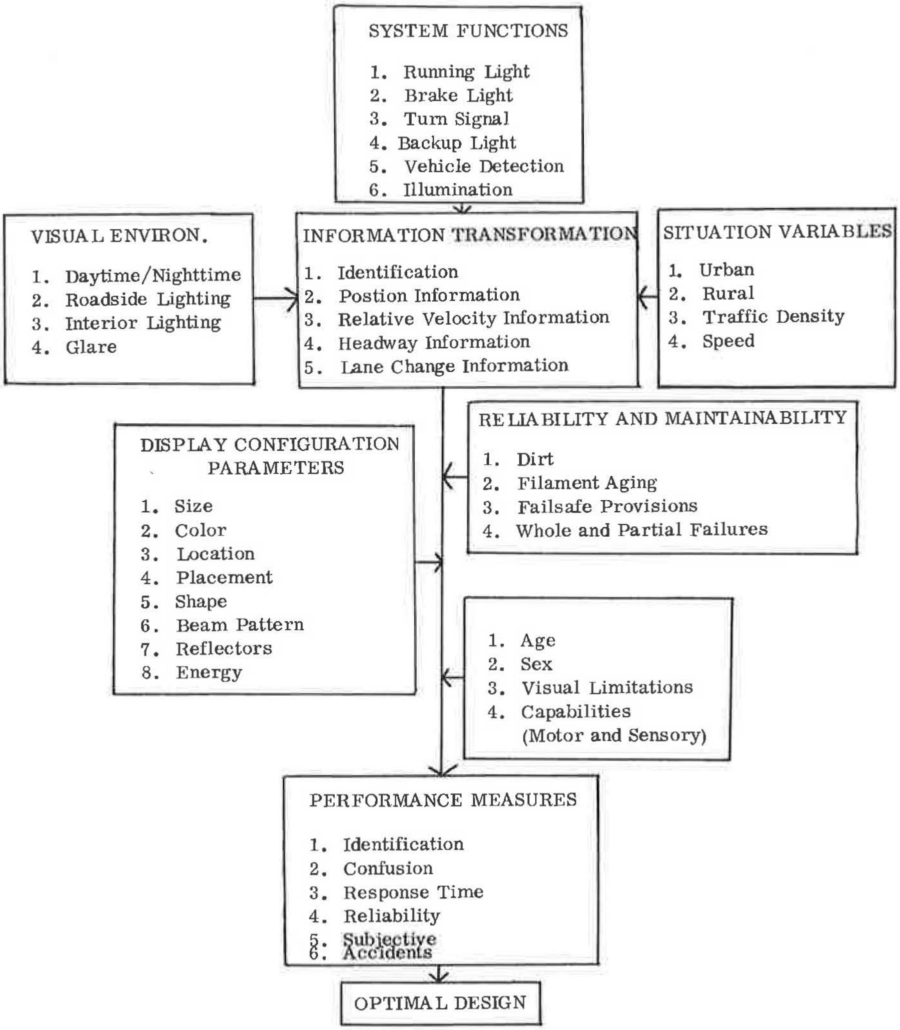

Figure 1. Factors in automobile signal system design.

compatible changes incorporating the latest in technological advances. Such small changes would have the advantage that the driving public might be more readily able to adapt to them than to major changes.

Any new system must be instantly understandable. Because each driver cannot personally be educated to system changes, the driver must have a natural response to the new information that is presented to him with whatever new presentation codes are used. For example, a purple signal has no obvious interpretation and hence its introduction into the highway scene could be disastrous because it might promote rather than minimize accidents. A system should also have redundant characteristics whenever possible, i.e., the use of 2 codes to provide the same information. Position and color, brightness and color, or position and brightness could be used to signal information so that if the first code is missed by the driver, either due to a visual abnormality or other system malfunction, the second code would yield the same message.

The Systems Research Group's philosophy centers around information transfer. This leads to the questions, What information should be presented to the driver? When should it be presented? How should it be presented? Of these, the most crucial issues involve what information is both necessary and possible to present to the following-car driver from such possibilities as position, presence of the vehicle, speed of the lead car, relative velocity of the 2 cars, and the relative acceleration of the 2 cars. This information is currently presented in the car-following situation by the static and dynamic physical position of the vehicles with respect to each other and with respect to the environment. The ability of the driver to obtain information from this natural display is not known completely, although Rockwell and Snider (10) have made some initial determinations of man's abilities to sense these kinds of information in some common car-following situations. In the design or selection of an alternate to the current taillight system, man's psychophysical capabilities should be considered because any signal system that is adopted for use on the vehicle should be capable of resulting in performance that is at least as good as the performance exhibited by the human without the signal system. Care should also be taken in evaluating automobile signal systems. This will ensure that a particular taillight design facilitating the transfer of 1 type of information pertinent to the driving task but impairing the transfer of other types of information is not adopted.

With respect to when signal system information should be presented to a following-car driver, it is helpful to consider a temporal model of the car-following phenomena. Given a situation in which a following car approaches a lead vehicle that is traveling at a slower speed, one can identify at any point in time a headway or a time to collision. If a collision is to be avoided, 6 events must occur within this time. These include (a) detection of the lead vehicle by the following-car driver; (b) determination of lead vehicle mode, such as running, braking, or turning; (c) estimation of rate of change information; (d) decision by the following-car driver concerning the appropriate response; (e) response on the part of the following-car driver in applying the decided on action; and (f) response on the part of the following vehicle. Each of these events consumes time. Too much time devoted to any one of these events will not leave sufficient time for the other events to take place and a collision could occur. Improvements in vehicle rear-light information coding systems can be expected to reduce the time required for mode determination, rate of change estimation, and decision-making.

VISUAL CHARACTERISTICS OF COLORED SIGNAL LIGHTS

Many proposed experimental signal systems incorporate lights of colors other than red. Some information concerning the visual characteristics of colored signal lights is reported in the literature.

When a light is just visible in the primary visual axis, it is nearly colorless. As the intensity of the light is increased or its distance from the observer shortened, red lights may be distinguished from lights of other colors, but lights of other colors still look alike. On further increase of intensity we distinguish green, amber, white, and blue in that order (13).

Studies in peripheral color vision have yielded different results. All parts of the retina do not have the same degree of sensitivity to color because of varying concentrations of cone cells in the periphery of the retina. In normal eyes the retina is sensitive to yellow over the largest area and to blue over one almost as large, to red over a still smaller area, and to green over the smallest (7).

Merrill J. Allen (1) has indicated that a lateral chromatic aberration of the eye called "chrome stereopis", present in two-thirds of the population, may have an effect on the depth perception of colored signals (1). This condition exists when the pupil is decentered nasally. The retina, therefore, receives only that part of the light passing through the edge of the lens. This part of the lens acts as a prism to separate the spectral colors on the retina. Because of this, reds appear farther away than they actually are, greens appear very nearly at their true location, and blues appear closer than they really are. Allen gives no indication of the severity of this phenomenon. On this basis, red would seem to be an illogical choice for a taillight because it may trick the driver into believing he has more headway than actually exists. Although amber was not considered in the previously mentioned study, there is reason to believe that it would appear somewhere between red and green because of its position in the spectrum.

The results of Allen's study may be given in the following matrix form:

Vision	Red	Amber	Green	Blue
Direct visibility	A	C	B	D
Peripheral visibility	C	A	D	B
Depth perception	D	C	A	B

In this tabulation, A indicates best performance and D indicates worst performance. Blue was rated above red and amber because it tends to appear closer than actuality; thus making the driver more conservative.

This matrix generally holds true for varying degrees of fog, clean air, daylight, and darkness. The absence of any change in the qualities caused by variations in ambient lighting may be attributed to the fact that no Purkinje shift can occur during the observation of signal lights at night. The eye is never really darkness-adapted under these conditions.

The principal effect of fog is to attenuate the light coming from a signal by scattering it. This is equivalent to reducing the intensity of the light itself, and this reduces the visual range of the signal both for detection and color recognition. In a true aqueous fog, all colors are scattered about equally so that their hue is not changed. A haze of smoke or dirt mainly reduces the intensity of a good blue or green signal and may make white and yellow lights appear somewhat reddish (13). It should be noted here that some researchers, notably Middleton (4) and McNicholas (3), believe that blue and green lights may be somewhat more spread or dispersed by fog than red or amber and therefore may appear closer. More intensive research may resolve this diversity of opinion.

RESULTS OF INITIAL SYSTEMS RESEARCH GROUP EXPERIMENTS

The Systems Research Group's first experiment in the area of rear-signal systems was partially directed toward the aim of testing new means of communication between vehicles via vehicle-borne taillight systems. In this experimentation sponsored by the National Cooperative Highway Research Program (11), 4 intervehicular signal systems—AID, Tri-light, NIL, and conventional signal systems—were compared. The display consisted of 5-in. square light units arranged, as shown in Figure 2. Conventional brake lights were displayed by the outer red lights. The Tri-light system used the vertical columns of red (brake pedal actuation), amber (no pedal actuation), and green (gas pedal actuation). The AID system employed the horizontal rows of red and green lights, actuated by vehicle acceleration, with the outer red signaling slight deceleration, the 2 outer reds a greater deceleration, and so on until all red lights were illuminated for a violent deceleration maneuver. The green lights functioned in a similar manner for acceleration. The NIL condition was one in which all lights were turned off and none was displayed during a vehicle maneuver. The following vehicle (driven by the subject) was equipped with a take-up reel and recorder to permit continuous recording of headway and relative velocity as well as vehicle velocity, pedal movements, and acceleration.

The analysis of the data obtained in this experiment indicated that both the AID and Tri-light systems resulted in decreased response times over the conventional system.

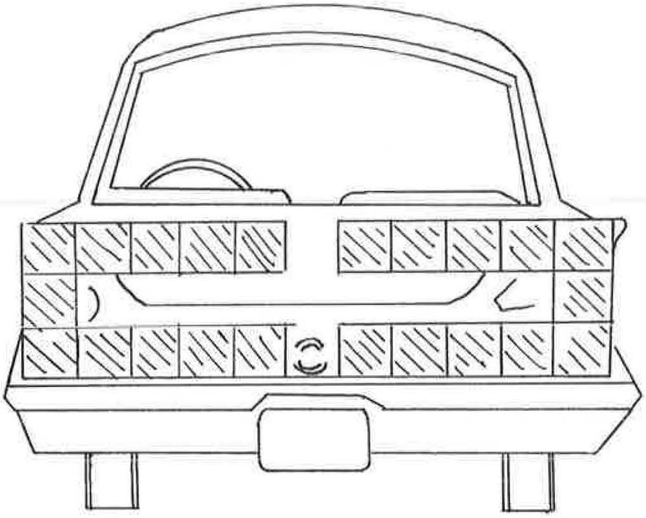

Figure 2. Arrangement of signal lights in previous experiments.

Response times under conventional and NIL systems (where drivers were left to detect decelerations by visual cues such as CANT and perceived relative velocity) were more than 3 times those obtained under the AID and Tri-light systems as shown in Figure 3. The greatest gains were obtained with the Tri-light system. Large differences between performance under conventional and that under AID or Tri-light clearly indicated the benefits obtainable from signaling small decelerations (e. g., coasting maneuvers by the lead car).

When performance under the 2 special systems (AID and Tri-light) was compared, it was found that the Tri-light system yielded slightly better performance during lead

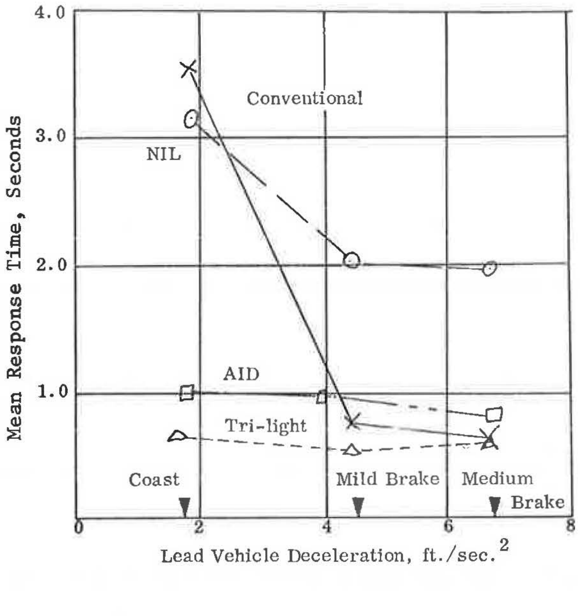

Figure 3. Experimental results.

vehicle deceleration and that both systems performed equally well during lead vehicle accelerations. This experiment was performed both at night and during the day. Essentially the same results were found for both periods of time.

DEVELOPMENT OF EXPERIMENTAL TESTING PROCEDURES

The experience of the Systems Research Group on this initial research project on vehicle rear-signal systems suggested some experimental procedures that were utilized in subsequent research projects. The testing procedures that evolved from the early research work of the Systems Research Group were designed to enable comparisons of different signal systems with respect to (a) performance in car-following situations; (b) performance in approach situations; (c) headway estimation performance; and (d) performance in coupling situations. Each of these performance tests will be described in more detail in the following.

EXPERIMENTS TO MEASURE PERFORMANCE IN CAR-FOLLOWING SITUATIONS

The experiments that were designed to measure performance in car-following situations were designed to measure those variables that could be associated with signal change detection errors and their relation to different signal systems. The major dependent variables considered in this experimentation included (a) reaction time, (b) headway changes, (c) relative velocity changes, (d) velocity changes, (e) brake pedal activity, and (f) gas pedal activity. The independent variables that were considered included the different signal systems.

The basic experimental procedure in the car-following situations required that the subject drive an instrumented vehicle at a fixed distance (usually 200 ft) behind a lead vehicle (usually traveling at a constant speed of 65 mph). The lead car then began a constant 10-sec deceleration that reduced the speed of the lead vehicle by 30 mph. This deceleration was signaled by the vehicle rear-signal system in a manner dependent on the type of signal system being utilized. After the 10-sec deceleration the lead vehicle began a 10-sec ramp acceleration to get the lead vehicle back to the original speed.

During the car-following experimentation, the following items of information were obtained for each maneuver (deceleration and acceleration of the lead vehicle):

1. Gas pedal response time—Time interval between initiation of the maneuver and the release of the gas pedal in the following vehicle;
2. Brake pedal response time—Time interval between initiation of the maneuver and the depression of the brake pedal in the following vehicle;
3. Gas pedal release interval—Time period that the subject's foot remained off the gas pedal;
4. Initial headway—Headway at the initiation of a maneuver;
5. Minimum relative velocity or maximum closing velocity—A negative quantity occurring during the period of closure;
6. Maximum relative velocity or maximum opening velocity—A positive quantity occurring during the acceleration period following the period of closure;
7. Percentage reduction in headway—A derived measure equal to the difference between the initial headway and the minimum headway divided by the initial headway; and
8. Acceleration response time—Period of time between the end of braking by the lead vehicle and depression of the gas pedal in the following vehicle.

It is recognized that drivers are more alert in an experiment of this kind than during normal freeway driving. This alertness was probably present for all trials and signal systems and, accordingly, did not affect direct comparison of signal-system performance. Absolute values such as response times, however, reflect the experimental conditions and generally are lower than one would expect under normal driving conditions void of this psychological set.

It is useful to divide system dynamics into 2 parts during a lead-vehicle maneuver. The first part begins with the deceleration of the lead vehicle and ends when zero relative velocity is regained. This period corresponds to the period of closure. The second part includes the remainder of the maneuver terminating when the lead vehicle reaches its initial speed of 65 mph. In the first part of the maneuver, during lead-vehicle deceleration, interest is primarily directed toward 5 measures of car following. These include (a) gas pedal response time, (b) brake pedal response time, (c) minimum relative velocity or maximum closing velocity, (d) percentage reduction in headway, and (e) minimum headway.

In the second part of the maneuver attention is transferred to car-following performance during acceleration by the lead vehicle. This portion of the maneuver is possibly less important from a safety point of view, but is more important in terms of traffic flow. In accordance with the preceding during this portion of the maneuver 2 measures of car-following performance are considered important: (a) acceleration response time, and (b) maximum relative velocity.

Acceleration response time represents the time interval from the beginning of the lead vehicle's acceleration until the following-car driver steps on the gas pedal of his vehicle. It is interesting to note that the drivers were not specifically instructed to respond to the cessation of the brake light on the lead vehicle. In this respect this measure might be taken to be a more natural indication of the response time to various signals than the initial response times exhibited at the beginning of the lead vehicle's deceleration. Both types of response times indicate essentially the same things about the signal systems.

Maximum relative velocity during the lead vehicle's acceleration forms a partial measure of the following driver's performance in interpreting and following the lead vehicle's acceleration.

EXPERIMENTS TO MEASURE PERFORMANCE IN APPROACH SITUATIONS

This experimentation was designed to determine the relation of magnitude estimation (confusion) errors in the overtaking situation to different signal systems. The major dependent variables that were considered in this phase of the experiment included (a) reaction time, and (b) confusion errors (judgment of whether signal is braking or running). The independent variables that were considered included the different signal systems.

Prior to the start of this part of the experiment, the subject was given instructions similar to the following:

> We are now going to ask you to drive this car at a distance of 1,000 ft behind the lead car. After you are at 1,000 ft the lights on the rear of the lead car will go out. They will remain out for a time; then they will come back on. When they come on, we would like you to judge as quickly as possible whether the car is displaying a brake light or a running light.
>
> If you decide that the car is displaying a running light, depress the gas pedal slightly. If you decide that a brake light is on, take your foot from the gas pedal and touch the brake pedal without slowing down.

After the instructions were given, the driver was guided to a headway distance of 1,000 ft by the experimenter. The subject then followed the lead car at this distance. Instructions were issued when necessary so that the subjects could maintain this headway of 1,000 ft. During this phase the lead car taillights followed the pattern shown in Figure 4. Note that the subject was always presented with a running light prior to the turning off of the taillight system. The basic purpose for this design was to simulate the situation where confusion exists as to which light (BL or RL) is functioning.

EXPERIMENTS TO MEASURE HEADWAY ESTIMATION PERFORMANCE

This experiment was designed to determine the effects of taillight design parameters (e.g., size, color, intensity, or placement) on the ability of subjects to estimate distances.

The experimental procedure required that the subjects sit in the front seat of the instrumented vehicle on a private road in an unlighted area behind 2 other vehicles.

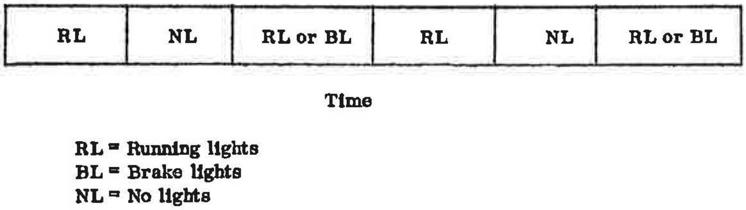

Figure 4. Taillight patterns.

One of these other vehicles was a sedan equipped with 2 red taillights mounted in a position corresponding to the position of most current conventional taillights (i.e., the lower left and right of the back of the vehicle). The subjects were given the following instructions:

> As you can see, we have 2 vehicles in front of you. The vehicle on your right will remain parked with its red lights on. The vehicle on the left with different signal lights will drive slowly up to and past the other vehicle, then it will back up. We would like you to press the button that you hold in your hand when you think the 2 vehicles are exactly side by side. We would like you to do this both when the vehicle on the left is moving forward past the parked vehicle and when it is moving backward past the parked vehicle. Again press the button when you think the 2 vehicles are side by side and please hold the button down for a second or two.

The lead vehicle slowly drove forward to a point about 600 ft in front of the experimental vehicle, and then slowly backed up to a point about 200 ft in front of the experimental vehicle.

From the oscillograph traces obtained in this phase of the experimentation, the actual headway of the lead car, at the moment the subject thought the lead car was as far away as the parked vehicle, was obtained. The target distance (i.e., the distance from the subject vehicle to the parked vehicle, with which the vehicle with the experimental signal systems was being compared) was subtracted from the actual headway, and an error headway was obtained.

EXPERIMENTS TO MEASURE PERFORMANCE IN COUPLING SITUATIONS

In addition to the car-following situation where the separation distance between vehicles is usually small and the approach situation where separation distances are large but are decreasing, a third situation might be identified. This situation could be labeled as the coupling of the lead vehicle and the following vehicle. The coupling condition lies at the interface of the car-following condition and the approach condition. Primary measures of performance in the coupling situation were considered to be the rate of change of headway during coupling and the headway at which the following vehicle levels off behind the lead vehicle.

The experimental procedure that was used in this experimentation required that the subjects drive the instrumented vehicle at a speed of 65 mph several thousand feet behind the lead vehicle also going 65 mph. The lead vehicle then slowed to 35 mph. The closing behavior in terms of the headway changes between the 2 vehicles was measured every half second with a 16-mm motion picture camera.

Prior to the start of the experimentation, the subjects were given the following instructions:

> You will follow the lead car at 65 mph. The lead car will slow up. You will close up behind the lead car as if you were on a 2-lane highway and were not able to pass.

The film collected in this phase of the experiment was projected on a standard calibrated screen, and the distance between the signal lights was measured. These meaurements were then converted to headways via a computer program and plotted by the computer.

RESULTS OF CURRENT SYSTEMS RESEARCH GROUP EXPERIMENTS

The Systems Research Group's second research project in the area of rear-signal systems was sponsored by the Ohio Department of Highways and the Federal Highway Administration. It was designed to compare a proposed amber-red taillight system to the conventional taillight system. Of particular interest in this experimental design was (a) the susceptibility of the present taillight system to confusions between the running light and the brake light; and (b) the reaction time and response of drivers to signals of the present system as compared to signals of the new system under car-following conditions.

Two automobiles were used in this experiment. One of these cars was used as a lead car and was equipped with the experimental signal systems. The experimental signal system consisted of 2 circular taillights on each side of the car. When tests were being made with the conventional system, only the top lamp on either side of the car was employed. This lamp served both as a running lamp and as a brake light. Braking was signaled by an increased intensity of the lamp. As can be seen, this system is similar to that found on almost all American-made automobiles.

In other tests where the amber-red taillight system was being used, both lamps on either side of the car were employed. The lower lamp, which was equipped with an amber lens, served as a running light. The top lamp, with the red lens, remained off, except when the brake in the lead car was applied.

The testing procedure that was employed on this project utilized primarily the previously mentioned car-following and approach experiments.

In the car-following experiment the subject driver was instructed to follow the lead car at a distance of 200 ft. After the driver obtained a distance of 200 ft and followed the lead car for a time, the lead car began a ramp deceleration from 65 mph to 35 mph and then began a ramp acceleration back to 65 mph. The beginning of this maneuver (taillight actuation of the lead car) was recorded in the following vehicle. On preselected maneuvers different luminance ratios were used to signal the braking of the lead car. Each subject was presented with 5 replications of the maneuver under each of 8 luminance ratios with the conventional red-braking, red-running light system. In addition each subject was given 10 trials where the brake was signaled by the appearance of a red light in conjunction with an amber running light.

The results of this phase of the experiment are shown in Figure 5. As the luminance ratio (the ratio of brake light intensity to running light intensity) is increased up to the minimum ratio of 1:5, recommended by the Society of Automotive Engineers, performance improves. Increases beyond the 1:5 ratio did not yield significant improvements. The subject performance with the amber-red taillight was found to be about the same as the performance with the conventional system with a 1:5 ratio.

In the approach experimentation described earlier, the subject was randomly presented with 5 presentations of 8 different intensities of red lights, ranging from running lamp intensity to about 22 times running lamp intensity. After the subject was presented with these 40 trials, the experiment was repeated, but this time the subject was told that amber lights only would signal the running condition whereas an amber running light and red brake light would be the signal for a braking maneuver. From this part of the experiment the following measures were obtained:

1. The percentage of time that a taillight (which varied in intensity from 1:1 luminance to 1:22 luminance) was identified as a brake light or as a running light;
2. The response time for depression of the gas pedal when the signal light was identified as a running light;
3. The response time for release of the gas pedal when the signal light was identified as a brake light; and
4. The response time for the depression of the brake pedal when the signal light was identified as a brake light.

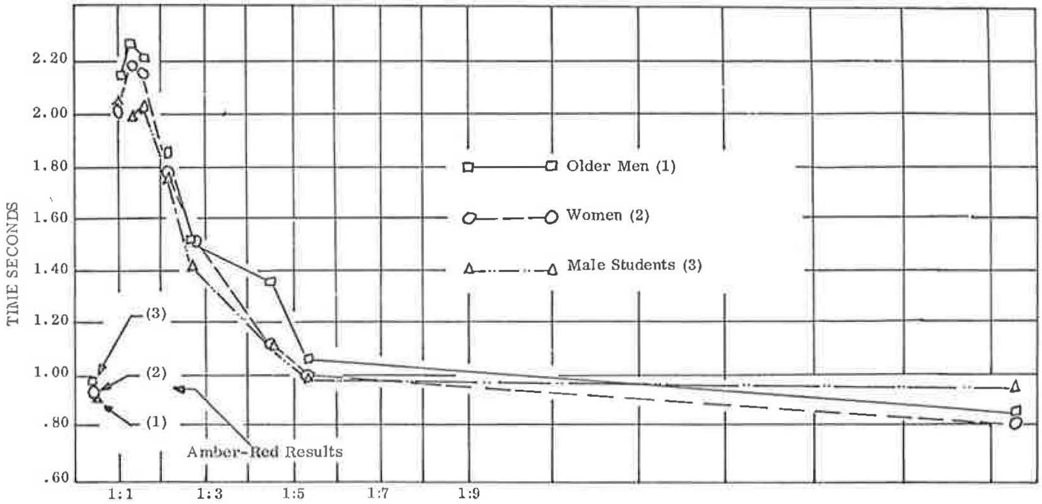

Figure 5. Running light to brake light intensity ratio.

The results of this study are given in Table 1. In general it was found that increases in the luminance ratio resulted in fewer confusion errors being made (i.e., brake lights being identified as running lights). The amber-red system noticeably improved performance with respect to decreasing the number of errors that were exhibited when an amber-red brake light was displayed. The response time measures failed to show any statistically significant differences across the various signal intensities.

EFFECT OF TAILLIGHT COLOR, LOCATION, PLACEMENT, AND SIZE ON DRIVING PERFORMANCE

The Systems Research Group's third research project, also sponsored by the Ohio Department of Highways and the Federal Highway Administration, was designed to expand the work done on past experiments to enable a more thorough evaluation of rear-end signal system characteristics in night driving. More specifically, the goals of this research were to (a) expand previous research work to include a thorough investigation of colors other than amber for running-light systems; (b) ascertain the effects of taillight location on driving performance; (c) determine the effects of taillight size on driving performance; (d) determine relationships among the 3 previously mentioned variables; (e) test for subject effects; and (f) ascertain the magnitude of the current automobile population with substandard taillight systems.

The testing procedure that was employed on this project consisted of all four of the experimental procedures described earlier. A total of 40 persons served as subjects in this experiment. These people came from 4 different groups, young men and young

TABLE 1

CONFUSION ERRORS—AMBER-RED VERSUS CONVENTIONAL SYSTEM

Category	Older Men	Male Students	Women
Percentage of running-light signals mistakenly called brake light			
Amber-red system	1.7	2.8	5.0
Conventional system (1:1)	3.2	12.7	7.0
Percentage of brake-light signals mistakenly called running light			
Amber-red system	0.0	0.9	2.0
Conventional system (1:5)	8.6	9.3	7.0

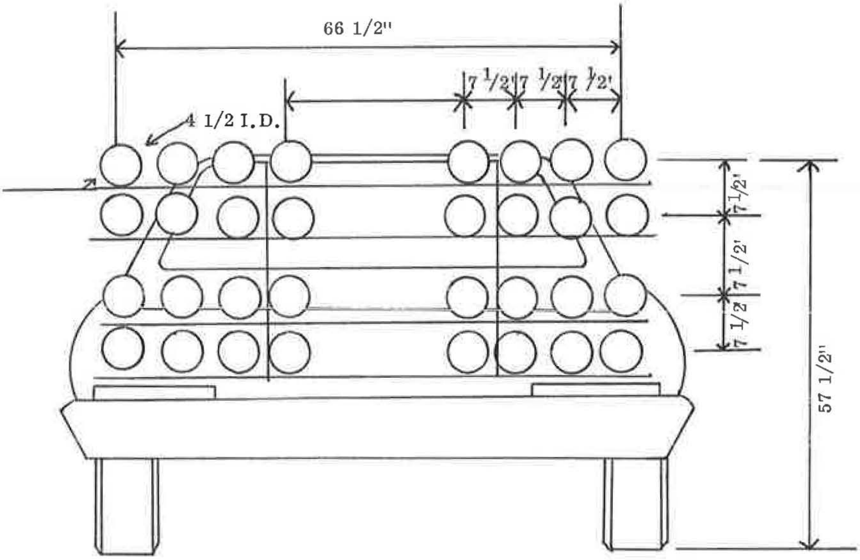

Figure 6. Experimental signal system.

women (under 25) and older men and older women (over 40). All road testing was done in instrumented vehicles (the same as those used previously) on Ohio freeways and secondary roads. The testing of the 40 subjects required 60 nights of successful experimentation and involved over 1,080 research man-hours (on the road) and over 16,000 research vehicle-miles.

	1	2	3	4
A	Red RB	Red RB	Amber	Green
B	Blue Green	Green	Red RB	Red RB
C	Red R	Amber	Amber	Green
D	Blue	Green	Blue Green	Red RB

Lamps on Left Side of Vehicle

Figure 7. Taillight configuration where R indicates that lights could be used as a running light and RB indicates that lights could be used as a running light or brake light.

Two automobiles were used in this experiment. The lead car was equipped with the experimental signal system (Figs. 6 and 7). The signal system consisted essentially of a 4-tiered rack on which the signal lamps could be placed. Lamps could be placed at any position on the rack from vertical and horizontal positions. Lamp lenses could be readily changed to allow different colored signals to be employed. Lamp sizes could be varied by the placement of sized filters over the colored lenses of the lamps. Lamp intensities could be controlled by the use of neutral density light filters in conjunction with the colored lenses.

When tests were being made with the conventional system, only 1 red lamp on either side of the vehicle was employed. This lamp served both as a running light and as a brake light. Braking was signaled by an increased intensity of the lamp. In other tests where the double-red system was being tested, 2 red lamps on both sides of the car were used. A single red lamp signaled the running condition of the vehicle, while braking was signaled by the addition of the second red light that was of higher intensity.

In experimentation with color-change taillight systems, 2 lamps on each side of the car were employed. A single lamp (of some color other than red) was used to signal the running condition of the vehicle while braking was signaled as in the double-red system by the addition of a red light that was of higher intensity than that of the running light.

CAR-FOLLOWING PERFORMANCE AS A FUNCTION OF TAILLIGHT COLOR, SIZE, LOCATION, AND PLACEMENT

The car-following experiment on the project was designed to determine the relation of signal change detection errors to different signal systems (i. e., conventional, double-red, and color change).

The subject driver was instructed to follow the lead car at a distance of 200 ft. After the driver obtained a distance of 200 ft and followed the lead car for a time, the lead car began a ramp deceleration from 65 mph to 35 mph and then began a ramp acceleration back to 65 mph. The beginning of this maneuver (taillight actuation of the lead car) was recorded in the following vehicle. On preselected maneuvers different signal systems were used to signal the braking of the lead car. Each subject was presented with 2 replications of the maneuver under each of 21 different signal systems. These 21 different signal systems are given in Table 2. The colors of the signal system conform where possible to specifications of the Commission Internationale de l'Eclairage.

In general, significant differences were noted with respect to gas pedal response time when the conventional systems were compared against color-change systems (Fig. 8). The other performance measures failed to distinguish differences among the systems.

CONFUSABILITY AS A FUNCTION OF TAILLIGHT COLOR, LOCATION, PLACEMENT, AND INTENSITY

In the approach experiments that were conducted on this project, the subjects were presented with 3 replications of each of the 21 different signal systems employed in phase 1 of the research. One of the replications consisted of presenting the signal in the running light mode. A second and third replication employed both the running light and the brake light with the brake light 2.5 and 5 times as intense as the running light respectively.

In general, it was found that the conventional system resulted in a larger number of errors when a running light or a low-intensity brake light was exhibited when compared to a color-change or a double-red system.

Gas pedal response times for the conventional system were also greater than for any other types of systems. The other response time performance measures failed to show any differences across the various signal systems tested.

EFFECT OF TAILLIGHT COLOR, SIZE, PLACEMENT, AND INTENSITY ON DISTANCE-ESTIMATION ABILITY OF SUBJECTS

This experiment was designed to determine the effects of taillight color, placement, size, and intensity on the ability of the subject to estimate distances. The experimental

TABLE 2

SIGNAL SYSTEMS TESTED IN PHASE 1

First Replication	Second Replication	System Type	First Replication	Second Replication	System Type
A1 red	A1 red	Conventional	D2 green	A1 red	Color change
B4 red	B4 red	Conventional	D1 blue	A1 red	Color change
B4 red	D4 red	Conventional	D2 green	A1 red	Color change
A1 red	A2 red	Double red	A4 green	A1 red	Color change
C1 red	A1 red	Double red	B2 green	A2 red	Color change
A1 red	B3 red	Double red	B2 green	B3 red	Color change
B3 red	B4 red	Double red	D3 blue-green	B3 red	Color change
A3 amber	A1 red	Color change	C3 amber	B3 red	Color change
A4 green	A2 red	Color change	A3 amber	A2 red	Color change
B2 green	B4 red	Color change	B2 green	B3 red	Color change
B1 blue-green	B3 red	Color change			

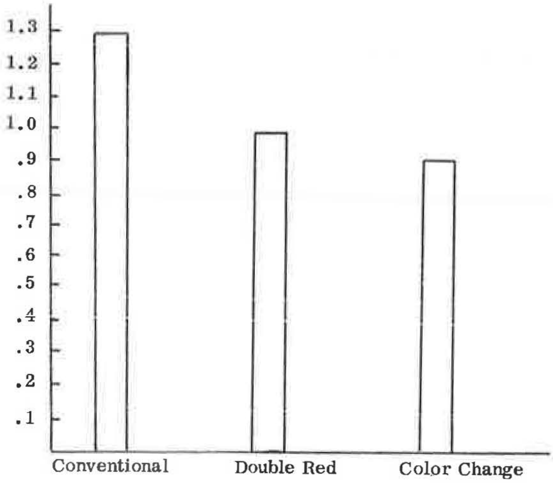

Figure 8. Gas pedal response time to lead-vehicle deceleration versus signal system. (Note: Graph combines data from 21 signal systems tested with 40 subjects and 80 replications per subject.)

procedure required the subjects to sit in the front seat of the instrumented vehicle and to judge when the instrumented vehicle with the experimental signal system was adjacent to a vehicle that had red taillights in the normal (D1) position and was parked 400 ft from the instrumented vehicle.

In this experiment each of the 5 colors previously tested on the project (red, amber, green, blue, and blue-green) were tested in the A1, D1, and D4 positions of the taillight rack. In addition, small red lights in the D1 position were compared to larger red lights in the D1 position.

The data from this experiment indicated that colors have a highly significant effect on the subject's ability to estimate distances. Red was found to appear farthest away and blue or blue-green was found to appear closest. This is the ordering that would be expected due to the presence of the chrome stereopsis phenomenon mentioned previously.

Table 3 gives the order of the taillight colors on distance estimation. A Wilcoxon Matched Pairs signed rank test was used to test for this effect of color on distance estimation. When high-intensity red lights (braking intensity) in the high outside position were compared with low-intensity red lights in the same position, no significant differences were found.

When the low outside position was compared to the high outside position by using the previously mentioned test, lights in the high outside position were found to appear closer than lights in the low outside position. This effect was significant at the 0.001 level for both the opening and the closing headway conditions.

When small red lights were compared to large red lights in the D1 position, the small lights were found to appear farther away. This effect was found to be significant at the 0.05 level for the closing headway condition. No significant effects were found for the opening headway condition.

TABLE 3

HEADWAY ESTIMATION RESULTS

Ordering	Position A1		Position D1		Position D4	
	Opening Headway	Closing Headway	Opening Headway	Closing Headway	Opening Headway	Closing Headway
Appears farthest away						
1	Red	Red	Red	Red	Red	Red
2	Amber	Amber	Amber	Green	Amber	Red
3	Green	Green	Green	Amber	Green	Green
4	Blue-green	Blue-green	Blue	Blue-green	Blue	Blue
Appears closest						
5	Blue	Blue	Blue	Blue	Blue-green	Blue-green
Level of significance of ordering	0.001	0.01	0.001	0.001	0.001	0.001

EFFECTS OF TAILLIGHT COLOR, SIZE, AND PLACEMENT ON DRIVING BEHAVIOR OF SUBJECTS IN AN OVERTAKING SITUATION

This experiment was designed to determine the effects of taillight color, size, and placement on the driving behavior of subjects in an overtaking situation. The experimental procedure that was used required that the subjects drive the instrumented vehicle at a speed of 65 mph several thousand feet behind the lead vehicle that was also going 65 mph. The lead vehicle then slowed to 35 mph without giving a brake signal. The closing behavior in terms of headway changes between the 2 vehicles was measured with a 16-mm motion picture camera.

Examination of the data from this phase of the experiment indicated that taillight color, size, and placement had no effect on the subject's performance in the overtaking situation of this experiment.

FIELD STUDY OF AUTOMOBILE BRAKE LIGHT TO RUNNING LIGHT INTENSITY RATIOS

In addition to the 4 types of tests that were performed on this project and in view of the results found in previous research, it was decided to extensively sample the vehicle population of the state of Ohio to determine what percentage of the population of vehicles had substandard taillight systems (i. e., vehicles with less than 1:5 running-light-to-brake-light intensity ratio).

The data obtained from this portion of the research indicated that approximately 15 percent of the vehicles observed had inadequate taillight systems as shown in Figure 9. A large percentage of the cars with inadequate taillight systems had defective lights (i. e., broken or burnt-out lights).

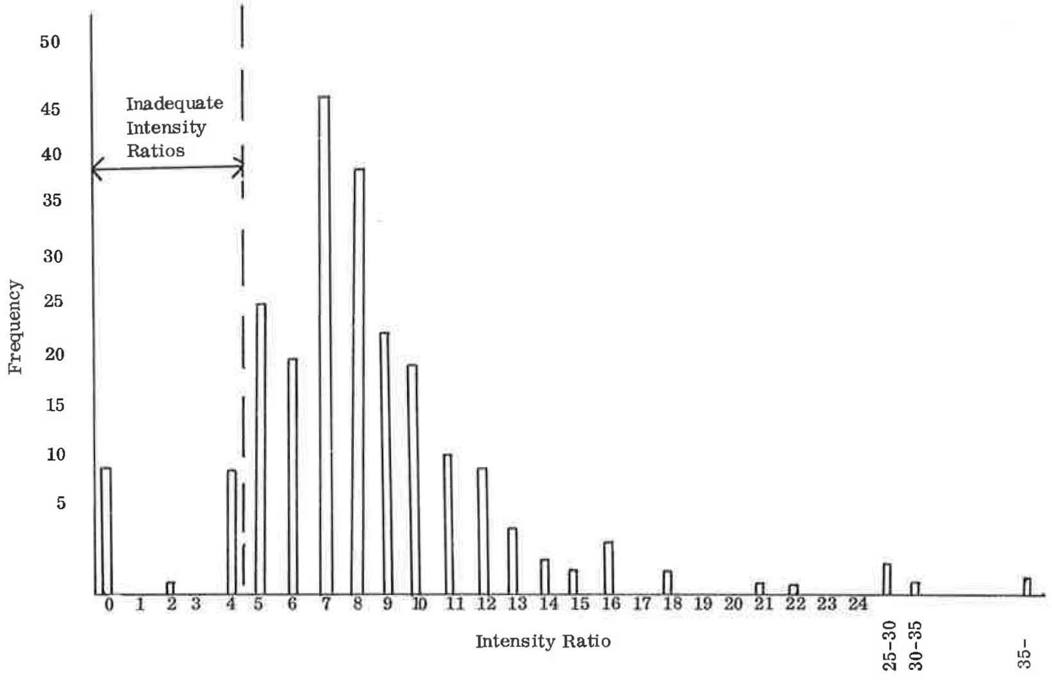

Figure 9. Intensity ratio versus frequency.

RECENT SYSTEMS RESEARCH GROUP STUDIES

In another experiment conducted by the Systems Research Group for the National Highway Safety Bureau, 4 taillight systems were tested. The systems included in addition to the conventional (C) system are as follows:

1. A Tri-light system (TL) similar to the one tested previously.
2. An acceleration Tri-light that presented a green light when the vehicle accelerated or when it decelerated very slightly, a yellow light when the vehicle decelerated mildly, and a red light for more extreme decelerations. Two acceleration systems were studied. They were sensitive (SAC) and moderate (AC) acceleration systems.
3. A headway-relative velocity (H-RV) command system that presented a green and a yellow light to the following-car driver if he followed at the correct distance (proportional to the following-car velocity), a green light if he was too far back, and a yellow light, a yellow light and a red light, or a red light as he became progressively closer.

These systems were tested in the 4 types of experimental tests described previously.

In analyzing the results of the experimentation on this project, performance measures obtained with the experimental systems were compared to the performance measures obtained with the conventional system. Two of the more sensitive performance measures are presented: gas pedal response time (GPRT) and headway variance. A ratio of these performance measures of the experimental systems to the performance measures of the conventional system was formed. These performance ratios permitted an easy determination of the effectiveness of the experimental systems. For these 2 performance measures, values less than one indicate an improvement over the conventional system. Figures 10, 11, 12, and 13 show the results.

One of the major results, shown in Figure 10, is that the Tri-light and acceleration systems produced larger headway variance than the conventional system under steady-state, car-following conditions only. These findings are in contrast to the smaller headway variance for the coasting and braking maneuvers while using the Tri-light and acceleration systems. This difference is explained in part by the steady-state, car-following condition using a large headway variance for one of the subjects. It is also possible that the apparent distance of the green light might affect the results.

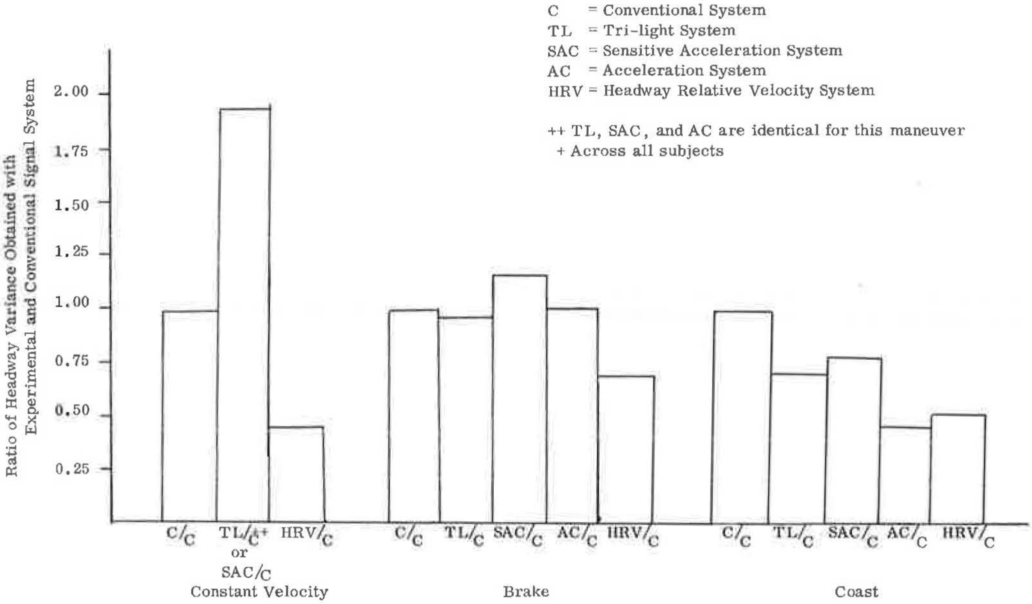

Figure 10. Ratio of headway obtained with experimental and conventional systems versus maneuver (night data).

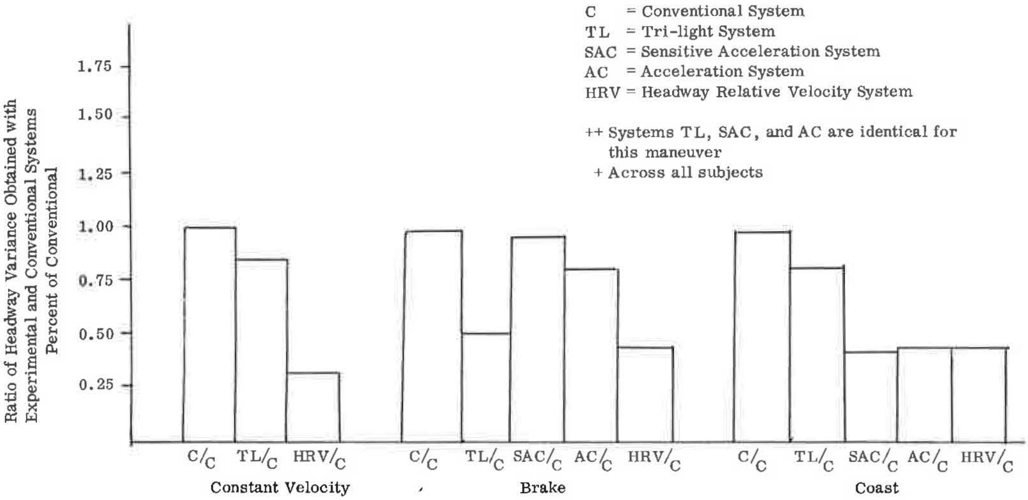

Figure 11. Ratio of headway obtained with experimental and conventional systems versus maneuver (day data).

The headway variance figures show that for both daytime and nighttime tests the H-RV system is the most effective system tested in terms of reduction of headway variance. The headway variance reduction ranges in value from a ratio of 0.69 of conventional system headway variance at night during the braking maneuver to a ratio of 0.325 of conventional system headway variance (H-Var) during the daytime for a constant velocity maneuver.

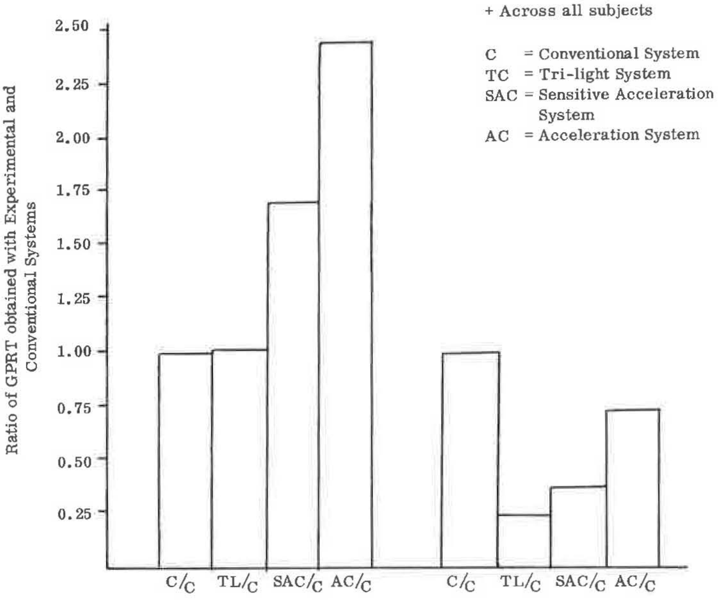

Figure 12. Ratio of gas pedal response time (GPRT) with experimental and conventional systems versus maneuver (night data).

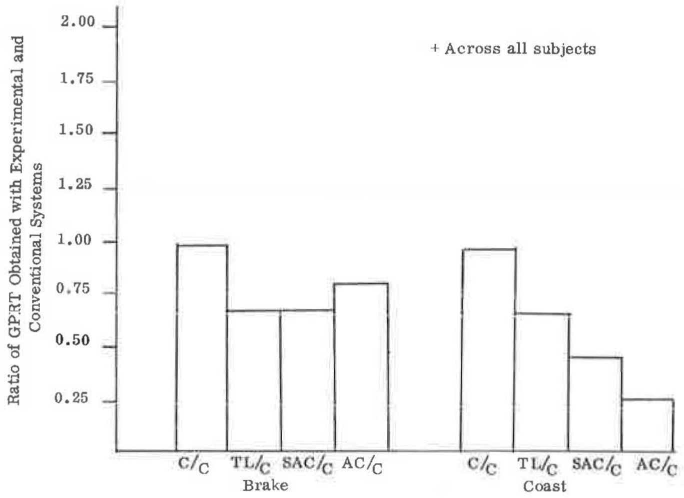

Figure 13. Ratio of gas pedal response time (GPRT) with experimental and conventional systems versus maneuver (day data).

Performance improvements were noted across all subjects. This suggests that technological efforts should be channeled into developing vehicle-based sensing systems that might be used to display the headway and relative velocity to the driver.

The other performance measure used as an aid in making a direct comparison of the systems was the gas pedal response time (GPRT). Figure 12 shows the comparison of the systems by maneuver for the GPRT. At night the conventional and Tri-light systems were almost identical with a ratio of 1.02 of conventional GPRT for the Tri-light. However, for a coast maneuver, the Tri-light system was superior to all others with a ratio of 0.21 of the conventional GPRT value. The mean GPRT for the Tri-light system on a coast maneuver was 0.75 sec as opposed to 3.5 sec for the conventional system.

These results are almost identical to those obtained by Rockwell and Safford in 1963, as shown in Figure 3. In this experimentation, systems were tested with different subjects by different researchers with different signal lamps and results still were nearly identical. During the daytime, as measured by GPRT, the Tri-light system is more effective than the conventional system. The braking maneuver resulted in a GPRT ratio of 0.68 of the conventional system's GPRT. The coast maneuver resulted in a GPRT ratio of 0.68 of the conventional system's GPRT.

CONFUSABILITY STUDY

The confusability study indicated the superiority of the tri-color system. It resulted in no errors made by following-car drivers in determining the mode of the lead car, indicating that the incorporation of colors other than red in a taillight system does not produce any detrimental results. This is in agreement with the studies previously mentioned in this paper.

TIME SERIES ANALYSIS

Use of time series analysis is a method of studying and comparing signal systems in the car-following mode by looking at the phase lag of the velocity profiles of the 2 vehicles, and specifically the cross correlation of the velocities of the 2 vehicles.

The data obtained in this experiment suggested that response lags of 1 to 1.5 sec for the conventional system were reduced to a third of this value by the use of the Tri-light. This is a natural result because the Tri-light system was designed to give the driver advance information and permit him to track the lead car more effectively.

In addition to testing the previously mentioned systems, the Systems Research Group also tested a "fusion light." The fusion light incorporated a lens with a distinctive pattern, portions of which would become visible at different distances. The use of a fusion light was found to result in reduced headway variance when compared with a conventional system with similar lamps but different lenses.

CONCLUSION

This paper has attempted to point out some of the philosophical and methodological problems associated with studying alternatives to the current automobile taillight. In addition, some of the visual problems associated with the presentation of colored lights to humans were mentioned.

The results of several research projects conducted by the Systems Research Group were presented. These results show that almost any change from the current conventional system results in an improvement. The results do not, however, point to an optimum system. It cannot be stated that the optimizing of a single aspect of a system holding all else constant will result in a better system. For example, the detectability of the current conventional system could be improved by increasing the intensity of the signal one hundred times. If this were done, further increases in intensity for purposes of signaling, braking, or turning would very likely suffer. This points out the fact that if an alternate to the current system is to be found, all aspects of system functions will have to be considered.

The extent to which the research results presented in this paper can be generalized to different driving situations cannot be stated absolutely. The fact that all of the research reported in this paper was conducted in "real" automobiles and on actual highways tends to make the results more readily acceptable than if they had been collected in the laboratory. It is also felt that the differences in the tested signal systems were to a certain extent marked by the fact that subjects in the experiment were alert to what was expected of them. Larger differences between systems might be expected if naive subjects (a wider spectrum of a driver's capability) were presented with the alternative systems.

The research that has been discussed here has shown that changes in the informational content and changes in the methods of presentation of the current taillight system results in improvements. Research efforts should be made to explore the aspects of automobile rear-signal systems not covered by this and other research material.

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Driver Judgments as Influenced by Vehicular Lighting at Intersections

NICHOLAS G. TSONGOS and RICHARD N. SCHWAB,
Federal Highway Administration, U.S. Department of Transportation

The driver's judgments and decisions at a right-angle nonsignalized intersection in relation to the degree of glare exposure were examined by using both conventional and polarized headlighting. The study was conducted on a runway of an airport in a dark rural environment. Two types of procedures were employed during the test. In the first, the subject driver stationed in a vehicle was asked to judge the "last safe moment" to start across the intersection ahead of the approaching test vehicle from the right. In the second procedure he performed the crossing maneuver. Two age groups, of 10 male drivers each, were recruited to participate in the experiment. Statistical analyses show significant differences in the driver's reaction among different lighting modes. Under the more glaring conditions, the subject drivers required longer gap-acceptance times and there was greater variance in the data. Both age groups had the same pattern of gap-acceptance values for each lighting mode. In the performance runs, the younger age group had shorter gap-acceptance values and less variability among drivers. Although low-beam lamps were least bothersome, according to the discomfort glare evaluation done by the subject drivers, both polarized high-beam systems studied were superior to conventional high-beam systems.

•THE DRIVER'S BEHAVIOR at a street intersection is a complex series of judgments and decisions. The driver, as he approaches or waits at a nonsignalized intersection, visually searches for oncoming vehicles on the other legs of the intersection. If there is an approaching vehicle, the driver probably estimates the distance and speed of that vehicle and its likely maneuver on reaching the intersection. He then weighs these judgments and decides whether it is safe to enter the intersection.

This task becomes more complicated at night. The oncoming vehicle's head lamps may make it easier to detect the presence of the vehicle, but glare from these headlights makes estimation of speed and distance more difficult. Where no fixed source of illumination is present, details of the surrounding environment are lacking and the oncoming vehicle's headlights will increase the already difficult visual task.

During the past quarter of a century, a number of improvements have been suggested for the control of head-lamp beams to improve the night driving environment. One of the most promising methods for reducing glare and improving visibility involves the use of linear polarizers at 45 deg to the horizontal on the head lamps, with the driver viewing his surroundings through a parallel analyzer or viewer. As 2 vehicles so equipped approached each other, the polarizer over the lamps of the 1 vehicle would be crossed to the analyzer on the other vehicle and no direct glare would be transmitted. Most of the research involving polarized headlighting has been involved with target detection and other visibility types of situations in a head-on encounter between 2 vehicles. Little or no attention has been devoted to the right-angle situation,

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where glare alone may be the most important variable affecting driver behavior. Yet as the driver moves from the rural into the suburban environment, the frequency of these right-angle encounters increases. In the suburban environment, gap acceptance is a critical parameter for head-lamp design because speeds are lower and sight distance requirements are less critical.

In a recent study by Tsongos and Weiner (1), an isolated, unlighted, suburban intersection was observed both day and night. Differences in gap-acceptance probability of day and night drivers were noted, particularly near the end of the gap-size distribution. The nighttime driver was more likely than his daytime counterpart to reject a very short gap (2 and 3 sec). It is at this part of the encounter that the disability glare phenomenon approached its maximum and that even small errors in judgment can become critical.

Because almost all of the vehicles observed during this study were using low-beam head lamps, it was not possible to determine whether glare was indeed a factor in the rejection of these short gaps. However, with at least one of the common suggested analyzer designs for a polarized headlighting system, glare would be increased in the right-angle situation. It was the purpose, therefore, of this experiment to control the degree of glare exposure and evaluate the behavior of drivers in making gap-acceptance judgments by using both conventional head lamps and polarized lighting with 2 differing types of analyzer systems.

TEST PROCEDURES

The experiment was conducted on a runway at the Beltsville Agricultural Research Center Airport operated by the U.S. Department of Agriculture. This airport is closed at night and, therefore, the experiment was run under highly controlled environmental conditions. The environment was that of a dark rural area with no extraneous light sources. The test was performed only under clear atmosphere and on a dry road surface.

The airport consisted of 2 intersecting runways, each approximately ¾ mile long. An at-grade intersection with a unidirectional highway was simulated at a point near where the 2 runways crossed. There was a 3,200-ft long constant grade approach from the subject driver's right side. The surface had recently been repaved with a black asphalt overlay, and two 12-ft lanes had been marked on it with 4-in., nonreflective, white solid edge markings and dashed centerline.

A subject driver was stationed in a vehicle sitting at the intersection as shown in Figure 1. A test driver was stationed at the end of the runway. On command the test driver turned on his vehicle's lights, accelerated to constant speed, proceeded down the lane nearest the subject vehicle, and approached it at a right angle. Once the test driver had passed the subject driver, he turned around and proceeded back to the starting point to set up for the next run. The test driver and experimenter communicated via mobile radios.

Two types of experimental procedures were used during the study. In the first, called the judgment series, the subject was asked to judge the "last safe moment" to start across the intersection ahead of the test vehicle and signal his decision by pushing a large metallic button located on a stand just outside his window. In this case, he kept his vehicle stationary while reacting. In the second procedure, called the performance series, the subject actually performed the crossing maneuver. Which of the 2 procedures were to be used for a given run was signaled to the subject by switching on 1 of 2 lights located across the intersection when the approaching test vehicle was 1,600 ft from the intersection. A red light was used to indicate a judgment run and a green light for a run in which an actual crossing was to be made.

It was felt that the first type of procedure would allow for better control of the stimulus condition and would have less inherent variability. It was therefore possible to use fewer subjects under more experimental conditions. The second procedure did have a higher degree of realism, more closely paralleling the real-world driving situation. However, it also involved some accident risks, and for this reason the bulk of the experiment was carried out with the semidynamic procedure of only 1 car moving.

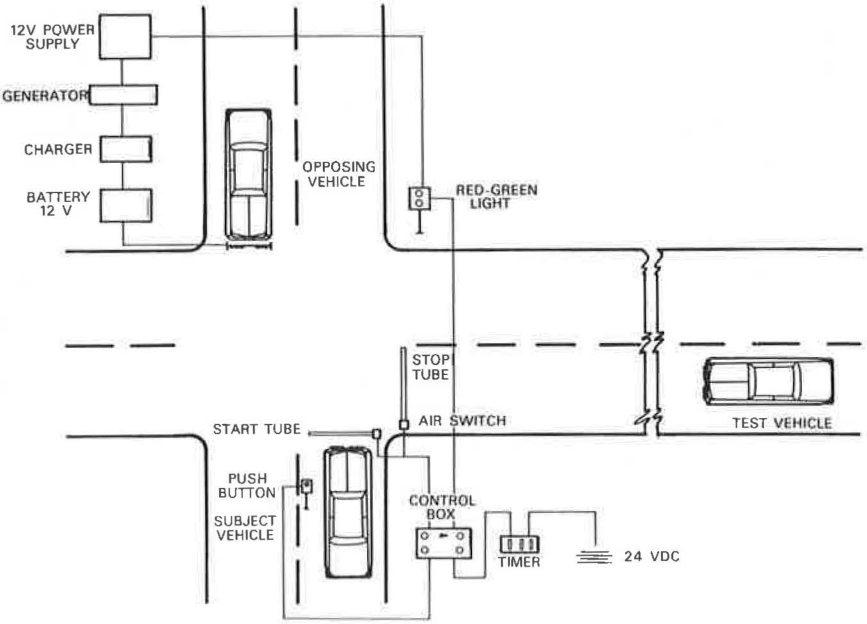


Figure 1. Intersection layout.

Eight fully dynamic runs with both vehicles moving were interspersed with the semidynamic runs within a random pattern to keep the experimental subject realistic in the responses.

When the red light was on and the subject signaled his decision by touching the large, metallic push button, which was 6 in. in diameter, an electrical pulse started a transistorized timer running. The timer continued running until the test vehicle entered the intersection and crossed the pneumatic tube connected to an air switch (Fig. 1). The elapsed time between the moment of decision and the arrival of the test vehicle at the intersection was thus recorded to the nearest millisecond. The gap size was measured in terms of time. This measurement was converted to distance based on a constant speed for the test vehicle. This was done to allow the data from more than one speed to be pulled for analysis purposes. Because the test vehicle had obtained this predetermined velocity before the 1,600-ft point, the consistent-speed assumption was reasonable.

During the performance runs when the signal light was green, the subject vehicle crossed a pneumatic tube placed just in front of the vehicle's front tires to start the timer. Otherwise, the same instrumentation was used. In order to provide an additional stresser to the experimental situation, an opposing vehicle was placed across the intersection from the subject vehicle. During all of the performance runs and for one-half of the judgment runs, the opposing vehicle's head lamps were turned on. These head lamps were operated in the same mode as those of both the subject and test vehicles. At the start of an experimental run, the subject was required to observe the signal lamp approximately 15 ft to the left of the opposing vehicle, as shown in Figure 2.

At this point he was subjected to considerable glare under some of the head-lamp operational modes, and his visual adaptation was somewhat elevated. When the test vehicle was 1,600 ft away and the signal lamp was turned on, the subject could shift his visual attention toward the test vehicle and, therefore, was no longer influenced directly by the glare from the opposing vehicle.

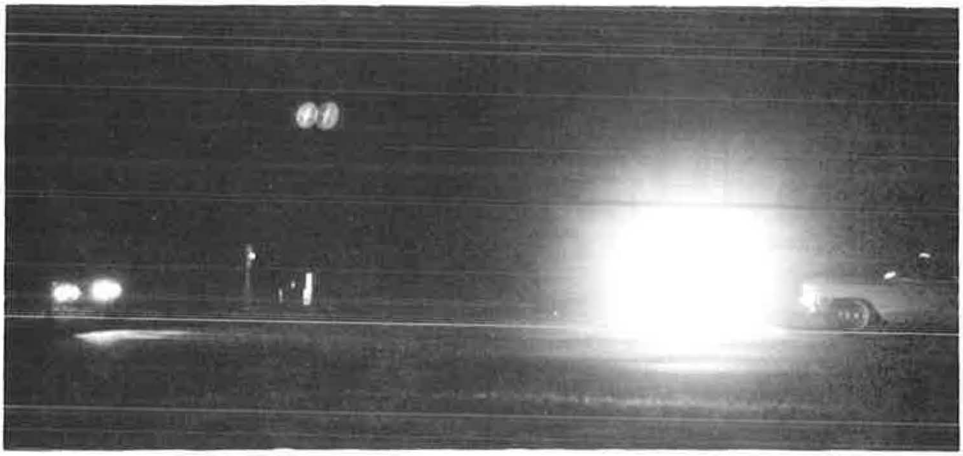


Figure 2. Intersection during the experiment. Test vehicle is approaching with high beam.

The test vehicle was driven at a constant speed for each experimental run. To avoid the use of distance cues, 4 test vehicle speeds—20, 30, 45, and 60 mph—were used for the judgment conditions, and 2 speeds—20 and 45 mph—were used for the performance runs. The order of the runs was completely random with each subject receiving a different order to reduce any effects of learning and fatigue on the end results. A total of 40 experimental runs was used with each subject.

On completion of each experimental run, the subject was asked to complete a subjective evaluation of his discomfort caused by the glare to which he was exposed during the previous run. A copy of the form used is shown in Figure 3.

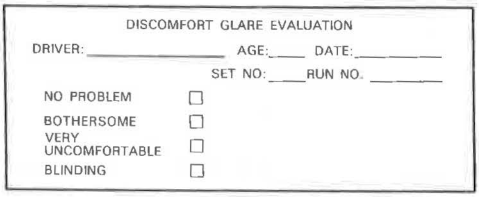
VEHICULAR LIGHTING MODES

Four types of lighting systems were used on the 3 vehicles involved in the experiment. These consisted of the following:

1. Conventional low beam,
2. Conventional high beam,
3. Polarized high beam with visor, and
4. Polarized high beam with glasses.

During each run, however, only 1 system was used and all vehicles displayed the same lighting system.

Polarized light cannot be identified as such by the naked eye, but when suitably viewed through an analyzer is found to behave differently (Figs. 4 and 5). As early as 1920, Short and Chubb pointed out the possibility of a polarized type of headlighting system (3). This system would provide a "light-lock" illumination in which drivers would have adequate visibility to see objects on the road between approaching vehicles but in which neither driver would recieve glare directly from the other vehicle's head lamps. By viewing these lamps through a crossed polarizer, a driver would perceive the approaching vehicle's head lamps as dim spots of light about as noticeable as parking lamps (Fig. 5).



DISCOMFORT GLARE EVALUATION

DRIVER: ____________ AGE: ____ DATE: ________

SET NO: ____ RUN NO. ________

NO PROBLEM ☐

BOTHERSOME ☐

VERY UNCOMFORTABLE ☐

BLINDING ☐

Figure 3. Subjective evaluation form.

In a recent series of studies by Hemion (4, 6) and Hare (5), polarized lighting systems have been investigated and shown to

Figure 4. High-intensity head lamps without analyzer.

be a more effective method of illumination than conventional systems for the highway-meeting situation. Because it was the purpose of this experiment to study gap-acceptance behavior under various degrees of glare, a polarized system was adopted and 2 types of analyzers were used. The first condition involved a visor form that was attached to the normal sun visor. This gave good glare protection to the subject looking straight ahead at the signal light and opposing vehicle, but when he looked at the test vehicle he was exposed to a glaring intensity similar to conventional high beam. The second type of analyzer was in the form of a pair of glasses that, therefore, moved with the subject's head. The degree of protection, therefore, was closer to that of conventional low beam for this right-angle situation.

Figure 5. High-intensity head lamps with analyzer.

Each vehicle was equipped with the standard 12-volt, 5¾-in. diameter, type 4001 and 4002 sealed-beam head-lamp system. The low-beam filaments operated at 50 watts each, and 4 high-beam filaments each required 37.5 watts. These were mounted on a horizontal line in the standard manner to conform to Motor Vehicle Safety Standard No. 108. Two additional 5¾-in. diameter, type 4001 head lamps, each rated at 100 watts, were mounted just inside the other lamps and replaced

Figure 6. Vehicle equipped with a sealed-beam head-lamp system.

the lower wattage 4001 unit for the polarized system. Figure 6 shows the test vehicle shortly after this study was conducted. (The additional lamp just to the right of the license plate was not present during this experiment.) For practical reasons, the lamps of the stationary opposing vehicle were mounted on a test stand directly in front of the vehicle instead of being physically attached and were connected with a 12-volt battery, which, in turn, was charged continuously so that the intensity of the head lamps remained the same throughout the experiment. To produce the polarized beams, dichroic filters were placed in front of the head lamps and were aligned so that the plane of vibration of the emergent light was 45 deg to the horizontal plane. The axis of the analyzer had the same orientation as the head lamps and, therefore, was perpendicular to that of oncoming head lamps.

EXPERIMENTAL DRIVERS

Two groups of 10 licensed male drivers each were recruited to participate in the experiment. Each driver was used only once, completing all 40 experimental runs on 1 night (for 1 driver from each group, the runs could not be completed within the same night and were completed on a second night). The first group of drivers consisted primarily of college students in their twenties with a minimum of 2 years' driving experience. The second group was mainly nonengineering personnel from 2 local highway departments. This group was selected to evaluate the effect of driver's age on the experimental situation. All drivers in this group were over 50 years of age.

Berg (2) has shown that older drivers are much more sensitive to glare than are younger drivers. Both contrast thresholds and recovery time after exposure to glare are relatively constant until approximately ages 40 and 45, and then they deteriorate rapidly. It was, therefore, hypothesized that the older group, while having more driving experience, would be relatively poorer as a group in making the type of visual judgment and reaction required in this test.

The subject arrived at the test site after dark and was taken to a trailer parked about ½ mile from the intersection and given a standardized vision test. If the subject driver normally used glasses for driving, they were used during all phases of the testing. The results of the vision tests are given in Table 1. While still in the trailer, the subject was given a set of written instructions and some biographical information was obtained. Only when all the equipment was set up and operating, was the subject brought out to the intersection. He was given 2 practice runs—one performance and one judgment—before the actual experimental runs began.

TABLE 1

DRIVER VISUAL CHARACTERISTICS AND AGE

Driver	Phoria		Acuity			Stereopsis Depth (percent)	Age
	Vertical	Lateral	Right	Left	Both		
18 to 30 Years Old[a]							
1	0.17	-0.66	20/20	20/17	20/18	88.5	23
2	0.17	0.33	20/33	20/29	20/25	76.5	21
3	0.17	0.33	20/20	20/18	20/18	102.4	20
4	0.50	4.33	20/22	20/29	20/22	96.0	23
5	0.17	1.33	20/20	20/18	20/20	96.0	20
6	0.50	-0.66	20/20	20/22	20/20	88.5	21
7	0.17	2.33	20/20	20/18	20/17	106.5	20
8	0.50	1.33	20/18	20/18	20/18	102.4	21
9	0.17	2.33	20/17	20/20	20/20	96.0	19
10	0.17	2.33	20/22	20/25	20/22	88.5	20
Over 50 Years Old[b]							
1	0.50	-1.66	20/22	20/20	20/18	103.6	62
2	0.17	-1.66	20/18	20/18	20/18	102.4	60
3	0.17	7.33	20/29	20/40	20/29	56.6	70
4	1.00	5.33	20/25	20/22	20/22	76.5	60
5	0.17	0.33	20/20	20/18	20/18	56.6	53
6	0.17	1.33	20/20	20/22	20/18	84.4	51
7	0.50	4.33	20/22	20/20	20/18	103.6	57
8	0.17	1.33	20/25	20/25	20/29	76.5	54
9	0.17	3.33	20/20	20/20	20/18	76.5	50
10	0.5	-0.66	20/17	20/17	20/17	96.0	54

[a] Average age, 20.8 years; average driving experience, 4.5 years.
[b] Average age, 57 years; average driving experience, 35.8 years.

RESULTS

The data for gap size, elapsed time between the action taken (decision) by the subject driver, and the arrival of the approaching test vehicle at the intersection, were first transformed into distance based on the appropriate test vehicle speed in order to combine the data from runs conducted at different speeds. An analysis of variance was performed on each experimental series to determine whether the observed differences in gap-acceptance means were real differences or due to variance in the experimental situations. As expected there were significant differences among lighting modes on both tests in judgment and performance and also between age groups in the performance test.

Lighting Mode

Further analyses were made to ascertain which of the lighting modes contributed to these differences. A summary of these analyses is given in Table 2. The data from the performance and the judgment series indicated statistically significant differences at the 5 percent level of confidence on the combinations of low beam versus high beam and low beam versus polarized beam with visor. The data from the performance test alone showed 2 additional combinations to be significant: high beam versus polarized beam with glasses and polarized beam with visor versus polarized beam with glasses. This is probably because the driver was more alert during the performance runs and stimulated from the involved risks, the test being performed under more realistic conditions.

In general, it can be concluded that the drivers required a slightly longer gap in traffic under those situations where the glare level was highest, that is, high beam and polarized beam with visor. This difference in gap acceptance was no greater than 50 ft under most situations (Tables 3 and 4). Figure 7a shows the mean values for all 10 drivers of each age group for the performance run. Comparable data from the 20- and 45-mph judgment run are shown in Figure 7b. The data show similar trends, and small differences in the judgment runs are due largely to the experimental situation.

TABLE 2

SUMMARY OF ANALYSES OF VARIANCE ON LIGHTING MODE COMBINATIONS

Source of Variation	F-Ratio	Significant at 5 Percent Level[a]
Judgment test		
Low beam and high beam	3.02	Yes
Low beam and polarized beam with glasses	1.58	No
Low beam and polarized beam with visor	4.44	Yes
High beam and polarized beam with glasses	0.176	No
High beam and polarized beam with visor	0.190	No
Polarized beam with glasses and with visor	0.670	No
Performance test		
Low beam and high beam	4.67	Yes
Low beam and polarized beam with glasses	0.033	No
Low beam and polarized beam with visor	6.13	Yes
High beam and polarized beam with glasses	4.52	Yes
High beam and polarized beam with visor	0.16	No
Polarized beam with glasses and with visor	7.57	Yes

[a] Judgment, 2.97; performance, 4.41.

TABLE 3

MEAN GAP ACCEPTANCE AND STANDARD DEVIATION VALUES IN FEET—PERFORMANCE TEST

Age Group and Speed	Low Beam		Polarized Beam With Glasses		Polarized Beam With Visor		High Beam	
	Gap	Standard Deviation	Gap	Standard Deviation	Gap	Standard Deviation	Gap	Standard Deviation
20 and 45 mph								
Both groups	223.2	73.81	227.1	76.89	285.0	82.12	277.2	86.10
18 to 30 years old	206.1	75.40	234.3	70.62	279.5	87.33	270.5	82.05
Over 50 years old	240.3	72.31	220.0	88.15	290.6	103.52	284.0	91.26
20 mph								
18 to 30 years old	160.2	66.59	186.2	72.68	242.6	58.25	293.3	60.85
Over 50 years old	185.2	64.22	198.3	71.98	272.6	88.52	224.4	80.54
45 mph								
18 to 30 years old	252.0	67.37	282.4	79.26	316.4	98.19	301.7	94.08
Over 50 years old	295.4	91.63	241.7	80.89	308.6	74.96	343.7	110.63

TABLE 4

MEAN GAP ACCEPTANCE AND STANDARD DEVIATION VALUES IN FEET—JUDGMENT TEST

Age Group and Speed	Low Beam		Polarized Beam With Glasses		Polarized Beam With Visor		High Beam	
	Gap	Standard Deviation	Gap	Standard Deviation	Gap	Standard Deviation	Gap	Standard Deviation
20, 30, 45, and 60 mph								
Both groups	253.2	65.4	273.5	61.4	285.4	06.4	279.2	88.8
18 to 30 years old	256.0	78.5	280.3	78.9	281.2	108.8	283.2	89.0
Over 50 years old	250.1	71.5	266.7	66.2	289.7	89.4	274.0	79.2
20 mph								
18 to 30 years old	195.8	65.66	190.7	50.80	185.9	55.13	186.8	56.65
Over 50 years old	204.2	54.60	225.3	59.90	243.4	76.37	231.7	57.47
30 mph								
18 to 30 years old	236.4	73.57	265.4	95.57	271.3	131.87	270.3	110.81
Over 50 years old	232.7	80.08	249.6	74.90	272.1	69.79	255.4	80.92
40 mph								
18 to 30 years old	254.4	85.54	294.2	90.49	295.2	106.74	313.8	103.24
Over 50 years old	264.9	89.74	276.6	74.87	304.8	91.06	285.0	88.16
60 mph								
18 to 30 years old	339.8	92.72	370.9	105.53	372.3	129.49	375.3	128.12
Over 50 years old	300.1	98.30	315.3	68.63	338.5	125.65	324.2	124.01

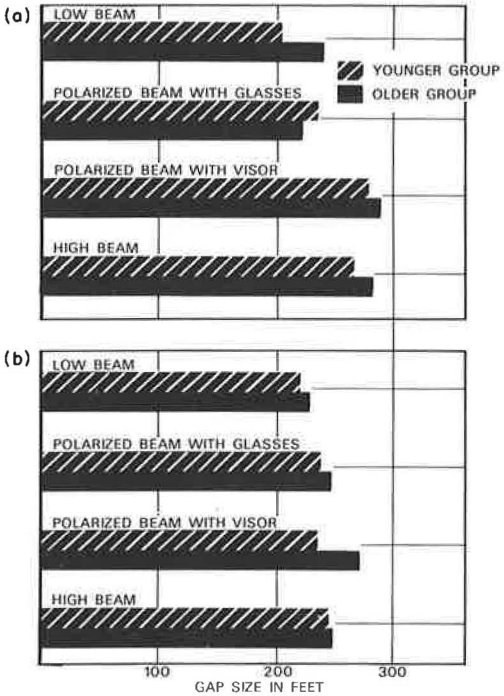


Figure 7. Mean gap-acceptance distance for each lighting mode and age group—20 and 45 mph—(a) performance test, (b) judgment test.

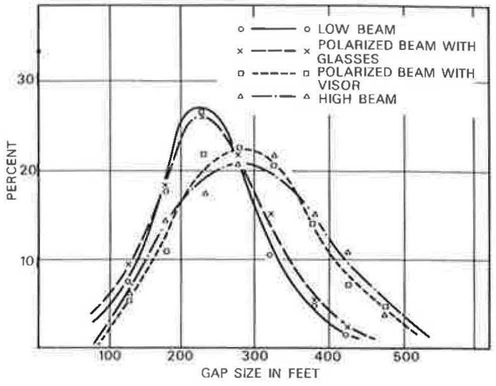


Figure 8. Distribution of gap acceptance for each lighting mode—performance test.

The high beam and polarized beam with visor produced almost identical distributions of gap size as shown in Figure 8 for the performance runs. Greater variability was observed in those runs employing these 2 modes (Table 3 and Fig. 8). The data for low beam and polarized beam with glasses again clustered about the same points and demonstrated much less variability. The judgment runs lead to much the same conclusion, but the differences are less striking. The test situation was developed to explore the effect of the glare from a vehicle approaching at a 90-deg angle to the orientation of the subject vehicle. The visor in the subject vehicle was mounted on the sun visor and only protected the subject from glare when he was looking straight ahead. When the subject turned his head to look at the test vehicle, he was not protected by the visor and, therefore, received approximately the same glaring intensity as with the high beam. The glasses, on the other hand, provided protection regardless of which way the driver turned his head. From the preceding consideration, it would appear evident that glare level was the prime factor causing the differences among the 4 lighting mode conditions.

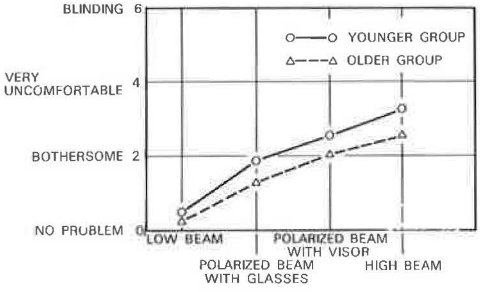


Figure 9. Discomfort glare evaluation for each lighting mode.

Discomfort Ratings

As discussed in the preceding, the subjects were asked to evaluate their discomfort at the completion of each run. The results are shown in Figure 9. As expected, the best rating (lowest numerical score) was for the low-beam conditions for both age groups, and the worst was for the high-beam conditions; the 2 polarized conditions were in between. In all probability the polarized condition with glasses would have been given lower discomfort scores if the drivers had had an opportunity to align the axis of their glasses perpendicular to the

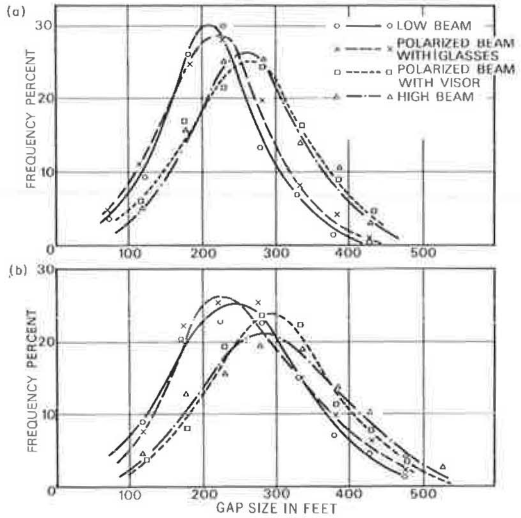
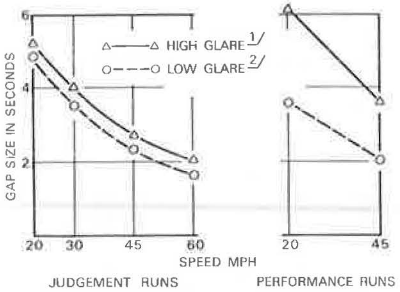


Figure 10. Distribution of gap acceptance for each lighting mode and age group—performance test—(a) younger group, (b) older group.



1/ HIGH BEAM & POLARIZED BEAM WITH VISOR

2/ LOW BEAM & POLARIZED BEAM WITH GLASSES

Figure 11. Mean gap-acceptance times for each speed.

axis of the polarizers on the approaching vehicle. This is quite easy to do in a head-on meeting situation, but, when the approaching vehicle is at 90 deg, the normal tilt of the driver's head makes this more difficult. Two of 20 drivers, both in the older group, objected and hesitantly used the polarized glasses for the required runs. This was probably because of the general hesitancy of people in the older age ranges to wear glasses.

The numerical rating of discomfort was, contrary to expectation, somewhat lower for the older group of subjects. Individuals in the over-50-years-of-age category generally have a higher sensitivity to glare and, therefore, it was expected that they would experience somewhat greater discomfort. One explanation of the result obtained is that, because these subjects had experienced somewhat greater problems in night driving, they overcompensated in their subjective evaluations. Another possibility is that this particular group of subjects was not typical of the over-50 category. It was much more difficult to recruit the older subjects, and it is quite likely that our older group had better visual abilities than those suggested by the normative data published for that age group. The 2 age groups showed statistically significant differences on the performance runs. Figure 10a and 10b compare the distributions of the 2 age groups for each lighting mode. The older group had a higher variability and possibly required somewhat longer distances to perform the task.

The effect of speed on gap acceptance was examined for the 4 speeds used during the experiment. The difference was not significant among lighting modes at various speeds on the judgment runs, but on the performance runs there was a statistically significant difference at the 5 percent level for the interaction of speed and lighting mode.

Figure 11 shows that the gap-acceptance times associated with high-glare lighting modes were greater during the performance runs. The lower speed produced longer gap times that presumably were due to the uncertainty with regard to the speed of the oncoming vehicle.

DISCUSSION AND SUMMARY

The study presented here was primarily designed to determine the effect of headlight glare from approaching vehicles on gap-acceptance behavior at a right-angle intersection. In general, the 4 vehicular lighting systems used could be divided into 2 subgroups: those producing a low level of glare at the eye of the subject driver, and those producing a higher level. There was a consistent pattern of differences among these modes, especially under the fully dynamic test condition in which the subject was forced into taking risks. Under the more glaring conditions, the subject drivers required a longer gap-acceptance time and there was greater variance in the data. This variance was not sufficiently large to cause the 2 distributions to completely overlap. When exposed to the high-glare conditions the subjects never accepted gaps quite as short as the extreme cases for the low-glare conditions. Therefore, the high-glare conditions appeared to make drivers behave more conservatively and to allow a somewhat greater margin of safety.

The advantage of low-glare systems of headlighting in terms of gap acceptance was significant, but whether it has any practical significance is questionable. In general, the differences were small; however, in the performance study, differences in mean values for the older group of subjects were as much as 100 ft or more (Table 3) between the extreme cases. This might have an adverse effect on traffic flow, particularly when a high volume exists on the main road, such as the volume during the evening peak hours. If a polarized headlight system is to be introduced to obtain the considerably superior forward visibility during meeting situations, which other studies have shown it to have, then more effort should be expended on the design of a better analyzer or viewer system to protect drivers during encounters with vehicles from the side. This may be especially desirable for older drivers, although there are several studies that show this group to drive less after dark.

There is evidence in this study that a satisfactory design for an analyzer in a polarized headlighting system can be produced. A polarized system using a visor that protects the driver from glare coming only from vehicles as they approached head-on produced much the same gap-acceptance distribution as the high-beam system. The situation was improved by use of glasses that provided protection to the sides also.

In the performance studies, the younger age group, in general, had lower gap-acceptance values and showed less variability in their performance than the over-50 group. In the judgment studies, the differences were less sharply defined. Both groups had the same pattern of acceptance values for the 4 lighting modes. In a discomfort glare evaluation, the majority of drivers in both groups expressed the belief that both polarized lighting systems were better than conventional high beams. However, low-beam lamps seemed least bothersome of all in the right-angle approach situation studied.

The experiment showed no significant difference among vehicular lighting modes at the different speeds. As might be expected, the minimum distances considered safe by our subjects for gap acceptance at low speeds were less than those accepted at higher speeds. However, in terms of time gap, the gaps were somewhat greater at lower speeds.

The comparison of the results of the 2 methods of study—performance versus judgment—indicates the necessity to go to the fully dynamic test situation for valid results in this type of complex behavioral situation. Until the subject is exposed to a situation in which he assumes what would appear to him to be his normal risk-taking situation, the result, while perhaps showing trends in the appropriate direction, will not necessarily be indicative of the real-world performance. Therefore, if further investigations should be made of the effect of vehicle lighting systems at intersections, these investigations should be done in fully dynamic test situations.

CONCLUSIONS

The authors derived the following conclusions:

1. The distance interval accepted by drivers as a minimum safe gap to cross an intersection was somewhat longer under conditions of forward vehicular illumination that produced more glare. There were also greater variances in the more glaring conditions.
2. If a polarized headlighting system is to be used, it is desirable to provide the driver with an analyzer system that protects him during encounters with vehicles from the side as well as during a head-on meeting situation.

3. The younger driver had shorter gap-acceptance values with less variable performance than did the older driver.
4. The subjective discomfort glare evaluation showed that each of the 2 polarized systems tested was superior to conventional high-beam systems. However, low-beam lamps were least bothersome for the situation studied.
5. The minimum time gap accepted was much greater at lower speeds.
6. If further investigations should be made of the effect of vehicle lighting at intersections, a fully dynamic test procedure should be used, particularly for high-glare conditions.

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Summary of Current Status of Knowledge on Rural Intersection Illumination

M. E. LIPINSKI, G. C. MEADOR, A. L. GILBRONSON, M. L. TRAYLOR, W. D. BERG, C. L. ANDERSON, and R. H. WORTMAN, Department of Civil Engineering and Highway Traffic Safety Center, University of Illinois, Urbana

The purpose of this report is to review the status of knowledge as of June 1968 regarding roadway illumination at rural at-grade intersections and to summarize current practices. Over 300 references have been reviewed. From this review of literature and the results of a survey of current practices, it was determined that very few research studies pertaining to illumination problems at rural at-grade intersections have been conducted; but the need for such work has been shown by the interest states and other organizations indicated in their replies to survey questionnaires. The scarcity of developed programs of intersection illumination across the country substantiates the need for standard lighting programs and warrants for these rural problem areas. Background information on the extent of current practices in the area of rural at-grade intersections was obtained by survey questionnaires sent to 49 state highway departments and various other organizations and industries concerned with roadway lighting problems. Replies indicated that very few programs were in operation but that there was a widespread interest in roadway illumination programs.

•ACCIDENT STATISTICS reveal that operating a motor vehicle is more hazardous at night than during daylight. Although there may be many reasons, such as tired or drunk drivers, for the increase in the nighttime accident rates, the primary difference between the 2 periods is the level of roadway illumination. Thus, the rate of nighttime accidents, which is 2 to 3 times greater than that for the daytime period, can probably be attributed to the reduced visibility at night.

The most comprehensive means of correcting poor nighttime visibility is roadway illumination. Highway lighting provides quick, accurate, and comfortable visual conditions for the driver at night and thus reduces nighttime accidents and attendant human misery, increases roadway capacity, facilitates traffic flow, and saves money and working time.

Fixed roadway lighting has been effectively utilized for a number of years in urban areas where illumination has generally reduced accident rates, improved traffic flow, and improved overall operating efficiency of the roadway. The use of street lighting or fixed roadway illumination in rural areas, however, has been limited. Although many illumination experts currently think that all high-speed highways should be illuminated, they realize that current financing and the extensive mileage of rural highways do not permit the lighting of all of these roadways. In essence, whether to light a section of roadway becomes a compromise between safety and economics, and priorities must be assigned to the locations of greatest need.

Accident rates at intersections are generally higher than elsewhere on the roadway because of the increase in the opportunity of conflict between motor vehicles and the increase in driver decisions and complexity of the driving task. It is reported that about 15 percent of fatal rural accidents and 25 percent of all rural motor vehicle

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Paper sponsored by Committee on Visibility.

accidents occur at intersections (1). The intersections, however, account for a very small portion of the total rural highway mileage.

In view of the urban experience with roadway illumination and the rural intersection problem, the rural intersection illumination project was initiated. The general objective of the study is to develop techniques and procedures for the selection of rural at-grade intersections to be illuminated and, subsequently, to determine the level and types of illumination to be used.

The value of intersection lighting has been demonstrated in several studies including one in Virginia where fatalities were reduced by 92 percent after the installation of lighting (24). However, this study analyzed data collected at 9 intersections located in urban areas. Further study is needed to determine more precisely the effect that illumination of rural intersections has on nighttime accident rates, capacity and flow improvement, and financial savings. This information would make it possible to establish a set of criteria or warrants for the illumination of rural intersections, with a view toward encouraging the more efficient use of available highway funds.

This report by the project staff compiles information as of June 1968 concerning roadway illumination of rural intersections. Although there has been a great amount of work accomplished in the general area of roadway illunination, very little research has been directed toward the rural area.

After more than 300 references dealing with roadway illumination were compiled the findings were organized into an overview of the status of knowledge about illumination of rural at-grade intersections. The various factors or characteristics of illumination have been considered individually in the report; but each phase or element must be considered as a part of the entire system if the installation of lighting is to be successful.

In addition to reviewing previous work, the project staff felt it should include, as an integral part of this status report, a summary of current rural intersection illumination practice. To determine the current status of rural at-grade illumination, questionnaires were sent to state and county highway departments and to other organizations concerned with this problem. The summary of replies to these questionnaires is included in this report.

HISTORY OF STREETLIGHTING

Although emphasis on the various objectives of streetlighting has changed during the past 400 years, the basic aims have remained the same: (a) crime reduction and civic betterment, (b) improved traffic capacity and operations, and (c) improved traffic safety.

Crime reduction was the primary motivation when Paris installed lighting systems as early as 1558. At that time the city was so plagued with robberies that the municipal government passed an ordinance requiring all citizens to keep lights burning in their front windows. Today, too, lighting is used to detect vandalism and make public areas safer. Evidence of the value of good streetlighting was offered by the "Christian Science Monitor", which stated in 1959 (61), "In both New York and Boston this year, careful tests comparing the number of crimes committed under bright lights and under dim, or inadequate, street lights have given convincing evidence that light bulbs can be used to fight crimes."

Civil betterment has been important to the illuminating engineer since 1880 when in Wabash, Indiana, giant arc lamps were placed atop the courthouse to light the business district. Merchants in other towns soon discovered that attractive streetlighting could draw customers to their shopping areas. This realization prompted the development of the "White-Way" ornamental lighting systems that were in popular use from 1907 to 1930.

Although crime reduction and civic betterment are important benefits of streetlighting, improved traffic capacity and operation and improved traffic safety are more directly related to a study of illumination of rural intersections. Since the 1920's, emphasis in streetlighting has been on these 2 goals, which will be discussed further in a later section on benefits of lighting.

The trend toward modern streetlighting began in 1924 when the International Commission on Illumination recommended that a study of streetlighting be undertaken and the findings be presented at its next meeting. During the same year, the National Bureau of Standards, in consultation with the Illuminating Engineering Society (IES), developed the first circular on streetlighting.

In 1925, the Council of IES voted to organize a committee on streetlighting; that committee, now known as the Roadway Lighting Committee, has been in existence ever since. Its purpose reflects the evolution toward scientific methods in streetlighting by that time and is stated by the Council as follows (62): "... to establish the scientific principles underlying street and highway lighting; to collect data on the results of the application of such principles to actual practice; and to prepare such reports thereon as will assist technicians and benefit the public."

The original IES Roadway Lighting Committee was composed of representatives of varied bodies such as government, industry, consulting firms, electric utilities, manufacturers, and universities. Thus, reports produced by the Committee integrated information from many sources with an interest in, or responsibility for, street and highway lighting. These reports have become authoritative sources for technical streetlighting knowledge. The Committee formulated, for example, the American Standard Practice for Roadway Lighting (2), which is approved by the American Standards Association and serves as a basis for new lighting systems installed by both city officials and utilities. Other publications of the Committee include the following: Principles of Street Lighting (1928), Code of Street Lighting (1930, 1935), Code of Highway Lighting (1937), Recommended Practice of Street Lighting (1940), and Recommended Practice of Street and Highway Lighting (1945).

In 1961, a new lighting system using the results of the most comprehensive survey ever taken up to that time was installed in Milwaukee. The new installation, a landmark in application of scientific knowledge to streetlighting, featured calculated control of light by means of refractors, which decreased the light directly below the luminaires and increased the light at points between adjacent luminaires. High mounting heights were used to help distribute the light and to minimize the glare and blinding effect. The entire installation conformed suprisingly closely to the requirements in the IES publication, Recommended Practice for Street Lighting, published 24 years later (62).

Just as the streetlighting program in the United States was gaining momentum, World War I interrupted most construction. By 1920, however, construction was again in full swing, and most utility companies began to replace their old lighting systems with the more efficient and economical incandescent filament bulbs. During the next decade, improvements involving light sources and luminaire design led to major changes in the existing methods of streetlighting. In 1934 both the mercury vapor lamp, rated at 400 watts, 1,500-hour life, and 35 lumens/watt, and the sodium vapor light were introduced. Both were designed for higher mounting heights (25 to 30 ft) than had previously been used. They provided more uniform light distributions, had higher utilization efficiency, and were easier to install and service than the systems they replaced.

When the importance of night vision in reducing traffic fatalities became apparent in the late 1930's, investigations were begun to determine the part streetlighting could play in accident prevention. On December 9, 1947, the Connecticut Highway Safety Commission reported on streets relighted in 1936 (62): "During the 10-year period, July 1, 1937, to July 1, 1947, there was a 76 percent reduction in night fatalities, a 78 percent reduction in night pedestrian accidents, a 71 percent reduction in night car-occupant injuries and a 58 percent reduction in all types of accidents."

With the onset of World War II, lighting progress came to a standstill once more; materials were difficult to obtain and the only construction permitted was that necessary to maintain the existing systems. Shortly after the end of the war, the Roadway Lighting Committee submitted to the Council the 1945 edition of Recommended Practice of Street and Highway Lighting. Included were recommendations for greater mounting heights for luminaires, a minimum lamp size of 2,500 lumens, and the classification of luminaires into the 5 lateral light distributions that are in use today (62).

The trend toward the mercury vapor lamp gained momentum in 1952 because of developments that increased its life expentancy. During the mid-1950's the color quality of the characteristic blue-green mercury light was improved by a coating of red-fluorescing phosphor on the interior of the outer bulb. Meanwhile the fluorescent bulb was being used in experimental installations to determine its feasibility for streetlighting. Early attempts proved economically unfeasible, but in 1952 a high-output fluorescent lamp with improved low temperature characteristics was combined with a new type of luminary to make fluorescent street lighting practical and attractive (62).

The trend in roadway lighting in the last 15 years has been toward arc lamps in the form of mercury arc discharge lamps. The use of 1,000-watt mercury lamps, producing more than 50,000 lumens in each luminary, is rapidly increasing as appreciation of the visibility really essential for night driving grows (55).

BENEFITS FROM ILLUMINATION

The illumination of rural at-grade intersections should be carried out with 2 primary objectives in mind: (a) reduction of accidents at the site, and (b) improvement of the capacity of the intersection and facilitation of traffic operations.

Accident Reduction

During 1967, traffic accidents killed 52,000 people, injured another 4.2 million and resulted in an economic loss to the nation of over $9 billion (3). The severity of nighttime accidents is pointed out by Baldwin whose study of traffic accidents during 1952 showed that 55 percent of the fatal accidents that year occurred during night hours (5). The Joint Committee of the Institute of Traffic Engineers and the Illuminating Engineering Society reported that during 1964 the rate of deaths per miles of travel at night was 2½ times as great as the day rate (50). The mileage death rate quoted by Baldwin using 1952 data was even more severe: 14 deaths in 100 million miles at night compared to 5 deaths every 100 million miles in daylight, exhibiting a ratio of almost 3 to 1.

These statistics indicate that nighttime creates special problems for drivers. There are substantial differences between day and night driving, the most obvious of which is visibility. Other factors that may contribute to night driving problems include fatigue, alcohol, and the type of driver on the road. Richards has stated (56) that "vision is necessary but not sufficient for safe and efficient night driving. Other factors, other senses, the coordination of the central nervous system, motor responses, the vehicle and the road, are also important and must be considered."

Lauer sampled drivers on highways in Iowa in each hour of the day (5). He reported that travel and age were inversely related at times when traffic flow was lightest. For instance, on rural roads between midnight and 7:00 a.m., 51 percent of the drivers were between the ages of 20 and 29, with most of them younger than 24. This same age group of drivers constituted only 23 percent of the daylight traffic. Lauer reported that a significant portion (about 10 percent of the 20- to 24-year-old age group) "flagrantly and dangerously violated safety rules from midnight to 4:00 a.m." He found only isolated cases of excessive speed among other age groups. Lauer's findings suggest that after midnight there is more reckless operation of motor vehicles than at any other time of the day (at least in proportion to the miles driven). Therefore, it is not surprising to find the death rate during dark hours relatively high.

Accurate information about the effect of fatigue on accidents is difficult to obtain. Although accidents in which the driver is reported as "apparently asleep" occur most often during the hours of darkness when most drivers are accustomed to sleep, no real quantitative measures are available to estimate the importance of this problem.

There is evidence to indicate that the incidence of alcohol consumption among drivers reaches a peak during hours of darkness. A study made in 1938 indicated very definite peaks in the time distribution curve for drivers under the influence of alcohol for both accident and nonaccident cases (5). In Michigan, 77 percent of the accidents involving drinking drivers occurred during the hours of darkness (5).

Reduced visibility is also a proven hazard to nighttime drivers. Increased illumination along the roadway leads to a reduction in nighttime accident rates (17). The analysis of the effect of lighting on accidents, however, is extremely complex. The installation of new lighting or the improvement of an existing system does not necessarily result in a decrease in the actual number of nighttime accidents (50). Before-and-after studies of illuminated areas are therefore often based on the percentage of nighttime accidents as compared with the total. This method takes into consideration the possible traffic fluctuations over a long period that generally appear as increases in total traffic. Ideally, lighting studies should be based on the rate of vehicle-miles of travel as determined by extensive traffic counts for both day and night.

In Kansas City, primary and secondary arteries in the urban area were lighted to levels of illumination believed at that time to be adequate for the traffic volume, as recommended in the 1947 American Standard Practice for Street and Highway Lighting (50). A study of all accidents was made then on nearly 93 miles of major routes, and the accident reduction was compared with the level of illumination provided on the various routes. Overall nighttime accidents along these routes decreased in direct proportion to the amount of illumination installed (Fig. 1). A comparison of only fatal and injury-producing accidents on these routes showed no improvement where streets were lighted to less than 0.4 footcandle (ft-c), but produced an average nighttime reduction of 53 percent for the better lighted routes (0.4 to 0.9 ft-c).

Similar studies in Connecticut, Indiana, and New Jersey reaffirmed the effectiveness of roadway lighting in reducing vehicular and pedestrian accidents. The Connecticut study was based on accident experience on 6 city streets before and after relighting. Day and night traffic increased about 24 percent and 29 percent respectively, indicating the general increased use of motor vehicles and also the preference on the part of motorists for driving on well-lighted streets. Although the number of day accidents increased after relighting, following the general trend of the increased traffic volume, the number of nighttime accidents was reduced by 24 percent in spite of the increase in night traffic volume (21).

A safety lighting program at approximately 60 locations was instituted in Indiana. The results of a study of the accident experience at several locations where reliable

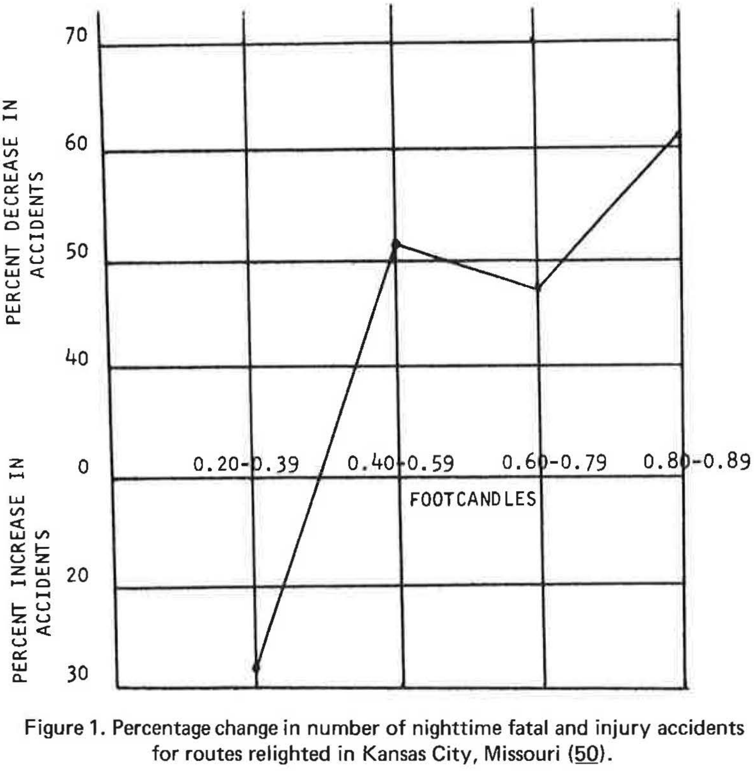

Figure 1. Percentage change in number of nighttime fatal and injury accidents for routes relighted in Kansas City, Missouri (50).

before-and-after accident information was available showed a significant reduction in accident statistics after illumination. At one intersection near Gary there were 3 fatalities in 11 night accidents in the year prior to the installation of 5 lights. The following year there was only 1 night accident (10).

In Trenton, New Jersey, the streetlighting system was improved by a 36 percent increase in average illumination (Fig. 2). Pedestrian nighttime accidents (fatal and injury) were reduced by 30 percent. The effective reduction, based on the ratio of daytime to nighttime accidents, was 37 percent whereas the overall nighttime reduction was 10 percent (50).

The subject of safety has received considerable attention in the past and will probably receive even more emphasis in the future. In analyzing the results of various accident studies, researchers often disagree because of improper definition of the problem. For example, research projects are frequently carried out on inadequately lighted

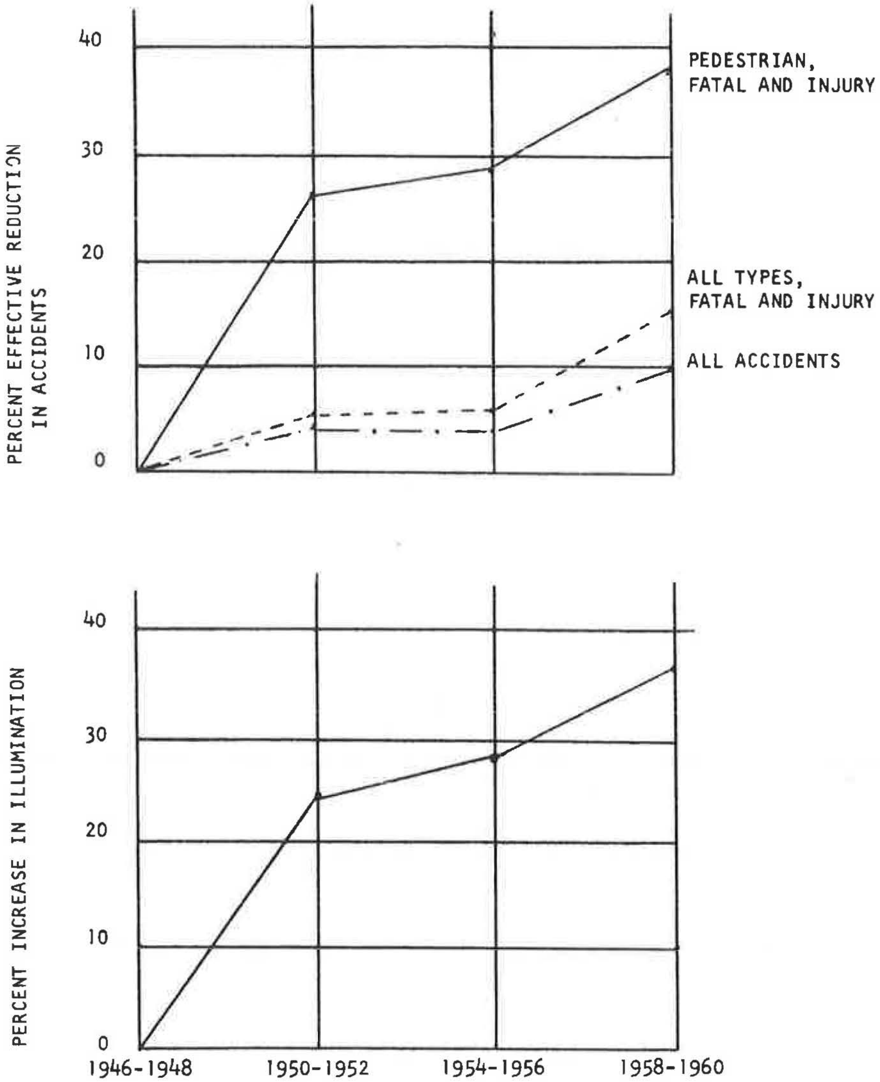

Figure 2. Effective reduction in pedestrian nighttime accidents in relation to increase in illumination levels in Trenton, New Jersey (50).

roads with low levels of illumination and uniformities below the minimum requirements. In such cases, with low levels of illumination, poor uniformity, and a considerable degree of glare, the lighting may not help the motorist as much as it hinders him. Before a lighting system is tested to determine its effectiveness in the reduction of accidents, the lighting system itself should be appraised by experts. The degree of necessary illumination is still open to consideration, but the effectiveness of better lighting in increasing road safety is not longer debatable in principle (72).

Capacity Improvement

Although accident reduction due to roadway lighting is an accepted fact, the effect of roadway lighting on capacity improvement is questionable. There is a long-established theory that fixed lighting might increase the ability of a given facility to carry its traffic load during the peak night hours, but no concrete information exists to confirm this hypothesis.

It is known, however, that basic lane capacity and minimum vehicular headway are directly related. Headway varies with speed, ranging downward from 3.1 sec at 10 mph to 1.7 sec at 38 mph, then increasing at about 0.1 sec per 10-mph increment of higher speed (11). Studies have shown that in the change from day to night driving conditions drivers reduce their speeds. Headway capacity measurements made on 2-lane rural highways have also shown that the average driver demands greater headways at night for the same speed brackets. Thus, both lowered speed and driver preference for increased headways lead to decreased nighttime capacities. If lighting helped curb either of these tendencies, the roadway could operate closer to daytime capacity.

In a study conducted at the Yale Bureau of Highway Traffic in 1957, researchers sought to determine the nighttime change in speeds and headways on an unlighted portion of a specific facility, and the change in speeds and headways on a similar section of the same facility that had been provided with fixed lighting (12). By comparing only the percentage of speed differentials between day and night at each location, they minimized the effect of unavoidable differences in physical site characteristics besides lighting. A before-and-after study would have been ideal in this situation, but such a location was not available at the time of the study; therefore, 2 sections of Route 15 in Connecticut were chosen. Data on these lighted and unlighted sections were collected and analyzed. It was concluded from this study that nighttime capacity loss due to lighting is equal to 5 percent at an urban design-hour volume of 1,500 vph. This has been shown to be equivalent to the loss that would accompany construction of a 10.5-ft wide instead of a 12-ft wide right lane. If pavement costs are figured conservatively at $6.00/sq yd, the wide lane costs about $1.00/lin ft more than the narrow pavement. For both directions of travel, an expenditure of $10,000 per mile for lighting might be similarly justified where maximum night capacity is desired (12).

For several reasons, the study's conclusions about the effect of lighting on vehicle speeds are debatable. Most important is the fact that data from which the speed differences were derived were taken from volumes that varied considerably. Second, the speed pattern on the route under study did not show a consistent response to different volumes. For these reasons, the researchers stated that capacity improvements as affected by speed are not clearly defined in the data gathered, and no positive contribution of lighting to speed could be determined on the basis of this study.

A more recent study conducted at the Texas Transportation Institute (19) investigated operational characteristics of highway traffic moving through an intersection where various illuminating systems had been installed; results in this case proved contrary to those reported by the Yale Bureau of Highway Traffic. The Texas study concluded that the entire range of illumination conditions considered did not appreciably affect the operational characteristics of the traffic stream. Even with an elaborate measuring system, it was not possible to detect significant differences in drivers' reactions to a wide range of illumination conditions. In other words, the benefits of illumination in the Texas study did not necessarily include an effect on the characteristics of traffic operations.

FACTORS IN THE DESIGN OF LIGHTING SYSTEMS

The main objective in designing a lighting system is to create an environment in which the motorist, under limited illumination, is able to receive sufficient information for precise and efficient vehicle operation (55). Achieving this goal requires consideration of some quantitative and qualitative factors that influence the design: night visibility, other human characteristics, glare, pavement reflectance, level of uniformity of illumination and photometric data, light sources, and economics.

Night Visibility

Roadway visibility denotes the ease of detection or recognition of road details by a driver. In general, the alertness of a driver tends to increase as visibility is improved; thus, fixed lighting installations that increase visibility at night produce safer conditions for both drivers and pedestrians (2). Visibility, or the ease of perception and recognition of objects, is dependent on 4 principal influences: size, contrast, brightness, and time.

1. The size of an object is technically defined as the angle subtended by the object at the eye. Thus, it depends on the distance of the object from the observer. The size of the critical detail of the object is of greater importance than the overall object size.
2. Contrast is an expression of the difference in brightness between the background and the critical detail of the object. Visibility is improved under conditions of increasing contrast. Discernment of roadway obstacles can occur under 3 contrast conditions: (a) brightness of the object lower than the brightness of the background (silhouette discernment), (b) brightness of the object higher than the background brightness (discernment by reverse silhouette), and (c) contrast in brightness of color on the surface of the object (recognition by surface detail).
3. Brightness is a measure of the amount of light reflected back to the eye of the observer. It is dependent on the level of illumination that is provided and on the reflectance characteristics of both pavement and object to be seen. The amount and patterns of illumination on the pavement must be sufficient to create the necessary brightness contrast needed for discernment. However, some control must be exercised over the maximum brightness in the driver's visual field, in order to reduce or eliminate glare that can impair the driver's vision.
4. All other factors being equal, the time required to see an object is directly dependent on the amount of illumination provided. As speed increases, the time available for driver recognition decreases, and illumination requirements increase. If either the object or the observer is in motion, the speed of vision increases in importance (27, 61).

Although these influences have been recognized and defined, they are not specifically evaluated in highway lighting design because of a shortage of information on pavement reflectance characteristics and limited methods of brightness calculation. Most street-lighting designs are presently made merely on the basis of average horizontal illumination (60). Assessment of night visibility under highway lighting conditions tends to be subjective in nature, with wide variations in interpretation among individual observers (60). Techniques for measuring visibilitics must, as much as possible, eliminate this subjective element by using objective indexes that can be correlated to visibility.

Threshold conditions, the conditions at which something is just perceivable, are the most satisfactory indexes in defining visibility. The threshold may be the minimum size of detail that can be seen, the time to perceive, the detectable brightness difference, and the minimum contrast at a given adaptation level. All 4 methods of reducing the visual scene to threshold have been used for special purposes by various researchers, but the method currently used to measure the visibility requirements for roadway visual tasks uses contrast as the control parameter (27). This factor was chosen because it appears to simulate roadway conditions where the objects are relatively large (greater than 1 minute of arc), time is substantial (greater than 0.01 sec), and average brightnesses are low (27).

Two major instruments designed to measure contrast thresholds are the Finch visibility meter and the Blackwell visual task evaluator (VTE). The Finch visibility meter will permit any object in the central field of view to be reduced to its contrast threshold. This is done by adding veiling brightness to both the object and its background at the same time that the actual brightness of the object and its background are reduced (27). The VTE is a device for introducing known amounts of contrast reduction to the point at which the visibility threshold is reached. The amount of contrast reduction required to bring the task down to the threshold level of visibility can be used to determine the illumination level required to perform the task at a selected level of adequacy. Currently, special procedures are required to apply this method to roadway tasks, but a model made especially for field use is under development (9). A variety of other instruments have been used in the past to measure visibility, but the majority of these, such as the Luckiesh mass visibility meter, use brightness as the threshold parameter. For this reason, they are not used extensively for roadway visibility studies. Simmons and Finch have reviewed the major characteristics of several of these instruments (60).

The effect of color, size, and shape of objects (or targets) on visibility is an important consideration. Experiments indicate that, as the object color becomes lighter, visibility increases noticeably (29). In other tests where visibility was determined for several types of targets (plane, 2-dimensional multiplane, and 3-dimensional plane) on roadways with 2 different brightness patterns (uniform and nonuniform), much greater variations in visibility resulted from the nonuniform pattern (27). In cases where nonuniform patterns were used in conjunction with small targets, it was possible to lose the target entirely in the dark area between the light patches. For tall, thin targets simulating a pedestrian, much less variation in visibility was obtained for both patterns.

Finch recommended that a minimum of 3 types of targets be used in visibility studies, as no one target is adequate for complete field evaluation (27). Suggested targets were a small plane area, a small multiplane surface, and a tall multiplane surface.

Blackwell has gathered extensive data on illumination of roadway visual tasks, especially on 2 major tasks: seeing a mannequin and a black dog at various distances down the roadway, with a variety of luminaire types, luminaire spacings, and pavement surfaces (8, 9). While the illumination requirements varied under different pavement conditions and with various types of luminaires and luminaire spacings, an average of 1.90 ft-c of horizontal illumination was required for adequate visibility of these targets when they appeared (200 ft ahead) in the driving lane and 5.7 ft-c at the same distance in the curb lane. At distances of 300 and 400 ft, illumination requirements for visibility were 9 and 48 ft-c respectively. It should be remembered that these values apply only to similar visual tasks in similar geometric situations.

The purpose of Blackwell's investigations was not to recommend impractical levels of illumination for roadway lighting, but to provide a basis for evaluating gains in visibility, and hence improvements in the safety of night driving through increased roadway illumination. Blackwell's studies also concluded the following:

1. Extremely high illumination values are required for the difficult visual tasks of seeing a brick obstacle or a simulated hole in the pavement.
2. When luminaire spacing is increased from 100 to 200 ft, more footcandles are required for seeing the dog, but fewer for the mannequin. This can be explained by the fact that, at longer luminaire spacings, the mannequin is viewed in reverse silhouette contrast.
3. In the curb lane, visual tasks are as difficult as they are in the driving lane or more difficult (9).

Blackwell undertook further studies of illumination by using a 1:10 scale-model simulation. The VTE was used to assess visibility when a mannequin was placed in various locations on a simulated highway illuminated by 4 different systems of fixed lighting. The commonly used nonuniform semi-cutoff distribution proved to be the worst system from the point of view of disability glare and, in terms of visibility, was distinctly inferior to the unusually uniform distributions produced by unorthodox systems (7).

Other Human Characteristics

Night vision depends on variables that interact to yield a complex pattern of visual conditions. The variables influencing night vision are related to environmental conditions as well as the nature of visual stimulus and the physiological state of the driver. These variables include dark adaptation, pre-exposure, color, acuity, depth perception, glare, light shock, age, oxygen deprivation, and visual field.

Dark Adaptation—This process, which becomes less efficient with age, allows a viewer to take maximum advantage of decreasing amounts of light. It is affected by 2 types of eye cells: the cones and the rods. Cone cells, which are proficient in color and form perception, function best under highway levels of illumination, and rod cells are more efficient under low levels. If the eye is deprived of light, cone cells adapt to the loss in 5 to 10 min after which time the rod cells take over the light-sensing function and adapt to low levels of illumination in 30 to 50 min. Because drivers commonly encounter frequent changes between very high and very low illumination, their eyes must adapt to achieve visual efficiency at the changing levels of illumination. Under high illumination a rapid rate of adaptation results from a moderate change in lighting; but when illumination is successively reduced, the rate of change slows down. The most proficient viewer is one who can most efficiently adapt in the shortest possible time (48).

Pre-Exposure—The degree of exposure influences the time required to adapt to low illumination levels. It has been shown experimentally that, as the eye is exposed to higher levels of illumination, night vision becomes considerably less efficient (71). If persons exposed to bright sunlight for several hours were to drive during twilight or early evening, they would be much less proficient at night vision than those who had not been previously exposed to the bright light.

Color—It has been demonstrated experimentally that exposure to ultraviolet light even for short periods reduces the rate of adaptation to low levels of illumination (70). Another study has shown that dark adaptation following exposure to a red light is significantly faster than adaptation following exposure to a white light (36).

Acuity—As illumination decreases, the acuity, or the capacity of the eye to resolve and discriminate objects, decreases. A study conducted to find the visual angle occupied by the thickness of line when it is just resolved showed that 10 min are required for low levels of illumination as compared with 0.50 sec at the highest illumination level, a range of 1,200 to 1 (37). The ability to discriminate objects is very important and should be maintained at the highest possible degree.

Depth Perception—Depth perception, which will vary with illumination changes, has been shown to decrease from 12 to 37 percent when illumination was reduced by 30 percent (48). Depth perception is especially critical when the observer is traveling at high speeds. In a study between accident-free drivers and accident repeaters, it was found that the accident-free group had superior acuity, lateral ocular balance, and perception.

Glare—A glare source present in the field of view often makes it nearly impossible to see. When the glare is eliminated, recovery is dependent on the brightness of the glare and duration of exposure. Older persons seem to be most susceptible to glare (48).

Light Shock—When a bright light is briefly shone on the retina, as often occurs in night driving, light shock results. If the bright light presentation is nonrepetitive, recovery is rapid. But repeated presentations cause cumulative effects: The greater the frequency, the greater is the delay in recovering accurate night vision (48).

Age—Experiments have shown that subjects of age 40 and over have a 30 to 60 percent greater reduction in night vision than those under 40 (49). Figure 3 shows general changes in visual functions with age.

Oxygen Deprivation (anoxia)—Lack of oxygen, or anoxia, hinders a person's ability to see dim objects against a very dark background. Anoxia's effect on visual sensitivity is greatest when the background is most dimly illuminated, and diminishes as background illumination increases (48).

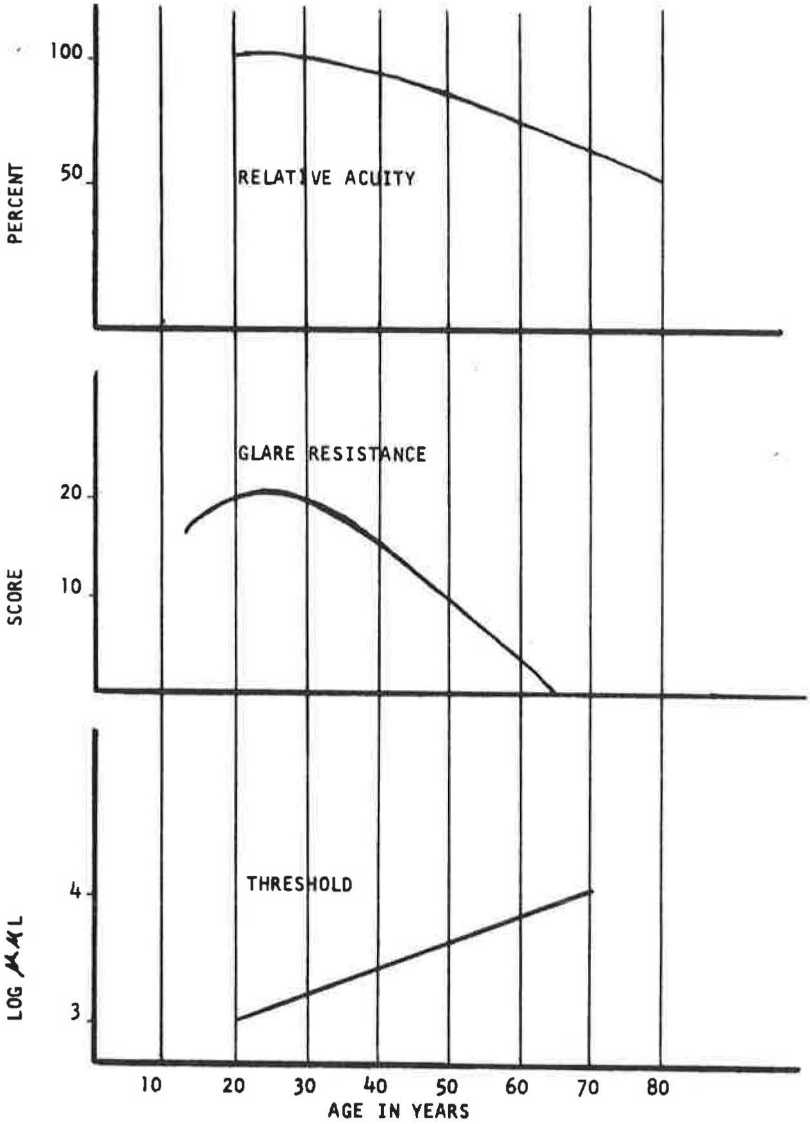

Figure 3. Influence of age on vision (56).

Visual Field—The space that is actively scanned by the eyes of the motorist without special effort or movement of the head is referred to as the visual field. In general, the visual field consists of a cone 30 deg in the vertical plane. Although visibility does extend almost 90 deg on each side of the line of vision, the zone beyond 30 deg is less important to the motorist. The visual field is apparently related to the distance of active central sight, which is about 200 ft. It we assume that a 25 deg cone exists on each side of the line of vision, the visual field for a 200-ft sight distance is 85 ft on either side of the line of sight (44).

Measurements of Driver Behavior—It seems reasonable to assume that advances in the control of environmental conditions, visual stimuli, and physiological states of the motorist will lead to improvements in night vision, thus measurably reducing the frequency and severity of accidents and increasing driver comfort (48). However , little is known about the effect of highway lighting on driver behavior. The tension created by decision-making, a possible quantitative measure of driver behavior, must be measurable. This need has led to the use of the galvanic skin response (GSR) test, the method used to detect changes in the electrical resistance of the skin due to perspiration. At the Texas Transportation Institute the GSR was used to evaluate the effect of different levels of illumination and geometric designs on driver tensions at a rural intersection (33). Results showed that increases in illumination brought a decrease in tension, and that the greatest tension occurred with no illumination. Both the number and the total magnitude of GSR responses decreased when illumination at the intersection was provided first by a single luminaire and then by a continuous lighting system. Also, as the complexity of each movement decreased or as the subjects became more familiar with the intersection, driver tension was reduced. Because the GSR readings can be translated into measures of driver comfort, a possible application of the results of this study is the development of a series of illumination warrants. Once the level of driver comfort desired is specified, the level of illumination necessary to satisfy this comfort rating can be estimated.

Glare

Glare is one of the major obstacles to overcome in achieving comfortable and effective visual conditions for night driving. Lighting system characteristics such as brightness of the pavement, uniformity, or horizontal illumination intensities can be calculated by applying mathematical methods, but glare does not lend itself to that treatment. The effects of disability and discomfort glare are relative and depend on many other qualities of the illumination system.

Glare may be described as the sensation experienced when the field of vision contains a light source that has a much higher intensity than the surrounding area; objects reflecting less light than the glare source then become impossible or nearly impossible to see. Current literature defines 2 kinds of glare: disability glare and discomfort glare. The former, also termed physiological glare, causes a measurable modification in the visual functions of the driver as a direct result of the presence of one or more luminous sources in the visual field (31). Discomfort glare, also termed psychological glare, is defined as glare that causes discomfort while not necessarily hindering the visual perception of objects appearing in the visual field (58). Thus, disability glare is primarily responsible for impairing the ability to perform a visual task, while discomfort glare influences the ease with which the individual can see.

Disability glare is a major hindrance to visual effectiveness. If a bright object is placed near the line of vision, some loss of visibility will occur. The degree of loss depends on (a) the quality of the visual organs, especially as related to visual acuity and the ability to readapt after being subjected to glare; (b) the brightness contrast ratio between the visual field luminance and the glare-producing source; (c) the quantity of direct light reaching the cornea; and (d) the relative position of the glare source in the visual field (44).

Discomfort glare is even less tangible than disability glare, because the definition of "comfortable seeing" varies among individuals. Color of light, luminous intensities, and relative location and size of luminous bodies are important factors in producing the sensation of comfort. Discomfort glare, although it affects the quality of a lighting system, often does not result in any appreciable loss of visibility (44).

The most common sources of glare are oncoming traffic headlights, flashing commercial billboards, and lighting system luminaries. Because of the last of these, glare is an important problem in the installation of lighting systems along the roadway. It is not difficult to understand that highly luminous bodies located in the active field of vision can completely destroy the effectiveness of an otherwise satisfactory lighting system. Theoretically there are methods of minimizing almost every type of glare, but unfortunately this problem is often handled ineffectively. Much research has been done in defining and predicting glare, but the reliability of such predictions is still a matter of controversy.

Lighting researchers are striving to find a satisfactory numerical yardstick for glare, a yardstick that will enable the designer to avoid excessive glare as easily as he avoids too low a level of illumination (46). But too few quantitative data are available on discomfort caused by glare from street lights and vertical footcandles incident on the eye of the motorist. The relation has not been defined sufficiently for use in predicting the degree of comfort to be expected from a proposed streetlighting installation.

Reid and Toenjes conducted a study in 1952 to appraise discomfort glare under 31 widely diversified streetlighting installations in Cleveland (51). Lighting appraisals were made on installations that included all 5 types of lateral light distributions. Average illumination ranged from 0.07 to 0.97 ft-c. Mounting heights ranged from 14 to 26.5 ft. Pavement surfaces included concrete, asphalt, and brick. Curb-to-curb pavement widths were 24 to 72 ft. The illuminants were filament lamps, with ratings from 2,500 to 15,000 lumens. Appraisals were made from the front seats of automobiles in the right driving lane with a Taylor-Pracejus illumination recorder. For ease of recording and charting, the comfort-discomfort glare appraisals were assigned rating numbers varying from "pleasant—not noticeable as glare", which has a value of 1, to "intolerable", which was assigned a value of 7. Reid and Toenjes's conclusions relevant to this study can be summarized as follows:

1. The great majority of streetlighting is glaring, in varying degree from mildly uncomfortable (rating of 4) to sharply uncomfortable (rating of 6); and
2. Comfort-discomfort appraisals and vertical footcandles on the eye appear to be related generally, provided that horizontal footcandles on the pavement are taken into account as an index of field brightness.

The results of this study held promise that factors affecting discomfort glare in streetlighting can be dealt with quantitatively.

There are at present at least 3 methods for numerically assessing the capacity of a light source to produce discomfort, as well as 1 method for calculating the magnitude of visual disability glare caused to drivers. The most common indexes for evaluating discomfort are the border line between comfort and discomfort (BCD index), M; the glare rating, G, which varies directly with discomfort; and the visual comfort index (VCI), which represents the percentage of a sample of normal observers for whom the light source is comfortable (34). A definite relationship exists between G and M, so that one can be computed from the other and each can be related to the percentage of people viewing with comfort (Figs. 4 and 5).

Guth and McWelis (35) propose the following method for determining M to evaluate a glare source:

$$M = \frac{B}{PF^{0.44}\,(w^{-0.21} - 1.28)}$$

where

B = BCD brightness in footlamberts (ft-L),
P = position index,
F = field brightness in ft-L, and
w = solid angle subtended by the source in steridians.

Following informal meetings arranged at Stockholm in 1951, in conjunction with the Commission Internationale de l'Eclairage, work on glare discomfort was carried on at the Building Research Station (40). At these meetings, which led to the assessment of glare known as the glare constant, G, it was agreed that the main factors governing glare discomfort are (a) luminance of the light source, (b) apparent size of the light source, (c) general level of adaptation, (d) position of the light source relative to the direction of viewing, and (e) luminance of the immediate surroundings of the light source. It was further agreed that glare discomfort could be assessed on the basis of an expression of the following form:

$$G = \frac{f^{(B_s)} \cdot f^{(Q)}}{f^{(B_b)} \cdot f^{(B_i)} \cdot f^{(\theta)}}$$

where

B_s = source luminance,
Q = apparent size of source,
B_b = adaptation luminance,
B_i = luminance of immediate surroundings of the source, and
θ = angle between direction of source and direction of viewing.

The higher the value of G, the greater is the degree of discomfort. Thus, greater source luminance and apparent size result in worse glare; greater adaptation level immediately surrounding the source or greater angle between direction of source and direction of viewing results in less glare.

Researchers are working to achieve international agreement on findings so they can promulgate an agreed method for the estimation of glare discomfort in practical lighting situations. Although the problem is simple at first glance, it is riddled with second- and third-order complexities. For example, the basic glare formula breaks down in a number of ways and cannot be regarded as more than a first-order approximation; there exists a wide variation of discomfort experiences in a random selection of people; and the problem of additivity of glare is very complex (40).

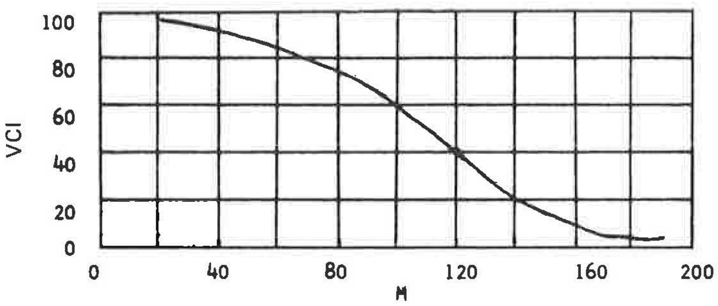

Figure 4. Relation of VCI to M.

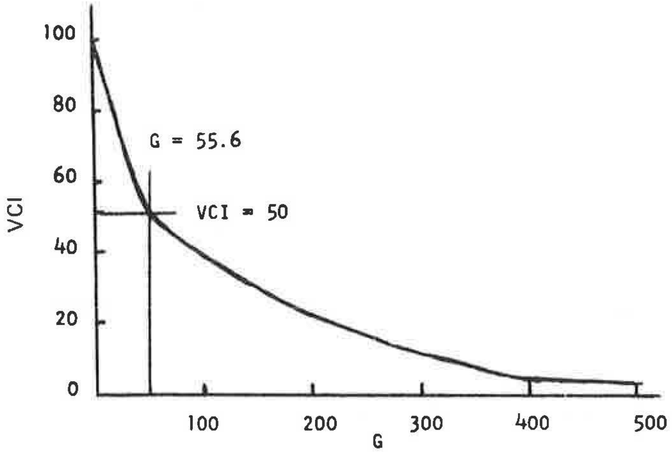

Figure 5. Relation of VCI to G.

The basic measurement not yet discussed, that used for disability veiling brightness, is also an approximation at best. Disability veiling brightness or disability glare is related to the total amount of light flux that enters the eye and the angular displacement of the glare sources from the normal line of sight. Holladay and Stiles have developed a standard formula for evaluating disability veiling brightness (DVB) as follows (18):

$$DVB = \frac{kE}{\theta^n}$$

where

E = the illumination at the driver's eye from the glare source on a plane perpendicular to the normal line of sight,
θ = the angle between the normal line of sight and the glare source, and
k and n = constants.

Using values for k and n of approximately 10 and 2 respectively yields the conventional formula (32) for calculating DVB:

$$DVB = \frac{10\pi E}{\theta^2}$$

This expression has been further modified to take into account the atmospheric absorption. The resultant expression (65) then may be expressed as

$$DVB = \frac{10\pi E_V}{\theta^2} \cdot T^x$$

where

T = the transmission factor for various atmospheric conditions per 100 ft, and
x = the distance from the glare source to the eye in hundreds of feet.

Christie and Fisher (18) conducted a study into the application of the Holladay and Stiles formula to streetlighting, investigating the validity of the formula at small angles (down to 1 deg) and the effect of age of the observer on the values of k and n. They discovered that the value of n varies with the range of θ involved. The value $n = 2.3$ was derived for the range $1.75 \text{ deg} \leq \theta \geq 4 \text{ deg}$, but a slightly lower value of n might be expected to apply to higher ranges of θ. Christie and Fisher also found that the parameter k depended on both the age of the observer, A, and the distribution of luminance over the background, $k = cA + d$, where c and d are constants, d being dependent on the background configuration. From their tests, the k found for observers aged A years was $k = (0.2\,A + 5.8)\pi$.

A recent study by Watson into the formula for calculating the disability glare effect from streetlights concluded that the value of n should be taken as 2.2 rather than 2.3 but that the value of k developed by Christie and Fisher was valid with the evidence available (67).

Although there are too many unknowns to construct a perfect system for evaluating glare in a luminous environment, the illuminating engineering profession is endeavoring to formulate and adapt a tentative standard system for this operation.

Pavement Reflectance

Brightening the pavement so that objects may be seen in silhouette is one of the principal objectives of street and highway lighting. The luminance or brightness is dependent mainly on the illumination that is present and the reflection characteristics of the pavement. The complexity of pavement reflection characteristics, however, has made it hard to make full allowance for them in designing lighting installations (16).

Two pavement characteristics affecting the amount of light reflected are color and texture. Their effect appears in two of the more common pavements in use today, bituminous mixtures and concrete. For instance, new concrete reflects approximately 25 percent of incident light, but this may be reduced to as much as 16 to 18 percent by the accumulation of carbon, oil, and chemicals that develop through use. Bituminous mixtures, however, initially have approximately 10 to 11 percent reflectance and after polishing have 12 to 14 percent reflectance.

Pavement brightness is also influenced by angle of incidence of the light and by the viewing angle. Incident light is related to actual brightness by multiplying the horizontal intensity by the coefficient of brightness (the ratio of the brightness in the viewing direction to the total incident illumination).

Light from fixed luminaires is reflected from the road surface in 5 ways: diffused, specular, spread, mixed, and retrodirective. Diffused reflection occurs when light scatters in all directions, independent of the direction from which the light ray comes. It usually does not contribute a great deal to pavement brightness because it occurs at an angle of incidence of near 90 deg to the pavement. Diffused reflection is the main reason that dark patches appear on the road directly under the luminaires and bright spots ahead of them (44).

Specular reflection is that obtained from mirror-like surfaces where a light ray and the exact image of the light source are reflected in the same direction as incoming rays and at an angle that is equal to the angle of incidence. Specular reflection, which generally occurs when pavement is wet, consists of extremely bright spots and streaks and can be detrimental to the driver's vision. Similar to specular reflection is spread reflection, in which light rays are reflected into a cone of light that is still directional in nature (61). Mixed reflection, which occurs on most surfaces, is a combination of diffused and specular types. A fifth type of light reflection is retrodirective, in which the light is reflected back in the direction of the source.

The most efficient light, by striking the road from an oblique angle and returning toward the eyes of the driver, creates road brightness and contrasts between the background and the task. Water produces varying types of reflection on different pavements. For example, smooth asphalt reflects much light in the form of continuous streaks or large patches, whereas a concrete surface may create a subdued specular reflection. Efforts have been made to improve road reflection by using light-colored pavement materials, but so far they have failed to offer economical solutions. Some attempts in Great Britain to incorporate white flint chips in a rolled asphalt surface have met with reasonably good results, but this method is limited because of a shortage of the mineral in other parts of the world (44).

Research in the area of pavement reflectance, undertaken in England's Road Research Laboratory in 1954 (16), revealed that in a street luminaires form a bright patch on the pavement which appears to the driver in the general shape of a T with the wide head reaching across the roadway approximately opposite the luminaire and the tail stretching toward the observer. The light distribution and nature of the surface dictate the exact shape of the patch, while the size is a function of the mounting height. The surfaces considered in this research include (a) rolled asphalt with precoated chippings, (b) nonskid rock asphalt, (c) machine finished concrete, (d) compressed rock asphalt, and (e) bituminous sand carpet. It was noted from these experiments that both coarse- and fine-textured surfaces produced short patches. This indicates that the shape of the pavement surface material, rather than the size of its features, dictates the area of the patch.

The Road Research Laboratory also investigated the effect of the surface texture, required to prevent skidding, on the formation of long patches by street luminaires. The use of sharp projections, which are necessary to prevent skidding, does have a tendency to destroy the specular reflections that form long patches. For instance, of the surfaces examined in the experiments, the only really large patch was obtained by the compressed rock asphalt, which is slippery when wet.

Appraisals of patches formed on the bituminous pavements when wet revealed that the type of patch is closely related to the texture depth. Results show that, with a small texture depth, a luminaire gives rise to a narrow bright streak. This leaves dark areas between which objects can be seen only with great difficulty. Rain affects the width of patches much less, however, when the depth is large. A texture depth of approximately 0.013 in. appears to give patches of reasonable width.

Similar investigations in the area of pavement reflectance have been performed in the United States. Of particular note is one conducted in Oregon of the reflecting properties of 7 types of pavements: (a) untreated gravel macadam, (b) bituminous macadam, (c) open type of asphaltic concrete pavement, (d) closed type of asphaltic concrete pavement, (e) new portland cement concrete pavement, (f) worn portland cement concrete pavement, and (g) smooth bituminous concrete pavement. The experimenters measured the reflectivity of both wet and dry pavements from a light having an angle of incidence of 17 deg and 45 deg. With the light at an angle of incidence of 45 deg (except on the 3 smooth pavements: old concrete, worn asphalt, and plain asphalt), dry pavements had almost complete absence of specular reflection. A comparison of the results obtained from both a 45-deg and a 17-deg angle showed that, as the angle of incidence decreases, the glare increases. A summary of the reflection properties of the 7 types of pavements is shown in Figure 6.

The reports that have been discussed dealt only with fixed lighting installations, but the question of the reflectance due to vehicle headlights is also important. In another test, the brightness caused by headlights was evaluated for 3 pavement types: plant-mixed surfacing, asphaltic concrete, and portland cement (29). The tests were performed under dry, damp, and wet conditions. Results showed that in dry conditions

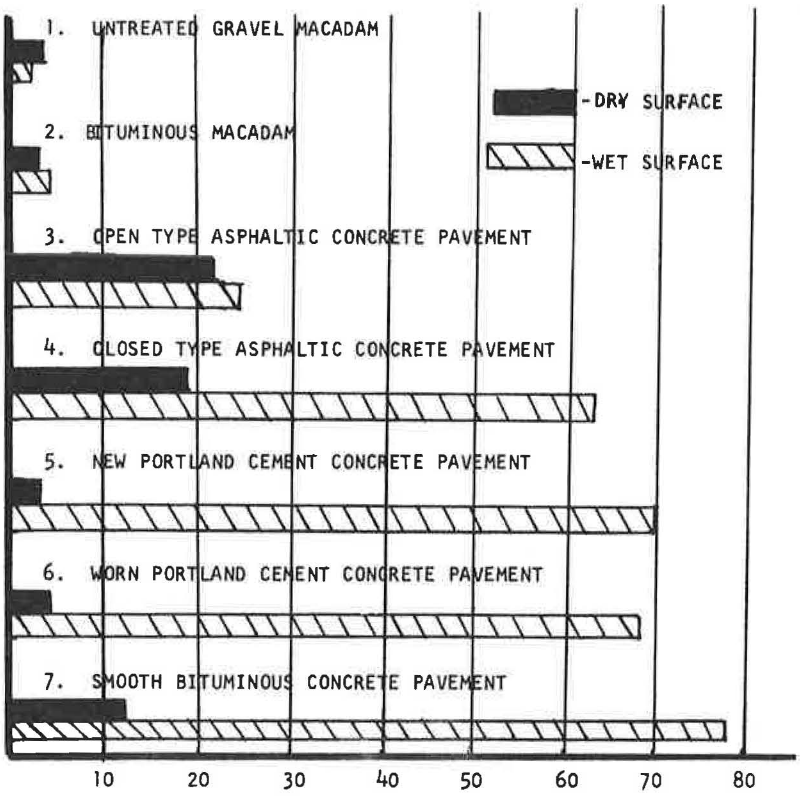

Figure 6. Percentage of intensity of illumination due to surface reflection for various types of road surfaces.

the portland cement concrete had the highest brightness of the 3 tested conditions. However, in wet conditions the asphaltic concrete brightness exceeded that of the portland cement concrete. While these results seem to conflict with those of the Oregon study, it should be noted that the Oregon study dealt with streetlight reflectance rather than with headlight reflectance.

Finch and King recently developed a pavement reflectometer for measuring the directional reflectance properties of pavement surfaces in the field (28). Their objective was to find a convenient means of measuring the luminance of a pavement so that more realistic light design specifications could be established. Present standards are inappropriately based on average horizontal illumination incident on the pavement surface rather than on the amount of light emitted from the surface in the direction of the observer. The major obstacle toward a more realistic design standard has been the lack of reliable information regarding pavement reflectance characteristics.

The authors stated that their reflectance-measuring device provided a relatively efficient means of accumulating comprehensive data on various types of pavement surfaces. Nevertheless, the actual data collection is a slow process; equipment setup time is about 3 hours. For this reason, they concluded that a laboratory testing program was the most desirable means for obtaining a large volume of data on several pavement surfaces.

The following year, Birkhoff, Pagen, and Snider (6) reported the results of an extensive laboratory investigation to determine a quantitative relationship between the microprofile characteristics of highway surfaces and pavement reflectance and skid resistance. Portland cement concrete and bituminous concrete laboratory specimens were tested over a wide range of incident light angles and reflectance angles. The microprofile of the surface of each specimen was measured by means of a specially developed device; then, the association between reflectance, microprofile, and skid resistance was evaluated.

The researchers concluded that the dominance of diffused or specular pavement reflectance depended on the angle of incidence. For all surface types, specular reflection was dominant when the angle of incidence was less than 10 deg. At other angles of incidence, the ratio between diffused and specular reflectance components depended on the pavement roughness, the fabricating direction, the observation direction, and the illumination incidence. Bituminous concrete showed an absolute reflectance ranging from 3 to 11 percent, while portland cement concrete varied from 15 to 40 percent. The authors were not able to relate their empirical measure of microprofile with surface type; this was attributed to the relatively small sample size being analyzed. However, skid resistance was found to vary directly with measures of microprofile. In view of the results of this study, further investigation of these parameters was recommended.

Level and Uniformity of Illumination and Photometric Data

Visibility is not necessarily directly dependent on horizontal levels of illumination; it depends, as well, on pavement brightness, relative contrasts between the task and background, uniformity ratio, disability glare, and dimensions of the visual field. However, even under the most favorable conditions, a minimum of light must be provided before the surroundings become visible. In highway lighting applications, the portion of light that effectively contributes to seeing is that part reflected and diffused from the pavement in the direction of the viewer's eye. It is desirable, therefore, to relate levels of illumination to the reflected light or luminous intensity of the pavement. Calculations based on roadway luminance are much more significant than those based on horizontal levels of illumination alone. Because road pavement reflectance can vary between 10 and 25 percent, the results of horizontal footcandle calculations can be in error by more than 100 percent in terms of actual effective reflected light.

In most European countries, illumination is expressed in terms of the average pavement luminance rather than of the horizontal intensities. The coefficient of luminance is related to the pavement surface reflectance and the luminaire light distribution characteristics (44), and is determined as follows:

$$\text{coefficient of luminance} = \frac{\text{average illumination, lux}}{\text{average luminance, candela/meter}^2}$$

TABLE 1

MINIMUM RECOMMENDED PAVEMENT ILLUMINATION IN FOOTCANDLES

Road Classification	Urban			Rural Where Recommended
	Downtown	Intermediate	Outlying	
Freeway	1.0	0.8	0.8	0.8
Expressway	1.2	1.0	0.8	0.8
Arterial	1.5	1.0	0.8	0.8
Collector	1.0	0.8	0.6	0.6
Local	0.6	0.6	0.4	0.2

Source: Ref. 44.

The following gives the average coefficients of luminance for various conditions:

Type of Luminaire	Surface	
	Dark	Bright
Cutoff	24	12
Semi-cutoff	18	9
Noncutoff	15	7

For equal pavement luminances, approximately twice as much incident light must be provided on an asphalt surface as on a light-colored concrete road. For example, a luminance of 1 cd/m^2 ($candela/meter^2$) or 0.292 ft-L corresponds to 24 lux or 2.2 ft-c for dark surfaces. For bright surfaces only half the value is required because of the reflectance characteristics of the surfaces. Although this method is still only approximate, it provides a better measure of actual lighting effectiveness than the method based on horizontal illumination units.

Road luminance is not exactly proportional to the average values of reflectance because the actual pattern of brightness of the road pavement depends on the specific directional reflectance relative to the viewer's position. The calculation of actual brightness, a complicated procedure, requires specific information on the luminaire used, the road reflectance qualities, and the point-by-point contribution from each relevant luminaire. Such information, however, is not generally available. Rex discusses the procedures of brightness calculations in his papers published on this subject (54, 55). Pavement brightness (PB) per luminaire at each station is computed by using constants per 1,000 candlepower developed from Reid-Chanon data:

$$PB = \frac{\text{luminaire candlepower}}{1{,}000} \times \text{PB constant}$$

The pavement brightness per horizontal footcandle depends on the direction of incident light from each luminaire in relation to driver-observer viewing position. The result of illumination at each station from each luminaire should be computed separately, then combined for the effect of several luminaires. The combined pavement brightness can be calculated from the candlepower constants and the sum of the brightness at each station produced by each luminaire. A further study of these papers is advisable for those interested in obtaining better results.

TABLE 2

RECOMMENDED AVERAGE HORIZONTAL FOOTCANDLE LEVEL IN URBAN AREAS

Road Classification	Downtown	Intermediate	Outlying and Rural
Major	2.00	1.2	0.9
Collector	1.2	0.9	0.6
Residential	0.9	0.6	0.2

Source: Ref. 2.

Because present illuminating standards are based on horizontal footcandle levels, the suggested minimum levels of illumination in terms of horizontal intensities, as proposed by Ketvirtis (44), are given in Table 1; average values proposed by the American Standard Practice for Roadway Lighting (2) are given in Table 2.

A commonly accepted method of expressing road illumination uniformity is the average to minimum ratio of horizontal intensities. At present in the United States, there are no specific regulations limiting the maximum to minimum ratio or describing ratios within the actual visual field.

Illuminating engineers know that a sudden change in the level of luminance produces a temporary reduction in visual acuity. The eye cannot adapt quickly to frequent changes in luminance levels; hence, visual acuity, a function of proper eye adaptation, is greatly disturbed by such changes. If uniformity ratios are high, the contrasts between the task and the background will vary; to equalize visual conditions, greater amounts of light are normally required. Tables 3 and 4 give suggested ratios of average to minimum and maximum to minimum illumination within pavement limits, as suggested by Ketvirtis (44). The American Standard Practice for Roadway Lighting (2) contains a chart showing suggested uniformity ratios versus luminaire spacing as a function of roadway width, but the uniformity ratios shown in that chart are average-to-minimum values only.

Box and Edman (12) suggest that the lowest footcandle value at any point on the pavement should not be less than $\frac{1}{3}$ of the average value except on residential streets where a minimum of $\frac{1}{6}$ is recommended. They further state that uniformity of illumination and brightness is a more important quality factor than has been previously realized. The new values they recommended represent a significant improvement over the old minimum values of $\frac{1}{4}$ and $\frac{1}{10}$ respectively.

Light distribution and control depend on the design of the luminaire optical system. To predict the performance of a highway-lighting system, the engineer must have information describing the complete luminaire performance, such as light beam intensities, light distribution pattern, utilization and efficiency, glare control, and luminaire mechanical features. Standardization of lighting design calculations requires uniformity in the classifications of lighting control and distribution patterns. Luminaire photometric data (44) normally consist of (a) isofootcandles, (b) utilization curves, (c) temperature and mounting height correction factors, and (d) candlepower distribution or isofootcandle diagram.

The illumination on a roadway surface produced by the light distribution from 1 or more luminaires may be shown by isofootcandle diagrams. These diagrams are graphical representations of points of equal illumination connected by a continuous line; the line may show footcandle values on a horizontal plane from a single unit having a definite mounting height, or a composite picture of the illumination from a number of sources arranged in any manner or at any mounting height. Isofootcandle diagrams are useful in the study of uniformity of illumination and in the determination of the level of illumination at any specific point. So that the curves will be applicable to all conditions, they are computed for a given mounting height with horizontal distances expressed in ratios of the actual distance to the mounting height. Correction factors for other mounting heights are usually given in the tabulation alongside the isofootcandle curves (2).

Utilization curves, available for various types of luminaires, afford a practical method for determination of lumens per square foot (average footcandles) over the roadway surface where lamp size, mounting heights, width of paved area, and spacing between luminaires are known or assumed.

The utilization curve indicates how much light falls on the roadway in terms of coefficient, but reveals little of the way in which the light is distributed. It must, therefore,

TABLE 3

RECOMMENDED AVERAGE TO MINIMUM RATIOS ON ROAD PAVEMENT

Road Classification	Urban			Rural
	Downtown	Intermediate	Outlying	
Freeway	2.5:1	2.5:1	2.5:1	2.5:1
Expressway	2.5:1	2.5:1	2.5:1	2.5:1
Arterial	2.5:1	2.5:1	3:1	3:1
Collector	2.5:1	3:1	3:1	3:1
Local	3:1	3:1	4:1	4:1

Source: Ref. 44.

TABLE 4

RECOMMENDED MAXIMUM TO MINIMUM RATIOS ON ROAD PAVEMENT

Road Classification	Urban			Rural
	Downtown	Intermediate	Outlying	
Freeway	6:1	6:1	6:1	6:1
Expressway	6:1	6:1	6:1	6:1
Arterial	6:1	6:1	8:1	8:1
Collector	6:1	8:1	8:1	8:1
Local	8:1	8:1	10:1	10:1

Source: Ref. 44.

be used in conjunction with the specific calculation to evaluate correctly the time performance of the luminaire, especially in terms of uniformity or compliance with the recommended ratio of minimum illumination value to the average illumination value (2).

The coefficient of utilization is the percentage of rated lamp lumens that will fall on either of 2 strip-like areas of infinite length, one stopping in front of the luminaire, and the other behind the luminaire, when the luminaire is level and oriented over the roadway in a manner equivalent to that in which it was tested. Because roadway width is expressed in terms of a ratio of luminaire mounting height to roadway width, the coefficient of utilization has no dimensions.

The formula (2) for determination of average horizontal footcandles is

Average footcandles = (lamp lumens at replacement time × coefficient of utilization × luminaire maintenance factor)/(spacing between luminaires in feet × width of roadway in feet)

Even though this information is satisfactory for single calculations of average road illumination, pole spacing, and maximum to minimum or average to minimum ratios, the rapidly advancing popularity of computers may necessitate adjustments in the format of information. More sophisticated methods of calculation in some areas are also desirable and, if developed, may call for more elaborate data on luminaire performance.

The American Standard Practice for Roadway Lighting (2) provides a detailed description of luminaire light distribution classification, which is determined by these criteria: (a) vertical light distribution, (b) lateral light distribution, and (c) control of light distribution above maximum candlepower.

Vertical light distributions are classified as short, medium, or long, depending on the location of the point of maximum candlepower with respect to the transverse roadway lines (TRL) expressed in multiples of mounting height (MH). For the short distribution, the maximum candlepower lies between 1.0 MH TRL and 2.25 MH TRL; for the medium, between 2.25 MH TRL and 3.75 MH TRL; and for the long, between 3.75 MH TRL and 6.0 MH TRL.

Lateral light distributions fall into 2 categories, depending on the location of the luminaire with regard to the area to be lighted. Those luminaires in the first group are designed to be mounted near the center of the area to be lighted; they have similar light distributions on both the house side and street side of the reference line. The second group includes all those luminaires intended to be mounted at or near the side of the area to be illuminated (2).

Control of candlepower in the upper portion of the beam above maximum candlepower is necessary in achieving a balance between the detrimental effects of increased glare and the benefits of increased pavement brightness at high vertical angles of light emission. There are 3 types of candlepower distribution control: cutoff, semi-cutoff, and noncutoff. The cutoff luminaries are those for which the candlepower beyond the limiting TRL does not numerically exceed 10 percent of the rated lumens of the light source used. The limiting TRL are (a) short distribution, 3.75 MH; (b) medium distribution, 6.0 MH; and (c) long distribution, 8.0 MH. In the semi-cutoff category and by using the same limiting TRL, the candlepower beyond the limiting TRL does not numerically exceed 30 percent of the rated lumens of the light source. The noncutoff category has no candlepower limitations in the zone above maximum candlepower (2).

Light Sources

There are 4 main types of light sources available for use in roadway lighting: incandescent, mercury vapor, sodium vapor, and fluorescent. The following paragraphs compare the most distinctive operating characteristics of these lamps and summarize the prime areas of application of each.

Efficiency—The efficiency of the incandescent lamp is relatively low, from 10 to 22 lumens per watt, depending on the lamp size and rated life (61). Standard mercury vapor lamps have higher efficiencies, ranging from 33.5 to 60.5 lumens per watt. Metal halide lamps, which operate on the same principles as the mercury vapor sources but contain additional metal additives, have even greater efficiencies, from 60 to 90 lumens per watt (15, 53). Conventional sodium vapor light sources have efficiencies approximately 2½ times greater than those of incandescent lamps, and the new high-pressure sodium lamps have the highest efficiencies of any of the commercially available sources, from 100 to 105 lumens per watt (41, 53). The efficiencies of fluorescent lamps range from 45 to 75 lumens per watt (61).

Life—Rated operating lives vary greatly among light sources, from the relatively short life of the incandescent lamp, 300 to 6,000 operating hours, to the very long-rated life of the mercury source, up to 24,000 hours (14, 73). Metal halide lamps, standard sodium vapor sources, and high-pressure sodium lamps all fall between these extremes, from 5,000 to 7,500 hours (22, 53). The operating life of a fluorescent source, generally rated at 7,500 to 12,500 hours, varies greatly according to the number of times the lamp is started; the more starts, the shorter is the operating life (61).

Electrical Limitations—Variations in supply voltage or current drastically affect life and light output for incandescent sources. A decrease of 10 percent in the operating voltage results in approximately 30 percent decrease in light output, while an increase of 10 percent results in a 35 percent increase in output (61). Conversely, an overvoltage operation of 5 percent can reduce the expected life by 55 percent (73). Mercury lamps require ballasts on multiple circuits to provide the high starting voltage needed, to supply adequate reactance to limit, and to regulate the current through the lamps. For series operation, individual lamp transformers are required. The type of ballast or transformer is determined by lamp and supply use. It takes approximately 5 minutes for the lamp to reach operating temperature and light output. Either undervoltage or overvoltage causes a shorter life (61). The high-pressure sodium source warms up in about 5 minutes and the standard sodium source needs about 30 minutes (53, 61). Both require ballasts determined by lamp and supply usage. The life of the fluorescent lamp is decreased by both undervoltage, which causes deterioration of electrodes, and overvoltage, which produces excessive heat (61). Ballasts are required for starting and operating fluorescent lamps.

Application—Incandescent lamps should be considered where low initial cost is important, operating hours are short, color acceptability is important, and maximum degree of light control is necessary. Mercury vapor sources are higher in initial cost but lower in operating expenses because of their longer lamp life; the mercury lamp has great appeal because of its modern appearance and efficiency. While clear mercury sources have been shown to create more glare than other lamps, color-improved sources with better visibility are available (23).

The conventional sodium lamp is no longer available in the United States because of high costs and the unpopular characteristic yellow color. European countries, however, regard it very highly, claiming that it is brighter and less glaring than mercury lamps of the same size and offers more visibility (22). But another study states that very little difference exists between sodium lamps and other sources with regard to glare or contrast sensitivities, although visual acuity was higher with the sodium source (23). The high-pressure sodium lamp, with high initial cost and low operating cost, is desirable at locations when annual usage is low and where high illumination and color rendition and a high degree of light control are important. Fluorescent lamps have the highest initial cost. They are mainly used in areas where low brightness is necessary, such as in commercial areas (53).

The present trend in streetlighting practice is definitely toward installation of mercury vapor lamps and other modern sources (such as high-pressure sodium and metal halide), which offer economical operation, availability of lamps and other components in a wide range of sizes, and long life. An Edison Electric Institute Survey showed that mercury vapor lamps account for 85 percent of the present sales of roadway lighting sources and that 92 percent of electric utility companies are converting their streetlighting systems to mercury lamps (52). Fluorescent lamps are being used more frequently for lighting broad areas, such as multilane expressways and intersections (13, 47). The so-called modern sources, such as high-pressure sodium and metal halide, are also being used where high illumination levels are desired.

Economics

In the design of highway lighting installations, one of the important considerations is the cost of the system in terms of initial and annual expense. Besides cost, the level of illumination, the appearance, and the existing equipment are other important factors in selecting the type of equipment to be used (14).

Knowing which elements are most significant in dollar value is important when analyzing the total cost of a lighting system. Ketvirtis (44) has cited the following elements that most affect cost:

1. Level of illumination—This is probably one of the elements most affecting the cost of a lighting system. The added requirements of increased illumination must often be met with more luminaires because lamp sizes are somewhat limited. When a larger lamp can be used in addition to a different type of light control, the result may be a cost savings on a per lumen basis. However, the cost of installation is not directly proportional to increased levels of illumination, because of the cost of such items as wiring, number of substations, and project engineering.
2. Road geometry—The width of the median and the shoulder as well as lane dimensions affect the lighting system layout. As the widths become larger, changes in pole arrangement and spacing will affect the system cost. Also, where there is a median, double luminaire mountings offer considerable savings.
3. Type of light source—Cost comparisons of mercury and fluorescent lighting systems on the basis of the same footcandle levels indicate that the latter is 20 to 30 percent more expensive. Also, mercury lamps are available in a wider variety of units and lend themselves to more precise control.
4. Types of poles—For lengths up to 30 ft, the cost of aluminum and steel poles are about the same, and concrete poles are less than half the cost of the metallic poles. For poles of 40 ft or longer, the cost of the aluminum rises much faster than that of the steel or concrete.
5. Wiring materials and installation—The cost of wiring and installation are significant factors, but to a lesser degree unless some unusual methods are used.
6. Mounting height—As the mounting height is increased, wider pole spacings become possible, so that fewer poles and luminaries are necessary and the cost of the system is reduced.

In comparing different types of systems, we must keep in mind that the comparison is only valid if the systems have similar quality and effectiveness. For economic comparisons, the level of illumination and uniformity are the most important factors; pavement brightness would be an even better criterion, but technology on this subject is not yet adequate.

In 1967, Thompson and Fransler developed a cost analysis based on equal levels of illumination (64). In this report cost summaries were prepared for 2-lane, 3-lane, and 4-lane roadways (Table 5). Initial average horizontal footcandles were computed for 1 direction, and uniformity was achieved through use of different lamp sizes and mounting heights (44).

For design of the best possible lighting system at the least cost, an economic analysis is necessary. That analysis should contain the type and description of luminaires to be used and data such as coefficient of utilization, average footcandles maintained, and energy rates. With this basic information, the initial and annual costs can be calculated. Initial costs include luminaires and accessories (wire and transformers); energy, cleaning, part replacement, and labor should be considered annual costs (63).

Although it has been stressed before that the most economical system should be sought, cost alone may not be the best means of selection. In many cases a more expensive installation will be justified because improved color rendition is desired; the new silver-white-colored mercury lamps can be used to obtain better color rendition and still retain the inherent operating economy of the mercury source. Factors such as this, and even aesthetic considerations, may relegate cost to a position of secondary importance (63).

TABLE 5

SUMMARY OF COSTS OF ROADWAY LIGHTING

Item	Mounting Height on 2-Lane Roadway			Mounting Height on 3-Lane Roadway			Mounting Height on 4-Lane Roadway		
	30 Ft	40 Ft	50 Ft	30 Ft	40 Ft	50 Ft	30 Ft	40 Ft	50 Ft
Light distribution type	11	11	11	11	11	11	111	111	111
Lamp watts	400	400	400	400	400	400	400	400	400
Uniformity ratio	3.0:1	3.0:1	1.4:1	3.0:1	3.0:1	1.8:1	3.0:1	2.4:1	2.2:1
Average initial horizontal footcandles	1.50	1.00	1.00	1.80	0.83	1.00	1.09	1.00	1.00
Minimum footcandles	0.50	0.33	0.72	0.53	0.27	0.55	0.36	0.43	0.47
Luminaire spacing, ft	195	250	210	150	255	190	185	180	160
Luminaires per mile	27	21	25	35	21	28	29	29	33
Initial cost per mile, $	17,550	15,750	21,875	22,750	15,750	24,500	18,850	21,750	28,875
Annual cost per mile, $	2,424	2,037	2,710	3,142	2,037	3,035	2,604	2,813	3,577
Equivalent capital, $	1,530	1,373	1,907	1,983	1,373	2,136	1,643	1,896	2,517
Equivalent maintenance, $	124	65	90	161	65	101	134	90	119
Power, $	770	599	713	998	599	798	827	827	941

Source: Ref. 64.

TRENDS IN LIGHTING SYSTEM DESIGN

The increased emphasis on improving visibility and providing visual comfort for the driver has resulted in many improvements in lighting system design. One of the most significant of these advances is the introduction of higher luminaire mounting heights, which increase the illumination level and, in addition, the field of vision, reduce glare, and increase uniformity. Research studies by Ketvirtis and by researchers at the Texas Transportation Institute have shown the following benefits from higher mounting heights:

1. Increased safety because the wider transverse spacing and longer longitudinal spacing means a reduction in the number of poles in the immediate vicinity of the roadway;
2. Better uniformity of illumination due to an increased area of the bright spot under the luminaire and a wider distribution of light than is possible with low mountings;
3. A reduction in glare because the light source is located at a greater height above the driver's line of vision;
4. An increase in the driver's visual field that, by permitting him to drive under more comfortable conditions, could increase roadway capacity;
5. Decreased maintenance caused by a reduction in the amount of dirt accumulating on the luminaries; and
6. A reduction in system costs through the elimination of a number of luminaires. Also, because of the improved uniformity and lower glare, lower illumination levels are necessary to provide adequate seeing conditions. A detailed economic study by Faucett (26) demonstrated that a system with higher mounting heights is more economical and has improved uniformity with regard to a conventional arrangement, if a reduction in level of illumination can be accepted (39, 43, 57, 58).

In spite of the benefits mentioned in the preceding, there are many reasons why higher luminaire mounting heights should not be used arbitrarily. Lindsay and Clark caution that changes in atmospheric conditions, such as fog, snow, and rain, cause attenuation of light flux that greatly reduces the illumination level and adversely affects illumination uniformity (45). At higher mounting heights these reductions are magnified and poor system performance results. Ketvirtis mentions that on narrow roads higher mountings may be wasteful because too large a percentage of the light falls on the surrounding area (39). Maintenance could also be a problem with higher mounting heights, unless trucks with sufficient reach to service the luminaries are available.

Another recent innovation in lighting practice is the use of floodlights mounted at 100 to 200 ft to illuminate intersections and interchanges. This technique, first tried experimentally in Europe, has some definite advantages over conventional lighting systems (38). First of all, such floodlights illuminate the entire area of the intersection, a benefit especially important at complex interchanges where drivers need a view of the entire area to plan maneuvers and to execute them in a systematic and safe manner. Second, fewer poles are required so that no forest of poles detracts from appearance and visibility. Third, glare is reduced with fewer light sources and higher mounting heights.

Economic comparisons between floodlighting and conventional lighting systems are difficult to obtain. With a conventional system the goal is to provide a specified horizontal footcandle level on the roadway without regard to the illumination level on the surrounding area. However, floodlighting is intended to illuminate the entire area and improve overall visibility. To accomplish this, it must display relief features, as well as the roadway surface; and illumination of these features is measured not in horizontal footcandles but in vertical footcandles, which enhance the visibility of objects presenting a vertical surface. In spite of this difficulty in comparison, a study conducted by Faucett indicated that, for equal average illumination on the roadway, floodlighting costs less than conventional streetlighting (25).

The concept of high-level intersection lighting is currently being studied by a research team at the Texas Transportation Institute (66). At test installations in both Fort Worth and Huntsville, Texas, professionals rated the high-level system superior to conventional lighting; the rating was a subjective one, based on the system's ability to produce a satisfactory night-driving environment. Other installations are now planned or under construction in Texas, Washington, and South Dakota (30, 66). The Texas Transportation Institute is conducting further research in an effort to establish performance criteria for interchange area lighting (66).

CURRENT STATUS OF RURAL AT-GRADE ILLUMINATION PROGRAMS

For this report the existence and extent of rural at-grade illumination programs in the U.S. was evaluated by contacting organizations involved in illuminating those highway intersections or manufacturing and supplying the necessary materials. Letters of inquiry were sent to (a) all of the state highway departments except Hawaii; (b) the American Road Builders' Association, which in turn forwarded the questionnaires to its county division and ultimately to its county associates; (c) highway departments in the provinces of Alberta, Ontario, and Quebec, Canada; and (d) 10 industrial firms. The particular questions in each of the letters of inquiry were as follows:

1. Does your organization have a rural at-grade intersection illumination program? If so, how many intersections have you lighted?
2. What current practices and techniques are followed in illuminating these intersections?
3. Have you developed specific warrants for the illumination of rural at-grade intersections? If so, what criteria were used to determine these warrants?
4. Has your organization undertaken research on the possible benefits of illumination? If so, what were the results?

Any additional comments or suggestions that the organizations may have felt applicable were also solicited. Replies were received from 47 states, 2 Canadian provinces, 2 counties, and 2 industrial firms.

Established rural at-grade illumination programs in this country are minimal; only 11 percent of the reporting states acknowledged that they had such programs in operation. However, 20 states have undertaken such illumination, whether they have instituted a specific program or not, and have illuminated more than 2,300 rural at-grade intersections over the past few years. These 20 states offered the bulk of the information on which this section is based.

Current practices in illuminating rural at-grade intersections are primarily based on the level of illumination and the uniformity ratio. The level of illumination varies with the existing and expected conditions, such as day-night accident rate comparisons, primary versus secondary roadway configurations, and surrounding environment. The levels of illumination, measured in average horizontal footcandles (lumens per square foot), ranged from 0.6 to 1.5 ft-c. The uniformity ratio represents the relationship of average horizontal footcandles to minimum horizontal footcandles on a roadway, as determined by the number and size of luminaires at the particular mounting heights and the geometric location. Uniformity ratios currently range from 3:1 to 6:1.

Variations in lighting techniques for particular situations include (a) use of luminaire lamp ratings of 400 to 1,000 watts, (b) choice of differing quantities of luminaires per location, (c) limitation of luminaries to mercury vapor, (d) variation of mounting heights from 30 to 50 ft (and, in some states, 100 ft or more), and (e) use of silhouette illumination techniques.

Through before-and-after studies in California, a significant reduction was observed in the night accident rate at intersections with improved lighting. The reply from Texas was the only one that reported any benefits resulting from research on rural at-grade intersection illumination, with increased area visibility as the major benefit. Replies from four other states offered information on the expected benefits of illumination—basically a decrease in number of accidents and an increase in area visibility.

Additional comments were received from only 2 states. A suggestion from New Hampshire was that grades, average daily traffic volume, geometrics, future plans, and community desires should determine the intersection layout, and a comment from the state of Washington was that the illumination efforts should be based on brightness rather than on average number of footcandles. The replies from the Canadian provinces, the counties, and the industrial firms did not supply any pertinent information beyond what was submitted by the states. Sixteen states showed an interest in supplementary knowledge, requesting the results of the study.

In view of the accumulated information, it is apparent that only a few states have realized the importance of establishing and implementing programs based on these criteria for illuminating rural at-grade intersections. Because motorists have to make most of their decisions in the areas of interchanges and intersections, the lighting in these areas must be carefully selected to help the motorist interpret functional features.

Although designed intersection lighting has existed since the early 1900's, warrants for its establishment have been neither conclusively determined nor universally accepted. Many authorities have developed their own lighting systems, considering factors such as quantity of accidents, accident rates, traffic volumes, signalization, channelization, and intersection geometrics.

An article in the July 1961 Traffic Quarterly, based on the results of a study at the Texas Transportation Institute, indicated that intersection illumination, signing, and design must be closely coordinated at the planning stage. The authors, Cleveland and Keese, concluded that no standard illumination design is adequate for the variety of geometric and environmental conditions encountered at all of the intersections (20). A 1960 report by the Ontario Department of Highways acknowledged the problems of developing a universal set of warrants by listing the many complex variables that should be considered: roadway geometry, traffic volume, turning movements, weather conditions, roadway surface materials and conditions, vehicle speed, headway, and driver psychology. The report suggested that these parameters be thoroughly investigated and coordinated for each intersection layout (42). An article by Williams in the November 1964 issue of Illuminating Engineering suggests that warrants for lighting should be aimed solely toward accident prevention (69). Ketvirtis, in his book Highway Lighting Engineering, discusses lighting warrants with the intention of establishing uniform warrants under which lighting should be provided and the levels needed for each (44). The conditions are systematically classified as follows:

Type of At-Grade Intersections	Class
Two illuminated roads	III
With high accident rate (3 per year or more)	II or I
Signalized	II or I
Channelized	II or I
Adjacent to areas of high-level illumination	II or I

The classes are described as follows: (a) Class I—partial illumination by a limited lighting system with luminaires at only key positions determined by geometrical features, such as the beginning of accelerating and decelerating lanes, left turns, bullnoses, and other road design features that require the motorist's special attention; (b) Class II—intermediate illumination by a limited lighting system with luminaires in key positions, plus additional lighting units required for ramps connecting to illuminated highways, or at-grade intersections with illuminated highways; and (c) Class III—full illumination by a complete road or interchange lighting system with luminaires at key positions and with all additional lighting units required to provide the specified level of illumination and pavement uniformity.

The similarity of criteria for roadway illumination warrants cited by the 29 replying states may be due to their adoption of the recommendations in the American Standard Practice for Roadway Lighting (2). In particular, traffic volume counts, number of accidents or accident rates, and intersection design were suggested principles of determination. The traffic volume counts were used in conjunction with warrants for traffic signals and in comparison with accident rates. Number of accidents and accident rates were submitted as comparisons of nighttime accidents with daytime accidents. Those states using accident rates as criteria had many varying comparison methods. Intersection design factors included geographical location, major and minor roadway delineations, channelization, and divisional islands. These were the only physical characteristics mentioned as criteria to determine the lighting warrants.

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Vision at Levels of Night Road Illumination: Literature 1967-1969

OSCAR W. RICHARDS, College of Optometry, Pacific University,
Forest Grove, Oregon

•THIS IS a consolidated review of research relating to vision at levels of night road illumination published in the 3-year period from 1967 to 1969.

Taylor (180) has prepared a graphic book on accidents, and Gramberg-Danielsen (81) has written a basic book on seeing and traffic that should be translated into English. Roadside hazards that should not exist are discussed by Blatnik (29). Sheppard has analyzed color vision from the engineering viewpoint (172), Nimeroff has revised the colorimetry handbook (148), and Wyszecki and Stiles have compiled a handbook of data on color (191). Arens (21) has revised his book, and the translation of LeGrand's book on light and color (130) has also been revised. Another book by LeGrand on form and space vision has been translated into English (129). Two useful books on experimental technique (174, 184) and a book by Fry on optics (75) are available. Ogle's book on optics (149) has been revised.

The report of the Committee on Vision of the National Academy of Sciences (24), reviews on vision (145, 163), the effects of drugs and alcohol on vision (12, 17, 85), a bibliography on carbon monoxide (51), and a source book for the literature on lighting (162) are new during this period. The analysis of seeing and driving by Byrnes (43) has been republished.

Ketvirtis (121) has written a book on lighting of roadways and automobiles, and some problems on night seeing. Economics (189), optimization of road lighting (164), and new measuring reflectometers (28, 123) are subjects of papers that were published. Increased lighting from 0.22 to 0.62 ft-c on the Connecticut Turnpike made little difference in visibility (98). Higher and better placed luminaires do contribute to seeing and efficiency (122). Tunnel lighting abroad is described by Schreuder (169). Several papers (181) on road lighting indicate possibilities for its improvement.

Papers on glare problems include the following: European evaluation of glare and low luminance (0.2 to 0.3 cd/m^2) sources (13); time for readaptation in relation to increased age (182); increased glare from polarizing glasses, especially plastic, due to surface haze (105); median widths or lateral separation to minimize glare (155, 108) and reflected and other glare light on driver vision (18, 104). Glare is more intense for wearers of contact lenses (25, 26). Tinted windshields, glasses, or contact lenses lessen glare but reduce seeing distance proportionately and should not be used at night (188). Median barriers are partially effective in reducing glare, but the best means is separation of roadways to minimize glare from oncoming lights.

Running lights appear to be useful in reducing accidents (47), and 2,000 cp or 45,000 ft-L with an area of 20 in^2. (about 5 in. in diameter) is recommended (124).

The high- and low-beam headlight studies show increase in use of low beams in Birmingham, Great Britain, and a decrease in pedestrian casualties (49). There are widely differing uses in various parts of the United States (88), which were observed to be independent of topography.

Headlights tend to position oncoming cars farther on their side of the centerline (7, 8). Davey (55) reviewed the headlight systems used in England and Europe with respect to the driver's vision. Lighting the hood of the car at night gave increased visual feedback and reduced tracking error by 40 percent (114). Allen (2) recommends

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Paper sponsored by Committee on Visibility.

adding a ring of retroreflective material around the headlight to show its position when the lamp is burned out and points out that disappearing headlights are not fail-safe and are often too dirty for effective use (4). Johanssen and Rumar (109, 110) propose a system for introducing polarized headlights. On nonilluminated roads, seeing distance at night was such that only 16 to 31 mph was safe (111).

The poor visibility of pedestrians wearing dark clothing was measured, and reflectorizing or white clothing was found to be necessary for reducing pedestrian deaths, especially when the driver has been drinking alcohol (90).

The chaotic arrangement of taillights on automobiles and possible relation of this to rear-end accidents have often been discussed (143, 156, 177). Mortimer's (144) tests indicate that separate taillights, turnlights, and stoplights are more effective, and he recommends an outside pair of green taillights, amber turnlight just inside the taillights, and a pair of red stoplights central to the turnlights. Projector and his associates (156) propose a system of red lights that provide different configurations to show a change in direction or speed of the car ahead. Gibson (78) recommends a tricolor system and possibly implies my support by referring to a paper of mine. This I deny, because any amber light on the rear of an automobile is ambiguous under various lighting conditions to deuteranomalous people. I favor only a system that furnishes information by changing shape (161). Problems of standardization and unification are available (156, 177).

In their paper on traffic signal cycles, Webster and Cobbe (187) in England recommend a 1.5-second perception-reaction time for a yellow signal clearance interval, and Jenkens (107) reports that they have compromised in Michigan on a 1.2-second interval.

Bugelski (34) describes an illusion wherein objects approaching a red signal light at night appear to go beyond the light when seen the distance of a city block away because, at at low angle of observation, a stimulus appears closer than another at or below eye level. Moving objects are not seen as well with raised or lowered gaze as when moving horizontally (100). Flashing lights proved less useful than expected (44).

Legibility of signs and their attention demand factors, contrast, color, and brightness were studied by Forbes and associates (70, 71, 72, 73). They recommend specifications for the design of signs and compromises with lighting conditions for best visibility at night. Pain (150) suggests that adding a relative brightness factor would refine Forbes's models. Allen (9) also gives recommended luminance values for signs, and Brass (30) gives values for internally lighted signs seen against a sky background. Further analysis of what signs are seen by drivers, when numbers of signs become too many, and what signs are good and bad continues (10, 108). Mackie (136) discusses learning progress for symbol types of signs, not all of which are self-explanatory to all people. Analysis of human factors has been applied in the design of warning devices (101).

The California fog study (45) reveals a reduction in speed of 5 to 8 mph in fog except in high-volume daytime and low-volume nighttime freeway operations when there is little change. In fog, red is most visible and green is useless; this is a strong argument against green taillights. In fog, present-day taillights have too little candlepower to be useful. Accidents due to fog were only 2 percent of all accidents and were judged insufficient to justify very expensive special protection, most of which was found to be of only slight help in accident reduction during the short periods of dangerous fog.

Lyman (135) provides 407 references on detection. Shea and Summers (171) discuss the problems of seeing distant points of light. Whitewall tires are recommended because they show better than black tires; reflectorization is considered to be better than white (3). Detection is reduced when it is required along with a mental task (113), and the diameter of the pupil of the eye is an index of the perceptual load. Visibility distances (166) for 140- by 40-cm cloth-covered objects of 3, 6, 16, and 82 percent reflectivity against dry, wet, and snowy roads vary from 34 m (112 ft, black on dry road) to 160 m (425 ft, white on wet road). On a snowy road, white was seen less well, 100 m (328 ft), and dark gray best 51 m (167 ft).

Lit (132) reviews visual acuity, and Cornog and Rose (52) report on the legibility of alphanumeric characters. Rattle and Foley-Fisher (158) correlate vernier acuity with intersaccadic interval. Burg (35) compares dynamic and static visual acuity, finding that the dynamic acuity correlates better with a static chart than with the Orthorater. A marked decrease in both dynamic and static acuity with age is reported, possibly from changes in the complex nature of accommodation and the pursuit task that involves resolution and coordination of eye and neck muscles. Munker (146) indicates a decrease in acuity during moving in traffic from a half to a tenth of that observed during a static test. Vertical vibration of the test target decreased acuity more than small horizontal vibration. The discussion, following the paper, objected to "dynamic" visual acuity and favored "kinetische" or kinetic visual acuity. Gordon and Michaels (80) analyze basic aspects of driver perception of static and moving visual fields.

The disc is a good representative target for testing contrast, and the differences found for various targets are reported by Guth and McNelis (87). Low contrast tests, a modified Titmus test, and an Allen's test show a decline in vision with age. The Allen 50 to 60 percent contrast showed no greater loss in average scores under mesopic conditions than did the 90 percent contrast Titmus test (73).

Pedestrian visibility was measured by Rumar (165) for varying contrast and headlight beam misalignment. Silhouette is no help within about 3 ft from the edge of the road. He recommends forcing the pedestrian to protect himself. Retroreflectorization of helmets for motorcyclists is recommended to increase their visibility (91). Allen (5) emphasizes that windshields should be replaced when the surface deteroriation forms a haze and lessens vision through the glass.

The color of signal lights and considerable information about colors and their seeability were compiled by Breckenridge (31). Daylight fluorescent orange is recommended for the protection of humans from accidents (140). Colored pavements are being tested (97). The value of red light for dark adaptation is questioned by Dohrn (61). The Stabells (176) found that colors can be seen at luminances below the break in the usual dark adaption curve, which indicates a need for revision of the duplicity theory.

Defective color vision remains stable over some years (65). Reaction times for red light are a tenth those of white light and a fourth those of green light (6). A detailed study of signal light recognition by color-vision defective people revealed errors for 11 percent at high and 13 percent at low intensity. More errors were made in daylight than at night! Amber was mistaken for red 22 percent of the time at high intensity and 24 percent at low intensity. Protans make mistakes at low but not at high intensity. Deutans have more difficulty seeing amber lights (173). The decreased visibility of red for protans measured by Clark (50) indicates that specific tinted glasses can delay the recognition of signals. The use of red filters of progressingly longer dominant wavelengths can be used to estimate the loss for identification of red signals (83).

Wearing sunglasses at night caused a British singer to be fined (15). Henderson's study (92) on yellow glasses and glare resistance gives conflicting findings that suggest that the technique used was inadequate. Phillips and Rutstein (151) report a detailed survey on amber night-driving glasses and new tests showing that their 10 subjects did not see as well with yellow glasses and had less glare resistance to yellow light. Plastic yellow spectacles were worse because of the increased veiling glare. Yellow headlight tests did not support the French claim of 8 percent increased visual acuity despite a 15 percent loss of light. Instead they found a 2.5 percent loss in vision. Increasing the luminance of the yellow to make up for the filter loss gave a slight 3 percent gain in visual acuity (48). Redetection was slower following glare from yellow light than it was following glare from white light of equal intensity, and more so for younger persons. Glare recovery decreases with increasing age (159).

Engine and other noises associated with driving heavy trucks have a low frequency spectrum, less than 600 Hz, and can increase the speech interference level far above 70 dB. Even though the danger of hearing loss over a long time is less in truck driving than in other noisier occupations, applicants for truck driving should be tested for hearing and documented by an audiogram (93).

Drugs usually have an adverse effect on seeing, and several recent publications discuss this problem (69, 84, 116, 134, 185). Green (85) lists 23 categories of drugs that may influence driving. Cooper (51) has prepared an extensive bibliography on carbon monoxide, and measurements of carbon monoxide concentrations are reported for several cities (32). Although the results (63) are inconclusive, prolonged simulation of driving performance may be better with Diazepam (Valium). Laroche (128) found that use of streptomycin and dihydrostreptomycin resulted in green blindness.

Crancer et al. (53) reported that during simulated driving, marihuana produced more speedometer errors and alcohol more accelerator, brake, signal, speedometer, and total errors.

All reports on alcohol indicate that accidents increase as the blood alcohol rises (12, 17, 103, 139, 102, 106, 142, 175, 179). A study of the effects of amitriptyline and alcohol together indicates that this antidepressant adds to the deleterious effects of alcohol on driving ability (127). When the visibility of a pedestrian is border line, the seeing distance declines rapidly for drivers after drinking alcohol. Only a reflectorized dummy is seen at 40 mph by drivers with a high blood alcohol concentration (90).

Reaction times of young drivers (20 to 25 years) to auditory stimulation within the car and to a light outside the car increase with increased driving time. Four hours of nonstop driving in daytime, darkness, and after one night of sleep deprivation showed no significant differences (133). Another study at Uppsala University gives physiological data on fatigue from simulated automobile driving (64). Pregnancy may have an adverse effect on night vision (60).

Beginning drivers are less dangerous than 18- to 20-year-old drivers. The worst accident rate was found for 18- to 20-year-old drivers with low mileage experience, next for the 21- to 22-year-olds with low mileage experience, and third for the 18- to 20-year-olds with median mileage experience (19). Allen (1) gives driving tips for the aged, and Planek et al. (152) present a broad survey of the problems of older drivers. Dynamic visual acuity declines with age (68). Burg's (37) analysis of the California data shows slight correlation between horizontal phoria and age and also shows a trend toward exophoria in older people, more so in females than males. The total visual field is greatest at 16 to 35 years and then declines with age. Females (except after age 80) show larger nasal and temporal fields than males, and the greatest differences are in the temporal fields (41). Light sensitivity was fairly level at ages 25 to 40 and thereafter declines. The luminance threshold appears to be more closely related to age than is glare recovery (36). Vision declines with age; older people need more light and, because it is not presently possible to provide better road lighting for oldsters, they are handicapped and gradually forced to give up driving at night (161).

Vision and driving were examined in a Texas symposium (181). Further analysis of the California data by Burg (38, 40) shows dynamic visual acuity has the best correlation with the driving record, followed by static visual acuity, fields, and glare recovery. Age, sex, and annual mileage driven play a large role in the driver record. The performance of males was better than that of females on static and dynamic visual acuity and lateral phorias, and the performance of females was better on fields, glare recovery, and low illumination thresholds (38).

Low luminance tends to draw the driver nearer to the center of the road and to cause him to reduce his speed. Drivers can maintain constant speed and lane position at 0.168 mL (137). Positive afterimages are discussed by Fry (76). Problems of seeing during naval operations at night provide some useful information on the night automobile driving problem (125).

More interest in driving problems is noted by the medical profession. MacFarland (138) reviews some aspects of accidents, Antia (20) tries to find predictors for accidents, and Gramberg-Danielsen (82) discusses some European court decisions. Abnormalities seen during an autopsy can explain some accidents due to visual disability, and more use of such findings are needed (194). One-eyed drivers may be more of a factor in accidents than earlier studies showed (120). One problem of the monocular driver is that he loses more time from seeing the road while he checks speed. An additional nearside mirror and goggles are recommended (33). Keeney (118, 119, 120) reviews various pathological conditions and their relation to safety in driving. Some, but not all, epileptics may be allowed to drive under specified conditions (66, 99). The accident record of medical and surgical patients is about the same as that of a random sample of male drivers (42). Keeney's (120) analyses of the medical aspects of the

Kentucky program showed that 10 percent of 1,153 drivers had medical conditions that interfered with safe driving.

Night myopia has been traced back to Maskelyne in 1758 by Levene (131), and Young (192) describes interrelations of myopia and personality.

A theoretical model is proposed for showing improvement of night vision from correction of the optical aberrations of the eyes (153). Bewley (27) points out the hazard from wide spectacle frames that block out parts of the field of view, reminding us of the earlier work of Weale (16). A poorly fitting spectacle frame decreases vision and increases driver annoyance and fatigue. Much of this hazard could be avoided if the fitting methods of Grolman (193) were followed.

Contact lenses and possibly serious complications are discussed, and Diamond (59) states that only one of a pilot-copilot team should be permitted to wear them during flight. Corneal contact lenses transmit into the eye more than 7 percent more light than do spectacle lenses, and the sensitivity of contact lens wearers to light is 11 percent more; both factors contribute to the increased glare experienced with contact lenses (25, 26). Davey (55, 56, 57) discusses the loss of visual fields from helmets and problems of protecting the vision of motorcyclists.

In Great Britain, 1 percent of 1,190 drivers tested had defective vision and 5 of these drivers were monocular. The Association of Optical Practitioners found 1.12 percent of drivers had substandard vision (16). In Munich, 92.7 percent of 106,140 drivers had vision better than 70 percent of the norm, and 0.1 percent had serious deficiency of less than 30 percent of the norm (147). A study in Tennessee of 175 drivers revealed that 20 had significant phorias, 15 had substandard acuity, 5 had poor (< 20/70) acuity, 45 had poor color vision, and 8 had field loss (94). Kaestner (112) reexamined about 13,000 records of Oregon drivers. The written test had more predictive value for males than for females and the road test had more for females than for males. Five-year accident averages and other data are included. Much useful information was gathered in Kentucky (120).

In its provisional standards for vision required for a driver's license, the American Medical Association divides vehicles into 3 classes: public service vehicles, taxis, and private cars (11). Acuities of 20/25, 20/40 in the bad eye, and 20/40 or better in one eye and fields of 30 deg nasal and temporal each eye, 30 deg, and 140 deg respectively are required for each class. Pathological limitations are listed. Lenses of more than 10 diopters are prohibited unless the visual field is 140 deg. Provision for special licenses and the frequency of examinations are discussed. New vision standards for Michigan drivers are described (126).

Powell (154) presents the viewpoint of the Illinois Secretary of State on license examination experience. License requirements are summarized for some European countries (183).

Keeney (119) discusses in-depth problems of vision testing, vision requirements for automobile driving, and the responsibility of judging cases of border-line visual abilities. A British viewpoint is stated (196). The vision of airline pilots at intermediate distances, especially in the over-45 age bracket, should be measured, and proper spectacle correction provided (89). Rates of vision responses are summarized by Sands (168). Although instruments are not as important in automobile driving as in flying, the changes in near vision should be kept in mind. Kaufmann (117) urges that a visual acuity of 1.0 be required in Germany. Almost every year someone points out the advantages of reflectorized license plates to increase the visibility of automobiles at night (46).

Consideration of what the driving task actually is rather than vaguely attributing it to seeing is a hopeful sign in the current literature. Mathematical analyses are initiated (77, 157). General rules and what to look for at night are listed by Fales (67). A research program is submitted for highway safety (22). Cumming (54) gives an analysis of the skills involved in driving and the advantages to be gained if the input of information to the driver is neither too little nor too much. Senders et al. (170) also consider the sensory information input and the abilities and limitations of the driver to process and respond properly to his task. Pilots are being tested under conditions of sensory input overload (62). At a 1969 Berkeley conference, factor analysis methods were proposed to find out what actually is the automobile driving task. The tendency to concentrate on a single element, when the driver's processing ability is overreached, is dangerous to safety and can spoil driver communications (190).

Burg (39, 40) summarizes the vision information and driving records of his large-scale California study. Dynamic visual acuity has the best relationship with the driving record; static visual acuity, glare resistance threshold, and field size may be useful tests. Seeing problems from within an automobile, design problems, and seeing needs are summarized by Gioia and Morphew (79). Seeing-timing data provided by Sands (168) are useful also at the slower rates of automobile driving. Fry (74) gives an analysis of the use of the eyes in steering an automobile. Planning ahead to correct misalignment with the road is necessary because steering is rate control (including reaction time); it may take a second for completion. Anticipation must be considered in the visual problem and task analysis. The overestimation or underestimation of actual speed by the driver needs to be included in the analysis of reaction timing (23), and accurate judgment of speed is important for much of the driving task (167). Presentation of information near where the eyes are viewing the road will save 0.4 second, the time necessary to accommodate and converge the eyes on the dashboard; this is a suggestion toward automation for the driver (178). Eye-movement analysis by Thomas (195) will be useful.

Specification for a convex mirror of not less than 1,200-mm radius and proper positioning of these mirrors are proposed with a discussion of learning to use convex rear-vision mirrors (186).

An instrumented car is in use in Holland for the study of driver behavior (141). Denton (58) describes a moving road simulator, and a new reaction time tester is reported (14). A television display used to investigate seeing from right, center, and left of the automobile indicates that the usual left side may not be the best position for the driver's eyes (115). A psychological questionnaire failed to identify risk-taking propensity of high- and low-accident-prone drivers (86).

A similar review of the literature on vision at levels of night illumination was made by the author in 1967 (160). In addition, a bibliography on night visibility (95) and one on headlight glare (96) are available.

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Driver Interactions and Delays in Freeway Traffic

DONALD A. GORDON, Traffic Systems Division,
U.S. Department of Transportation

The aim of the study was to describe the behavior of individual drivers in normal freeway traffic. An experimental car was driven at slow speeds of 50, 45, and 40 mph along an Interstate highway, causing overtaking drivers to react. Without their awareness, drivers were photographed from a tower and from the experimental vehicle on the road. The photographs were analyzed to show positional relationships of the experimental car and overtaking drivers and to show changes in lead distance between cars as a function of time. A driver who approached in a different lane from that of the experimental car and who was unobstructed passed without slowing. The experimental vehicle did not influence the speed of these passing drivers. Obstructed drivers, who changed lanes to pass, also did not slow down. On the basis of the data, it seems likely that the decision to shift is made at 250 ft of separation distance or less. Nine drivers of the 166 studied were obstructed and appreciably delayed. A typical obstructed driver shows a three-phase response. In the first (approach) phase, the driver moving at his desired pace starts to slow down in anticipation of being blocked. Next follows a delayed phase of from 15 to 35 seconds, where the driver moves to a slightly closer position or matches pace with the car in front. This phase is related to traditional car-following, but drivers' responses are too individualistic to be represented by any simple car-following equation. In the final (passing) phase, the driver assumes his original speed and moves ahead of the car in front. These reactions are partly explained by the driver's motivation to maintain pace and move ahead. Passing drivers and blocked drivers did not slow appreciably. Only when the driver was effectively blocked did he slow down. Traditional car-following did not occur frequently in this study, nor did drivers appear to want to follow the car ahead.

•THE MASONIC TOWER of Alexandria, Virginia, is a well-known landmark of the Washington, D.C., landscape (Fig. 1). For a brief period in the summer of 1969, the observation station of the Tower served as a photographic outlook for the study of freeway traffic reported here.

Characteristically, freeway traffic involves vehicular interaction that is not so severe that movements of the car are completely dictated by the movements of the vehicle in front. Although many studies have been made of highway traffic, little is known concerning the responses of the individual driver who is the active element in the system. Cars and roads do not react; only humans do. The study of the driver's responses and his psychology should reveal important information concerning the detailed mechanisms of traffic flow.

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It was considered important that drivers be observed under operational conditions and be unaware that they were under surveillance. It is doubtful that drivers would have lane-straddled, wobbled, and accepted gaps as they did if they knew that they were being observed in a formal experiment.

A "plant" vehicle was deliberately introduced into the highway stream. This car was driven at a speed slower than that of the traffic stream. Other drivers coming up from behind reacted to the plant. Their responses were photographed from the Tower and simultaneously from the plant vehicle itself.

Figure 1. Masonic Tower from which photographs were made of traffic on Interstate 495, a half mile away.

BACKGROUND OF THE PROBLEM

There is disagreement in the research literature on how drivers interact on the highway. The best known theory is associated with the work of Herman and his co-workers (1, 2). On the basis of experimental observations on a test track and in New York City tunnels, Herman derived the following equation to describe what has been called "car following":

$$\left[(d^2x)/(dt^2)\right]_{n+1} = \alpha_0 \frac{\left[(dx/dt)_n - (dx/dt)_{n+1}\right]}{x_n - x_{n+1}} \tag{1}$$

where

$(d^2x/dt^2)_{n+1}$ = the acceleration of the following car,
α_0 = a constant related to speed,
$(dx/dt)_n - (dx/dt)_{n+1}$ = the difference in speed between cars, and
$x_n - x_{n+1}$ = the headway distance between cars.

The equation states that the acceleration of the following car is directly proportional to the difference in speed between the 2 cars and inversely proportional to the distance between the vehicles. Herman and Gardels (1) have described the application of the car-following equation as follows:

> Follow-the-leader theory attempts to describe the behavior of a single lane of fairly dense traffic in terms of the detailed manner in which vehicles follow one another in the traffic stream. This condition of one-lane traffic with no passing is more common than the motorist accustomed to multilane turnpikes might think. No-passing situations still exist, in law or actuality, on many stretches of two-way roads and streets, in tunnels and on bridges. Even on multilane highways dense traffic often forces a driver to stay in one lane.
>
> In sum, the follow-the-leader equation works out to show that a driver tries to keep the relative speed between him and the vehicle in front as small as possible, and that the closer he is, the more attention he pays to the problem. If he is far away, he drives in a manner that is more or less independent of what the driver in front is doing.

It may be seen that Herman's equation is intended to describe the reaction of a driver to velocity changes of the car ahead. This follow-the-leader behavior is presumed to be characteristic of very dense traffic, and is possibly applicable to freeways. [A perceptual basis for Herman's equation has been suggested by Michaels (3). He has shown that there is a close relation between the form of Herman's equation and the angular expansion of an approaching car. The relation suggests that changes in the angular subtense of the vehicle ahead provide a perceptual basis for car-following.

If Herman's equation is integrated, the following relationship is obtained:

$$(dx/dt)_{n+1} = \alpha_0 \log\left[\frac{x_n(t) - x_{n+1}(t)}{L}\right] \quad (2)$$

where L is the effective length of the following car.

The variables in this equation—velocity of the following car and distance between cars—are convertible to concentration and flow, the master variables of traffic flow. The implication is that Herman has found a basis for traffic flow in the reactions of the individual following driver.

A quite different view of traffic interactions has been presented by Rockwell and Snider, who took film records from commercial trucks, during normally scheduled runs (4). Little evidence of car-following was found in the 40 or more hours of analyzed film:

> When a vehicle would pull in front of the research vehicle, the latter would either immediately pass or else reduce velocity until the influence of the leading vehicle was completely avoided. Car-following, as traditionally described, was observed to occur only when the research vehicle was attempting to pass the leading vehicle. An explanation for this general lack of car-following situations is that the drivers attempted to minimize the influence of leading vehicles upon their own longitudinal control. This is not surprising in view of the fatigue and stress associated with car-following over extended time periods.

Car-following was seldom found, even during peak traffic or behind the experimental car. The authors state that "only a small percentage of vehicles would car-follow, and then only under conditions of extremely large headway."

The results of Herman's study of car-following in tunnels and Rockwell and Snider's study of car-following on the open road seem to be in puzzling contradiction. The differences are partly explained by variances in traffic conditions. But the need seems strongly suggested for further studies of driver interactions in a variety of highway situations.

EQUIPMENT AND PROCEDURE

Photographic Procedure

The highway around the plant was photographed simultaneously from the Tower and the plant itself. The Tower view is approximately 400 ft above Interstate 495 (Fig. 2). Both sides of the highway can be seen from the Tower, except where the line of sight is obscured by 2 apartment houses.

Photographs were also taken through the rear window of the plant, with a 16 mm camera equipped with 14.5 mm wide-angle lens (Fig. 3). The backwards field of view was wide enough to cover all lanes and showed complete lane shifts of passing cars. The photographer in the plant car did not reveal to approaching drivers that pictures were being taken. He looked forward and did not touch the camera until told by radio communication from the Tower to start or stop picture-making.

Figure 2. Traffic on I-495 photographed from Tower.

Experimental Vehicle

The plant was a gray 1965 Dodge sedan equipped with speed governor. It was marked for identification by tape bands on its roof, hood, and trunk. These bands could be seen from the Tower, but were hardly visible to approaching drivers.

Experimental Course

The plant car shuttled on I-495 between exits 1N and 3. Photographs were taken on the stretch of highway 2.1 miles long between the Linnean overpass and exit 1N (Fig. 4). At closest, this highway is 0.6 mile from the Tower and, at farthest, 1.6 miles. The course has 3 lanes, except at Telegraph Road where exit lanes leave and entrance lanes come in. Posted speed limit is 65 mph. Traffic during the runs would probably be classified as "medium".

Figure 3. Traffic on I-495 photographed from experimental car.

Schedule of Runs

Photographs were made on 6 round-trip runs from the Linnean overpass to the 1N exit and back. During each round trip, a fixed speed was maintained. The first run was at 50 mph, followed by runs at 45 and 40 mph. This sequence was again repeated to give a total of 6 round trips. It will be noted that the plant traveled at speeds below the 65 mph limit, causing approaching drivers to react. The plant driver stayed in the first lane and shifted only when the first lane exited from the freeway. During the 6 runs, photographs were simultaneously taken from the Tower and the plant car.

ANALYSIS OF DATA

To an observer, the moving traffic stream appears as a bewildering confusion of passing, following, and shifting vehicles. It was necessary, therefore, to devise some

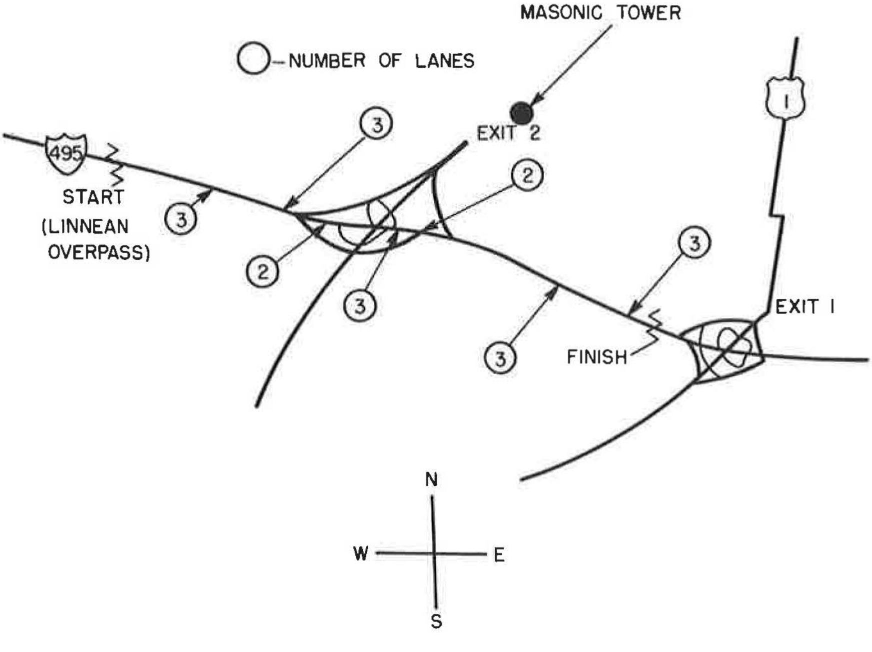

Figure 4. Experimental course.

method of classifying and analyzing individual driver reactions. The analysis was accomplished by means of occupancy diagrams, interaction summaries, and positional plots.

Occupancy Diagrams

Occupancy diagrams indicate the consecutive positional relationships of plant and interacting driver. Figure 5 shows occupancy diagrams modified from records of the sixth run. In diagram a, at the start of the run, vehicle A in the second lane passes the plant in lane 1 (right lane), without shifting lanes. In diagram b, vehicle B passes both the plant and vehicle C, which is behind and in the same lane as the plant. In diagram c, vehicle C shifts from the first to the second lane and passes the plant. In diagram d, the plant shifts to avoid being caught in the exit lane; vehicle D, which has been following, passes on the right. The occupancy work sheet also noted the lanes occupied by plant and vehicle, described the interacting car, i. e., "cream Volkswagen," and provided a letter designation for it. This letter identified the vehicle in all subsequent tabulations and charts.

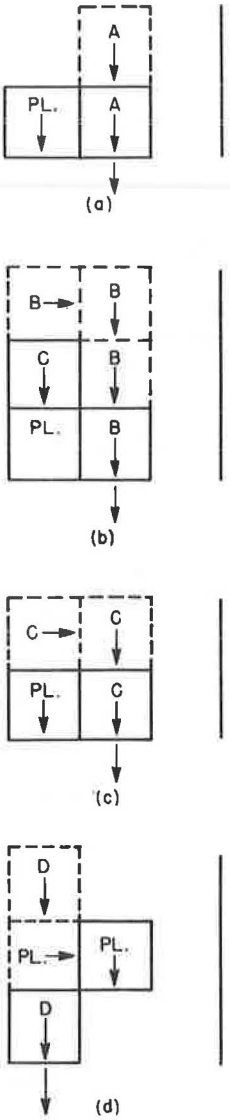

Figure 5. Occupancy diagrams.

Interaction Summary

The interaction summary included all driver interactions and their resolutions. Situations were classified as those where the approaching car was in a different lane from the plant and hence was not obstructed; or in the same lane and obstructed. If not obstructed, the vehicle passed by simply moving ahead. The obstructed cases were resolved by the subject car shifting to another lane or by the plant shifting. In some instances, the subject car was blocked and appreciably delayed. These cases are of special interest and were given a complete analysis.

Relative Position Graphs

A quantitative description of vehicular interactions was obtained by plotting the distance between the plant and overtaking vehicles as a function of time. A $\frac{5}{6}$-sec interval, representing a sampling rate of 1 frame in 20, was used in plotting the positional graphs.

In the analysis of the Tower photographs, screen image distance between cars was calibrated by reference to the known distance between the plant's hub caps (10 ft $1\frac{1}{2}$ in.). Distances in the plant car photographs were calculated from perspective changes. As a vehicle approached the plant, its angle and the related image on the screen increased inversely with distance. The relationship is expressed in the following formula:

$$d = k/\beta$$

where

d = the distance from the focal plane of the plant camera to the front of the observed vehicle;

β = the angle of some particular dimension, such as the distance between headlight centers, as represented by the measurement on the screen; and

k = a constant related to the size of the vehicular feature, the focal length of the camera and projector lenses, and the distance from projector to the screen.

This approximation of the tangent function is justified because the angles of interest are almost all less than 6 deg. The formula was applied by measuring the screen size β

with the distance d to the observed vehicle known and thus determining k. Once constant k was known, the distance associated with any β could be found.

Distance to the vehicle was first obtained by measuring the length on the screen between lane markers at the front of the approaching vehicle. The constant k was calibrated in this way at several distances and an average value selected. The change in dimension between the top of the roof to the shadow between the tires was used to measure β. A correction of 7 ft was subtracted to correct for camera to rear bumper distance.

RESULTS OF EXPERIMENT

A total of 166 "incidents" were recorded in which approaching drivers reacted to the slower moving plant (Table 1). It may be seen that 151 drivers (91 percent of the cases) were either unobstructed or escaped obstruction by simply shifting lanes. In 9 cases (5.4 percent of the incidents) the following car was appreciably delayed. More interactions occurred at the 40-mph plant speed than at more rapid speeds. An incident occurred on the average of once every 8.9 sec on 40-mph runs, every 11.1 sec on 45-mph runs, and every 19.4 sec on 50-mph runs. The number of incidents is related to the relative velocity of plant and highway traffic. A vehicle moving at 10 mph less than the traffic stream will encounter twice as many interactions, on the average, as one moving 5 mph slower than traffic.

Unobstructed Passes

Unobstructed passes are those that are made when the approaching driver is on a different lane from the plant and simply passes. An unobstructed pass was randomly chosen for analysis, from each of the 6 runs (Figs. 6 through 11). The identification of the vehicles follows that of the occupancy diagrams. For example, the first vehicle, which bears the notation 1K, was the kth (eleventh) vehicle in the first run. Plant speed was 50 mph in the first and fourth runs, 45 mph in the second and fifth runs, and 40 mph in the third and sixth runs. Lead distance in the figures is reckoned from the rear bumper of the plant to the front bumper of the oncoming car. Separation is zero when the bumpers are even with each other. The record for vehicle 6J may be seen to lack a zero point as the Tower view was obscured when this vehicle passed.

In none of these records does the driver change pace in passing. Except for vehicle 4K, all records show either straight lines of constant velocity or smooth curves of very slowly changing velocity. Vehicle 4K shows a dither response, which may well have been a personal idiosyncrasy. It appears that the typical unobstructed highway pass does not entail a slowing down or an increase in speed.

Obstruction Resolved by Driver Shifting Lanes

Obstructed drivers most frequently resolved the predicament by shifting lanes. Six cases that involved only the plant and the shifting vehicle are shown in Figures 12 through 17. These figures show that lane-shifting did not generally involve a change in

TABLE 1

SUMMARY OF DRIVER INTERACTIONS

Run	Speed (mph)	Subject Unobstructed and Passed	Subject Obstructed in Same Lane as Plant			Total
			Subject Shifted	Plant Shifted	Subject Delayed	
1	50	11	3	1	1	16
2	45	25	6	0	1	32
3	40	26	18	2	1	47
4	50	10	0	1	3	14
5	45	21	4	1	2	28
6	40	17	10	1	1	29
Total		110	41	6	9	166
Percent		66.3	24.7	3.6	5.4	100

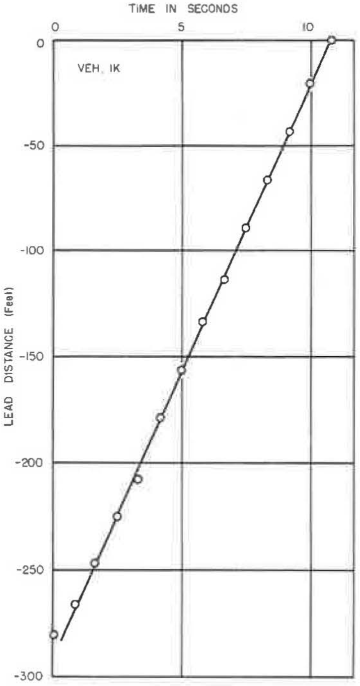

Figure 6. Lead distance of vehicle 1K in unobstructed passes.

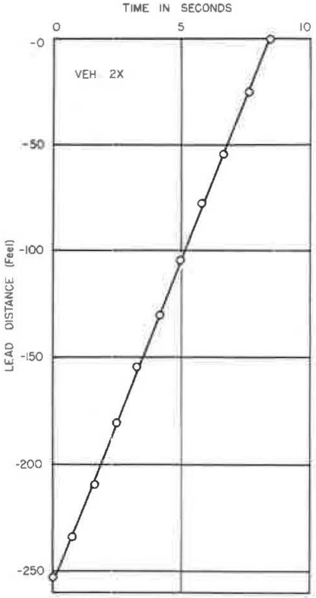

Figure 7. Lead distance of vehicle 2X in unobstructed passes.

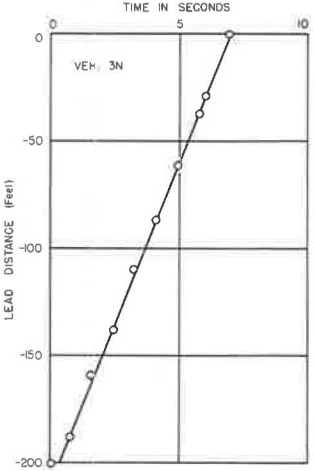

Figure 8. Lead distance of vehicle 3N in unobstructed passes.

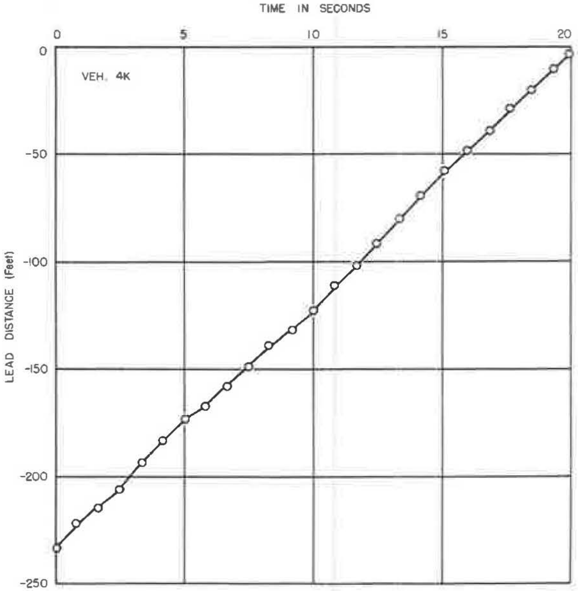

Figure 9. Lead distance of vehicle 4K in unobstructed passes.

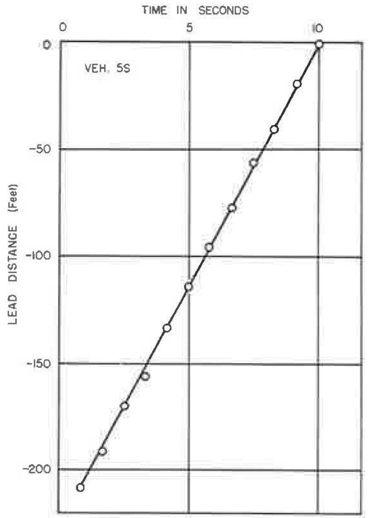

Figure 10. Lead distance of vehicle 5S in unobstructed passes.

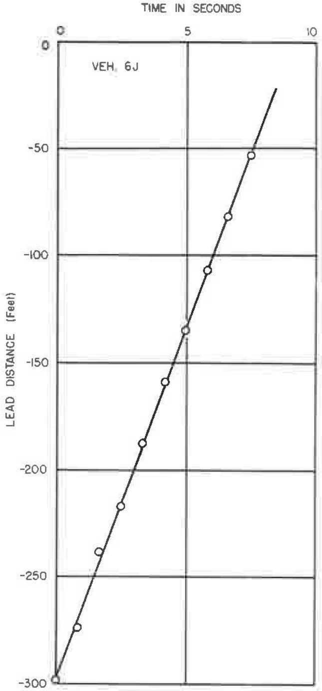

Figure 11. Lead distance of vehicle 6J in unobstructed passes.

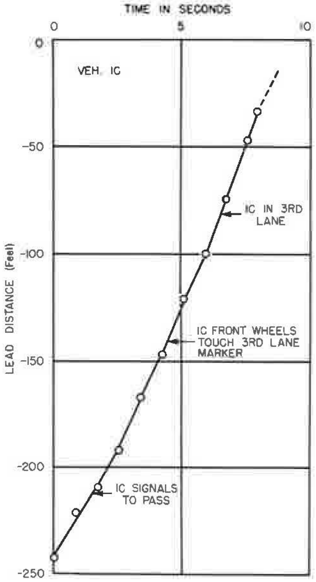

Figure 12. Lead distance of vehicle 1C in lane shifts.

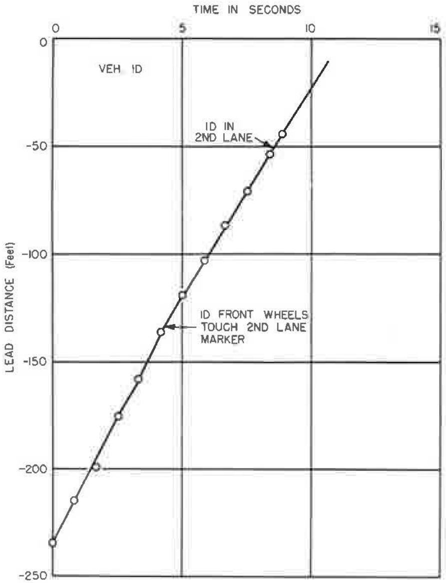

Figure 13. Lead distance of vehicle 1D in lane shifts.

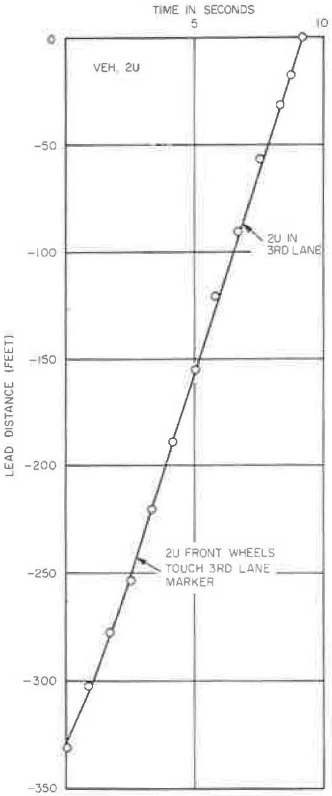

Figure 14. Lead distance of vehicle 2U in lane shifts.

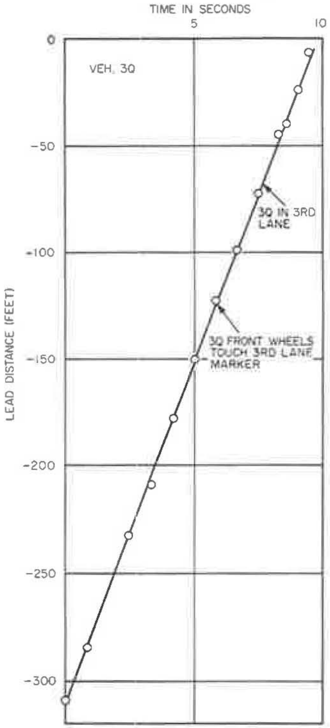

Figure 15. Lead distance of vehicle 3Q in lane shifts.

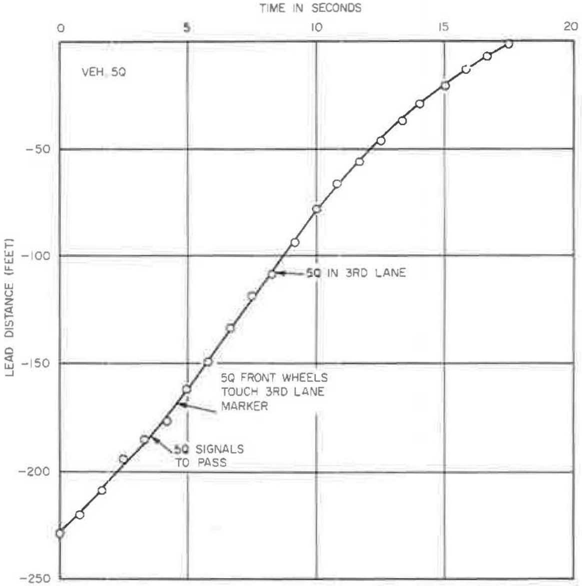

Figure 16. Lead distance of vehicle 5Q in lane shifts.

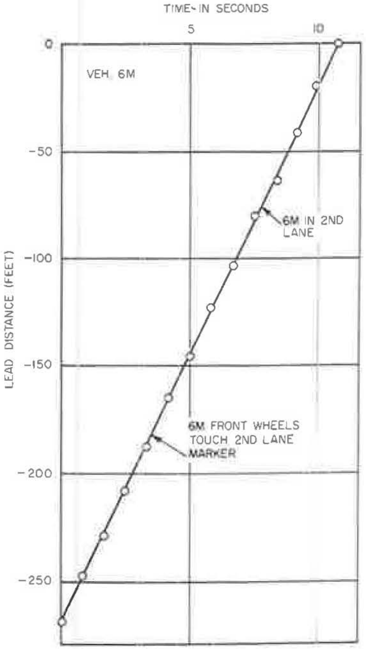

Figure 17. Lead distance of vehicle 6M in lane shifts.

pace. The driver of vehicle 5Q did speed up when the front wheels touched the lane marker at 168 ft, and he slowed down at a 106-ft distance from the plant. This driver's truck was loaded with bottled beverages, which may have accounted for his cautious approach.

The distances at which various phases of lane-shifting took place are shown in Figure 18. Eight drivers signaled before shifting. The signal was given at a median distance of 202½ ft, a range from 78 to 314 ft. The start of the shift, indicated by contact of the front tire with the lane marker, based on 30 overtaking drivers, occurred at a median distance 34.7 ft closer to the plant. The range was from 7 to 66 ft. Median lane contact was 148½ ft. The shift from tire contact to "in-lane" position required 2.2 sec (median). The range was from 1.08 to 5.58 seconds. [For comparison, Worrall and Bullen (5) give 160 and 110 ft as the mean (not median) distances for tire contact and in-lane position. Their figure for the average time required to shift is 2.91 sec. Because the distributions of distance and time are skewed, the results of the 2 studies are roughly comparable.]

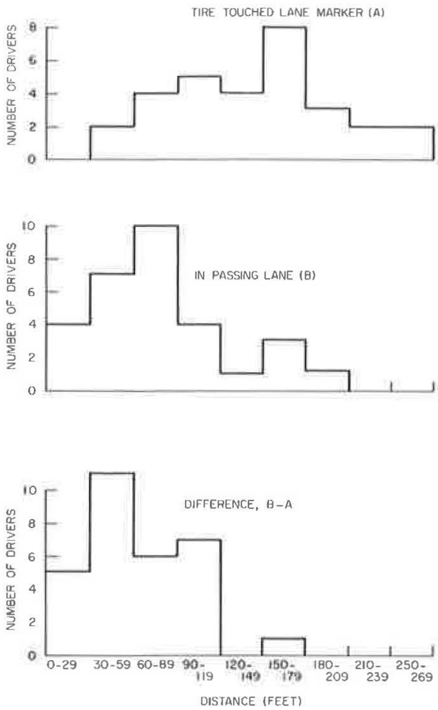

Figure 18. Distribution of lead distances of vehicles in lane shifts.

From these calculations, it appears that drivers start to react to an overtaken vehicle at distances of 300 ft or less. Lane-shifting quickly follows the signal to pass, and is completed at a distance of about 100 ft from the car in front. The distributions of Figure 18 indicate considerable variability associated with driver, vehicle, and traffic condition differences.

Vehicles Appreciably Delayed

Nine drivers (1 in 18 of those observed) were appreciably delayed by the traffic situation near the plant. The approaches of these 9 drivers to the plant are shown in Figures 19-27. The detailed characteristics of these records are as follows (Table 2):

1M—The record starts with 1M coming out of a merge, moving more slowly than the plant. 1M started to shift to the second lane to pass, but was blocked by the plant's move to the second lane. 1M slowed down to match pace and was then blocked by fast-moving 1K and 1L in the third lane. Later, 1M signaled, shifted lanes, and passed. The movements of 1M are seen to be in response to complete blockings by vehicles in addition to blocking by the plant. 1M matched pace and passed as soon as the opportunity afforded itself.

2E′—The record also starts with the subject car coming out of a merge, moving more slowly than the plant. For a period of about 10 sec, 2E′ followed the plant without attempting to shift and pass. 2E′ was then blocked by 2 trucks and matched pace with the plant, gaining about 10 ft in 13 sec. After an obscured period, 2E′ moved to the second lane and accelerated. The record shows an adaptive response to the merging, entry, and blocked situations; 2E′ passed when able. The approach phase is missing because 2E′ came from a merge.

3K′—The driver of 3K′ intended to leave the highway at exit 2. Vehicles 3I′ and 3J′ prevented him from passing the plant and entering the exit lane occupied by plant. The response of driver 3K′ was to move close to the plant and pass when the plant moved to the second lane. The record shows approach obstructed, and passing phases. The obstructed phase shows closing rather than a matching of pace with the plant.

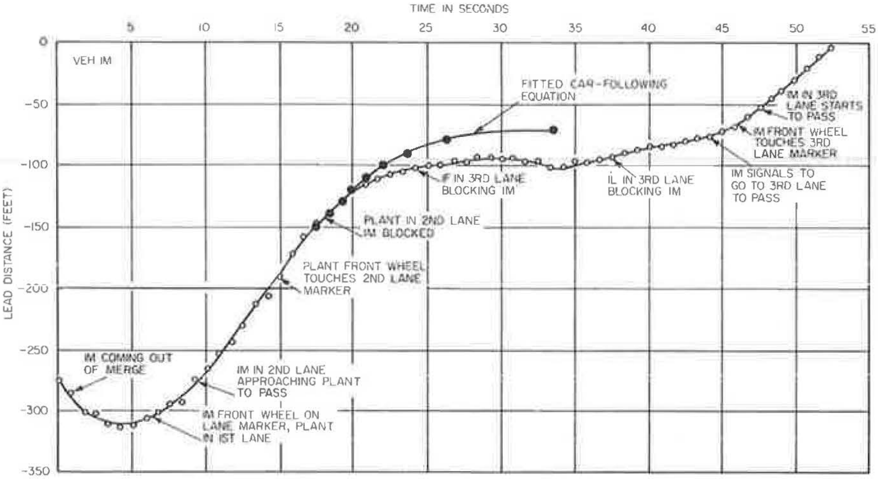

Figure 19. Lead distance of delayed vehicle 1M.

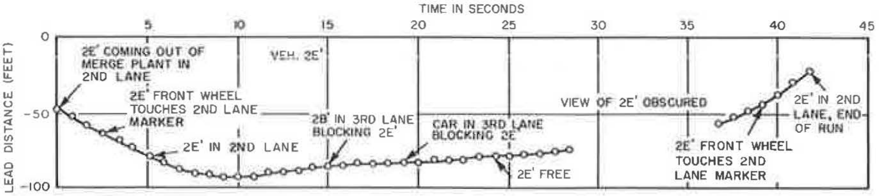

Figure 20. Lead distance of delayed vehicle 2E'.

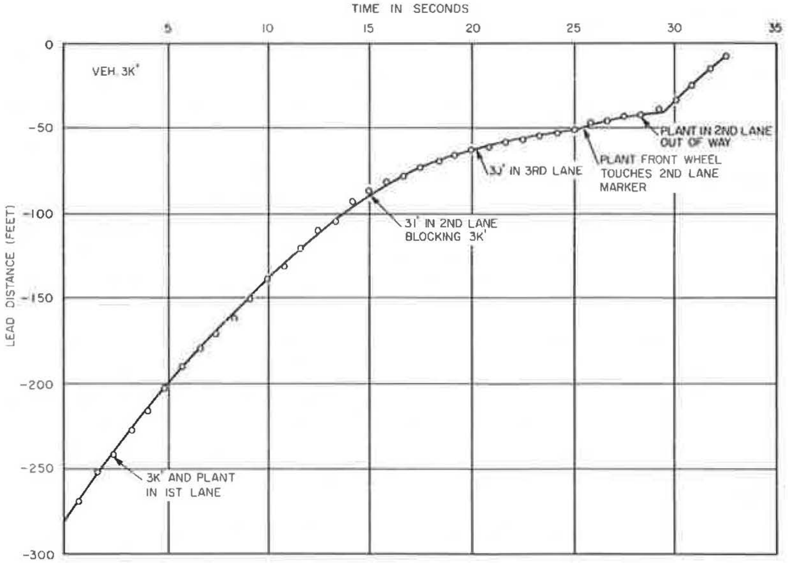

Figure 21. Lead distance of delayed vehicle 3K'.

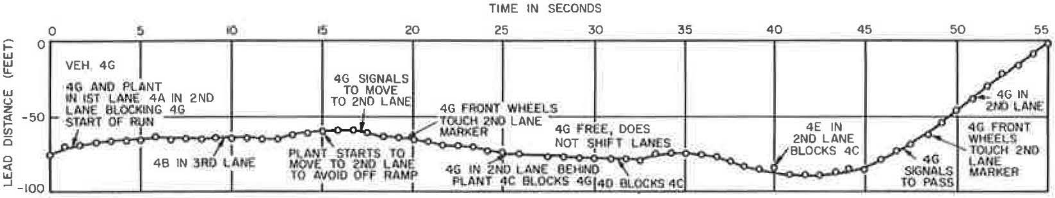

Figure 22. Lead distance of delayed vehicle 4G.

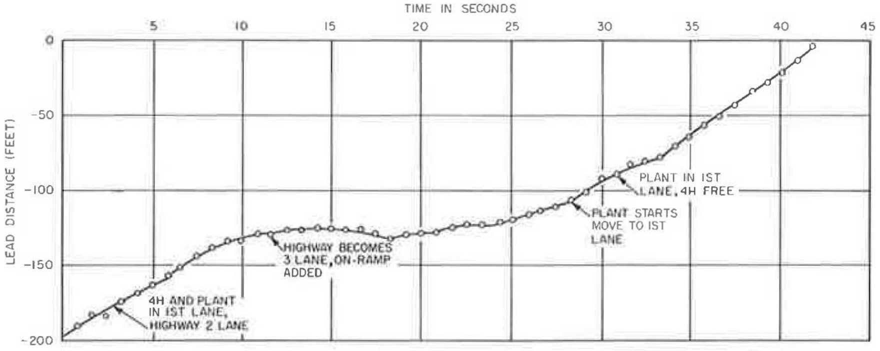

Figure 23. Lead distance of delayed vehicle 4H.

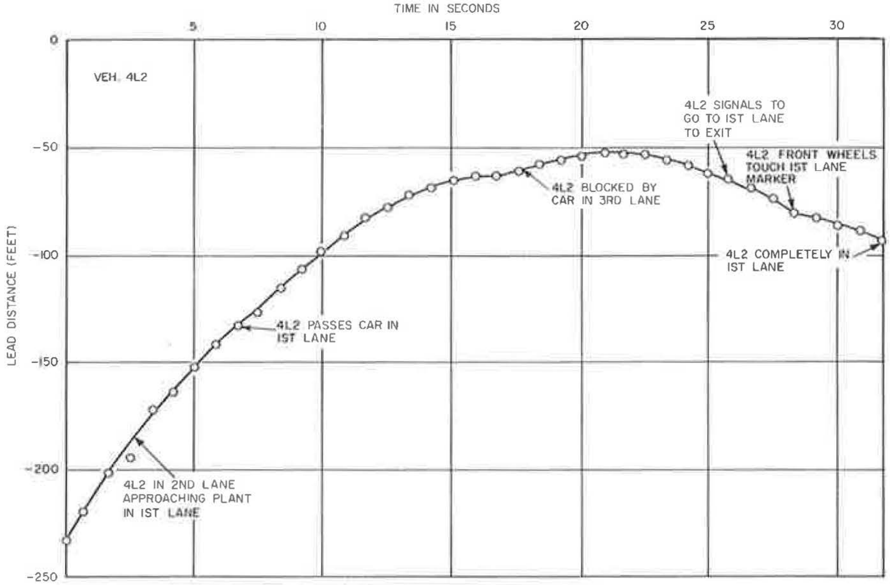

Figure 24. Lead distance of delayed vehicle 4L2.

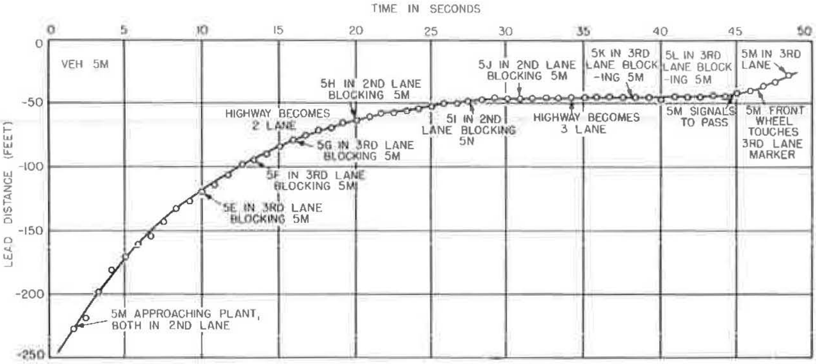

Figure 25. Lead distance of delayed vehicle 5M.

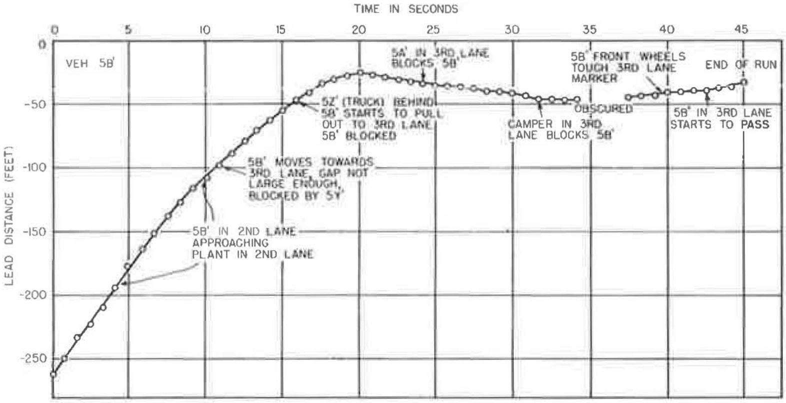

Figure 26. Lead distance of delayed vehicle 5B'.

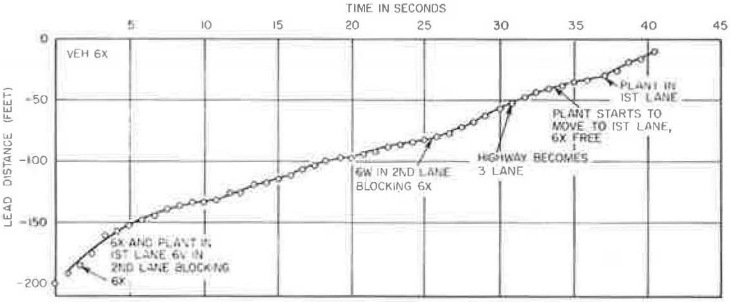

Figure 27. Lead distance of delayed vehicle 6X.

TABLE 2

RESOLUTION OF VEHICLE DELAYS

Vehicle	Original Speed (mph)	Cause of Delay	Delay Length (sec)	Time Lost (sec)	Distance Lost (ft)	Resolution
1M	60.4	Blocked by vehicles	20	3.96	351	Lane shift
2E′	51.1	Blocked by vehicles in passing lane	27	2.79	209	Lane shift
3K′	54.0	Blocked by vehicles in passing lane and by plant in exit lane	15	3.33	249	Plant shift
4G	60.2	Blocked by vehicles in passing lane	45	4.67	412	Lane shift[a]
4H	54.2	Badly loaded truck	20	1.44	114	Plant shift
4L2	61.4	Blocked by vehicles in passing lane and by plant in exit lane	15	4.34	391	Stayed behind in same lane as plant
5M	55.9	Blocked by vehicles in passing lane	30	6.49	532	Lane shift
5B′	56.4	Blocked by vehicles in passing lane	25	6.52	539	Lane shift[b]
6X		Blocked by vehicles in passing lane	30			Plant shift[c]
Total				33.54	2,797	
Avg	56.3[d]			4.19	349.6	

[a] Close to plant when record starts.

[b] Record ends before passing completed.

[c] It is not certain that this vehicle was delayed.

[d] Does not include vehicle 6X.

4G—The record starts at the beginning of the fourth run, with 4G and the plant moving at about the same speeds. 4G is blocked successively by 4A, 4C, and 4E, and could not pass on the right of the plant because this first lane became an off-ramp. There was a period of about 5 sec, between the passing of 4C and blocking by 4D, when 4G could have passed easily but did not. The final portion of the record shows acceleration to pass the plant.

4H—This truck was precariously loaded with 3 oil barrels piled end-to-end. The driver seemed to have his load in mind. The record shows a slow approach and pass when the plant shifted from the second to the first lane. There is no blocking by other vehicles. The approach was very slow, as the plant was moving at 40 mph. The record seems to indicate a reluctance on the part of the driver to make abrupt longitudinal or lateral movements.

4L2—This vehicle approached the plant close to the 1N exit. 4L2 was blocked from shifting by a vehicle in the third lane, and by the plant who occupied the exit lane. The response of 4L2 was not to pass—he followed the plant preparatory to exiting. The approach and obstructed phases are shown on the record, but not a passing phase.

5M—5M was an underpowered foreign car. As he approached the plant, he was blocked by 8 more rapidly moving cars in the passing lane. The end of the record shows the beginning of an acceleration to pass the plant. The trajectory is fairly flat during the time 5M is blocked.

5B′—After approaching, the driver of this car was blocked successively by 4 vehicles in the third lane and by a large moving van in the first lane. The driver started to move ahead when he had the opportunity. The record shows a conventional approach and a flat trajectory during blocking. The record does not show the final pass phase.

6X—This vehicle was exposed to the plant when a truck in front of it shifted lanes. 6X was blocked by 6V and 6W, moving at about the same speed in the third lane. The record shows that 6X moved slowly toward the plant and ahead when the plant shifted lanes. Vehicle 6X was blocked, but it is not certain that it was delayed.

Typically, these obstructed drivers show distinct approach, delayed, and passing phases (Figs. 19, 21, and 23). In the approach phase, the driver can see that traffic is massed ahead, but he is still far enough away not to have to react. He maintains pace or slows down slightly. In the second delayed phase, the driver is blocked by the plant and other vehicles. He matches pace or slowly approaches to within 50 to 100 ft of the vehicle in front. Individual reactions differ considerably. Driver 5M showed an almost constant spacing of about 55 ft for a full 20 seconds; 1M and 4H showed patterns of acceleration followed by slowing down; and 2E′ showed almost steady approach. Of the 9 drivers, 6 drivers decelerated gradually between the approach and delay phases, perhaps because they anticipated a blocked situation ahead. In 3 other cases, the transition to blocking was abrupt and immediate. In the final passing phase, the driver increased speed to get ahead of the plant. In the cases of drivers 1M, 3K′, and 4H, final speed seems to match the initial speed of approach. Generally drivers' responses appear too individualistic to be well represented by a simple car-following equation—whatever the applicability of such an equation to other, high-traffic density conditions. A comparison of results with the predictions of Herman's car-following equation has been made in Figure 19.

A car-following equation of the form

$$(dx/at)_{n+1} = \alpha_0 \frac{\log\left[X_n(t) - X_{n+1}(t)\right]}{L}$$

was fitted to the data of vehicle 1M, under the condition that LM pass 150 ft behind the plant 17.5 sec after the start of the run, and match speed with the plant at 70 ft. The required equation, solved for α_0 and L, is

$$(dx/dt)_{n+1} = 46.4 \log\left[X_n(t) - X_{n+1}(t)\right] - 85.6$$

This equation is represented by the filled circles of Figure 19. It may be seen that the car-following equation does not give a good fit to the approach of vehicle 1M. The equation appears to describe responses to velocity changes of the car in front rather than the approach of a rear driver. In the fitted equation, the rear car (1M) cannot approach closer than 70 ft unless the lead car itself slows down.

Traffic Delays

Vehicular delays may be evaluated by comparing delayed performance with the progress that would have been made if the car had not been slowed. [For example, if a vehicle originally moving at 88 ft/sec (60 mph) is slowed behind the plant to 66 ft/sec (45 mph) for a period of 10 sec, it has been delayed 10 x (88 - 66) = 220 ft. The time delay is 220/88 = 2.5 sec.] Delays are given in terms of time and distance in Table 2 for 8 of the 9 obstructed vehicles (vehicle 6X's record was not complete). Total delay of the 8 vehicles due to obstruction is 33.54 sec in the half hour of film record examined. While these lags may have been an annoyance to the drivers, they do not represent a very serious loss of time. Traffic flow would be speeded more by wider use of freeways and hurrying the slow driver than by eliminating the sort of transient delays encountered here.

DISCUSSION OF RESULTS

These findings clearly reveal the driver's motivation to keep moving at elected speed and to avoid being blocked. Only when the driver had no choice but to accept the situation did he slow down. Passing drivers and blocked drivers who escaped by shifting lanes did not slow up appreciably. Only 9 cars of the 166 observed were so trapped. When blocked, the driver slows, matches pace with the driver in front, and prepares to pass. As soon as blocking is removed, he moves ahead again.

This goal-directed view of driver motivation is in accord with the observations of Rockwell and Snider (4). Their study concerns the important case where the plant is moving at close to traffic stream speed and the oncoming driver is not greatly slowed if he has to follow. Under these circumstances the authors note that drivers did not follow, but immediately passed or else reduced velocity until the influence of the leading vehicle was completely avoided.

The driver's intention to move ahead is not compatible with instructions given in many car-following experiments to "follow at minimum safe distance" (or words to that effect). If the lead vehicle gets out of the way, the driver does not follow but keeps his course and possibly moves ahead. The intention of the driver is to move toward his destination, not to follow the vehicle in front. (Genuine car-following may be said to occur in funeral processions, in situations where the driver follows a preceding car in fog, or where the driver is being guided by the one in front to an unfamiliar address.)

While a typical delayed driver curve could be chosen for simulation purposes from Figures 19-27, such a curve would be something of an abstraction. Although drivers share a common motivation to move ahead, they execute their intentions in quite different ways. Furthermore, the driver is reacting to an entire situation and not merely to the vehicle in front. The film records show numerous instances of drivers moving toward the edge of the lane preparatory to shifting, and then moving back when they saw that a gap was not available. Although the driver's intention to move guides the maneuver, his moment-to-moment revisions of strategy, based on the changing situation, are also evident.

ACKNOWLEDGMENT

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Driver Eye-Movement Patterns Under Conditions of Prolonged Driving and Sleep Deprivation

N. A. KALUGER and G. L. SMITH, JR., Ohio State University

This study investigated the changes in eye-movement patterns of 3 drivers after prolonged driving and sleep deprivation. In the first experimental condition, subjects drove for approximately 9 hours with only minor stops for equipment setup and calibration on refueling. Prior to the second 9-hour driving task, the same subjects were deprived of sleep for 24 hours. Eye movements were filmed under open-road conditions (no traffic in the visual field) at 3 speeds: 40 to 50 mph, 60 to 70 mph, and 75 mph exact velocity maintenance. The eye movements were examined both spatially and temporally, and a new index—pursuit eye movements—was investigated.

•DRIVING has become a much easier task to perform due to a host of improvements, including smoother vehicle performance and better highway design. While driving at control speed on a modern freeway, the driver has less need to accelerate or brake. The driver still must steer continuously, but he is not confronted with many large turns. In short, the driver's primary function has become that of a monitor.

A survey of the National Safety Council shows that the percentage of all accidents that might be categorized as open-road accidents increased from 27.4 percent in 1946 to 35.8 percent in 1966 (1). The inherent boredom and fatigue associated with monitor or vigilance tasks might partially explain why these accidents have proportionately increased on freeways while other types have proportionately decreased (8). The similarity between low-demand vigilance tasks and long-term freeway driving has been discussed elsewhere by Safford (8). He proposed that many of the results of vigilance research could be applied to the turnpike driving problem. The development of the portable eye-movement system by Whalen, Rockwell, and Mourant (15) has provided the means of studying this problem through analysis of drivers' eye movements.

THE VISUAL TASK AS IT APPLIES TO DRIVING

The driving situation places the driver in an environment that is essentially dynamic. Although the physical position of the driver in relation to the vehicle is relatively unchanging over time due to the motion of the vehicle, he is monitoring signals that are many and varied and that evolve from a constantly changing background.

The driver's entire visual field contains information that can be classified into signals and nonsignals. Signals are meaningful information that require the driver to make a decision concerning the operation of his vehicle. Nonsignals, conversely, do not require a decision concerning the operation of the vehicle; they constitute a noise environment in which signals are interspersed.

According to Yarbus (17), "The order in which the observer's attention moves from one point of fixation to another, the duration of the fixations, the distinctive cyclic pat-

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tern of examination, and so on are determined by the nature of the object and the problem facing the observer at the moment of perception." Later he states that "foveal vision is reserved mainly for these elements containing essential information needed by the observer during perception."

The classical concepts of spatial and temporal expectancy are important to this problem. Spatial expectancy would entail consideration of the "expected values" of observing at various times. For example, if the expected value of information to be gained is greater for an area on the right side of the road than an area on the left side, the relative observing rate would be greater in the area to the right than the area to the left. A similar example could be described for temporal expectancy. Mackworth's statement (5) relating the two has been widely accepted: "...spatial expectancy is the dominant factor, but when it is not present temporal expectancy can begin to influence performance to some extent."

Senders' model of visual sampling behavior (10) provides some additional insight. Senders proposes that the time of the next observation can be extended until the probability of occurrence of a critical event within that interval exceeds some limit. When this "limit of safe operation" is exceeded, a new observation is taken. This describes a system that would respond to changes in the perceived environment by initiating a compensatory change in the time distribution of eye movements.

EFFECT OF STRESS

The degree to which the visual areas are spatially affected by stress is of considerable interest. It is reasonable to expect that stresses resulting from long-term vigilance would, in general, depress the expected values associated with spatial and temporal expectancies. This could result in a change in the eye movements alloted to spatial areas and temporal zones.

An article by Weltman and Egstrom (13) reveals that the ability to monitor a peripheral task becomes greatly impaired under stress, while the ability to control the central or frontal tasks is not significantly reduced. The subjects involved in Weltman's experiment were underwater divers and the stress was induced by fear. Weltman and Egstrom cite the work of Teichner (12) who reported that detection of a light signal in the visual perhiphery was adversely affected by sleep deprivation. The obvious conclusion is that signals reaching different retinal areas are not uniformly affected by stress. Weltman concluded that "whatever the genesis of this phenomenon, it seemingly occurs under varied conditions of psychological stress...."

In a somewhat different experiment, Mackworth (5) demonstrates that visual noise (i.e., incorrect signals similar to correct ones) causes "tunnel vision." He explains that the periphery of the retina could no longer accurately detect at a glance whether items were similar. Foveal performance was also affected to some extent by extra items in the periphery of the retina. Mackworth explains that, in order to reduce random search, eye movements must often be planned from data acquired by the peripheral retina. His main contention is that the addition of visual noise in the form of unwanted signals can destroy this vital peripheral matching.

Whatever the cause, sleep deprivation, fear, or visual noise, it seems apparent that the ability to detect signals on the peripheral retina is hindered to a greater degree than is the ability to detect foveal signals.

ACQUISITION OF INFORMATION

Unlike the stationary observer, the driver must sense his velocity and position in relation to the outside environment. The same stimuli that provide information relating to the decision aspects of the driving task also provide the information relating to velocity and position.

In terms of the visual field available to the driver, the linear motion of the vehicle is best translated into angular velocity. Gordon (2) accomplished the mathematical description of a moving ground plane. In general, the angular velocity of any point of the plane is directly proportional to the linear speed. In addition, angular velocity values are at a minimum in the foveal visual field along the direction of motion and at a maximum in the peripheral visual field close to the vehicle.

Salvatore (9) succeeded in demonstrating that velocity estimation is much more accurate when based on stimulation to the peripheral field rather than stimulation to the frontal field. According to Salvatore, frontal field refers to 25 deg centered on the direction of motion and peripheral field refers to the field subtended from 65 to 90 deg from the direction of motion.

In an effort to explain his results, Salvatore offered that linear velocity information is acquired peripherally because of the larger angular velocity information available in that area. For example, at a vehicular speed of 60 mph, a distant road sign 12.5 deg from the center of the vehicle's path has an angular velocity of 81 deg/sec; however, by the time the vehicle passes the road sign it has attained an angular velocity of 1,080 deg/sec. The results of his study show that velocity estimates, in addition to being poorer, were also lower when based on frontal information alone. Thus, a fatigued driver whose periphery has become "clouded," may tend to substitute frontal velocity information for peripheral velocity information. Salvatore states, "This may underlie the phenomenon of highway hypnosis which results in gross under-estimation of high speeds. The attention, after prolonged driving, may become restricted to the area normally fixated: the frontal field."

Furthermore, Salvatore believes that "perception of motion in the frontal field is detrimental to steering or tracking performance and would tend to be ignored in driving." Michaels (6) shows that acquisition of lateral position information is necessary in order to maintain the vehicle's position on the roadway. To determine the relative position of stimuli to each other and to the vehicle and its axis of direction, it would be advantageous to perceive them as stationary, which, of course, they are not. However, as compared with stimuli in the peripheral fields, stimuli in the frontal field are relatively stationary. It is believed that perception of the stable relationship of objects when they are frontal enables the driver to "aim" his vehicle on the roadway. Perhaps the passing of this stimulus by the vehicle provides, in addition to velocity information, a continuous feedback of performance of this tracking task. Subsequently, a peripheral detection deficiency caused by fatigue could lead to an impairment of this feedback loop, resulting in an inability to maintain lateral position.

PURSUIT EYE MOVEMENT

Pursuit movements provide a stationary retinal image for resolution when the object of resolution is in motion. This type of movement, however, is impossible without the presence of a moving object. Shakhnovich, Dzhanelidze, and Inauri (11) state that "the floating tracking motions of the eyeball are possible only when there is a moving object in the field of vision, the velocity of which exceeds the velocity of spontaneous drift of the eye." It is known that, when fixating on a still point, the micromovements of the eyeball consists of tremor, drift, and small jumps that return the images of the point on the retina to the center of the fixation zone. Past vehicular eye-movement studies (14, 18, 1) have shown that the majority of the receiving time is spent in the frontal area of minimal angular velocity. It is doubtful that fixations on objects in this area result in pursuit movements because the velocity of spontaneous drift was probably not often exceeded.

Woodworth and Schlosberg (16) mention the alternating pursuit movements and return saccades that occur with regularity when one is fixating on objects while riding a train or bus. Train and bus passengers are fixating out of side windows on environmental features that have attained angular velocities that undoubtedly exceed the spontaneous drift velocity of the eye. Drivers do not normally fixate in these nonfrontal areas. If they did, the tendency to make pursuit eye movements could be expected to increase.

EXPERIMENTAL METHODOLOGY AND DESIGN

The objective of this experiment was to study the effects of (a) sleep deprivation, and (b) prolonged driving on drivers' performance and drivers' eye-movement patterns.

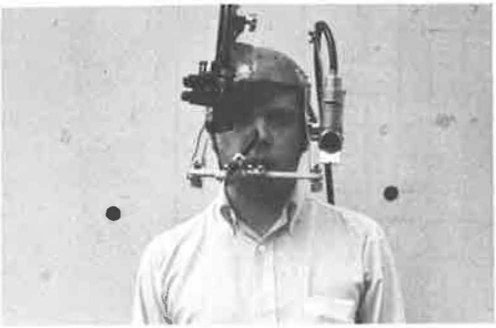


Figure 1. Subject wearing eye-marker equipment.

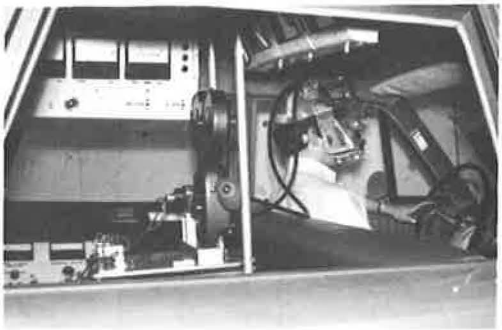


Figure 2. Experimental vehicle with mounted camera.

Eye-Marker Apparatus

The eye-marker apparatus is described in detail in a previous study by Whalen (14). In the system, the eyespot from the subject's right eye and the scene from the scene lens are superimposed by a beamsplitter. This picture is then recorded by a 16-mm Beaulieu motion picture camera. Figure 1 shows a subject wearing the eye-marker equipment. Figure 2 shows a subject in the experimental vehicle with the camera mounted on a platform in the rear seat compartment.

Experimental Design

The experimental design is shown in Figure 3. The pre-experimental preparation of the subjects was, of course, the primary control variable. For ease of reference, the treatments are designated as Run 1 and Run 2. Prior to Run 1 the subjects were instructed to obtain a normal night's rest at home. Prior to Run 2 the subjects were required to remain awake throughout the night at the Systems Engineering Building under the observation of a research assistant.

On each run, subjects drove three 150-mile laps. Each lap consisted of a predetermined section of Interstate highway. The travel time per lap was between 3 and 3½ hours. A special treatment occurred at the end of lap 3 during Run 2. The data, designated 3*, were collected following a rest stop during which the subjects were permitted normal "revival" activities. Within practical limitations, all experimentation was duplicated for each lap, permitting time behind the wheel to be treated in a discrete manner.

The eye-movement records that were taken included filming of 3 maneuvers: (a) open-road driving, 60 to 70 mph; (b) open-road driving, 40 to 50 mph; and (c) open-

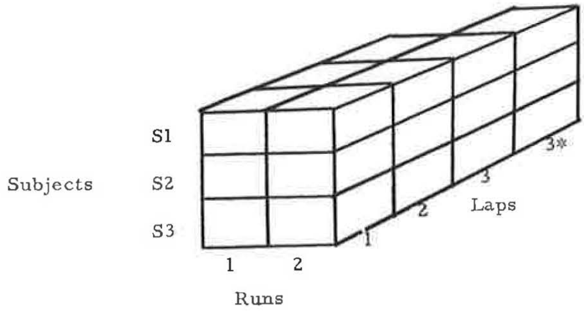


Figure 3. Experimental design.

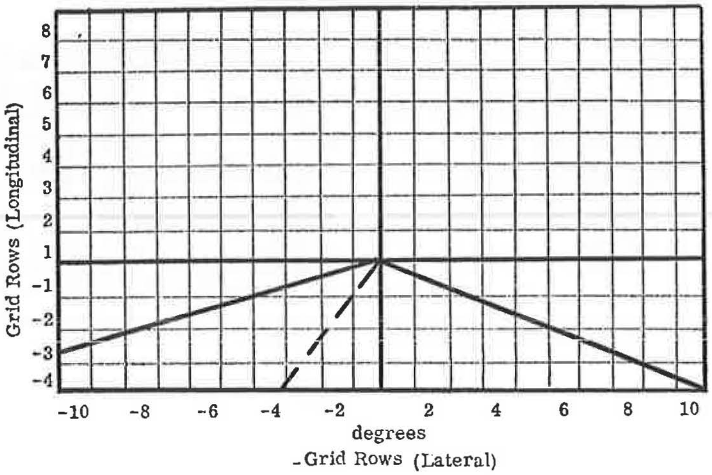


Figure 4. Film data reduction grid of 1-deg squares.

road driving, 75 mph velocity production. At least one 60-sec sample of eye-movement patterns during these maneuvers was filmed during each lap.

Because of inherent individual subject differences that have been observed in past eye-movement studies, subjects were treated as a separate factor. The 3 subjects were male studies at Ohio State University. The subjects selected were all experienced subjects and all had driven the test vehicle previously.

Data Reduction Procedures

The grid shown in Figure 4 was used to relate the eye-movement data directly to the highway. The 2 slanting lines were used to align the centerline and the right-edge line delineating the right lane for each frame of film. Thus, fixations were located relative to the environment despite head and trunk movements and changes of vehicle position. The grid squares measured 1 deg and were coded by the letters and numbers shown in

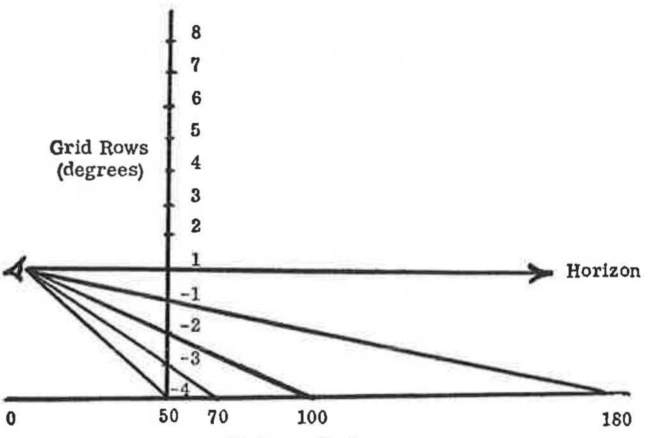


Figure 5. Relation of the grid to the driver's eye.

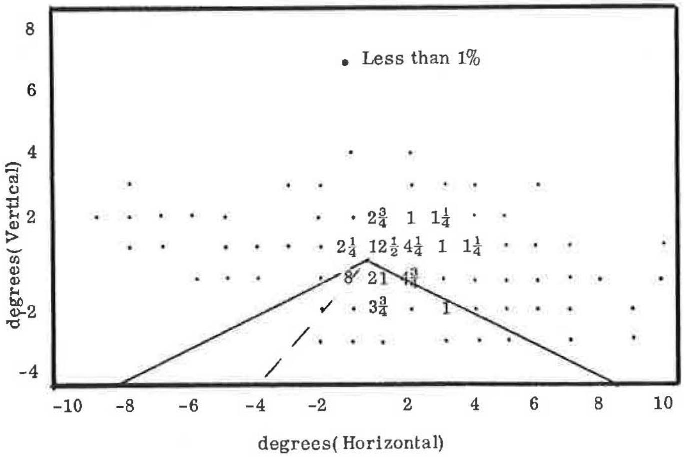
the vertical and horizontal directions. In addition to the locating of fixations by grid square, the feature in the environment that the eyespot intersected was recorded. These features include highway lane markers, signs, and bridges. Frames that did not contain an eyespot were tallied collectively as "out-of-view." This category includes blinking, fixations on the rear view mirror or speedometer, and fixations outside the field of view of the scene lens. Figure 5 shows the relation of the grid to the driver's eyes.

RESULTS

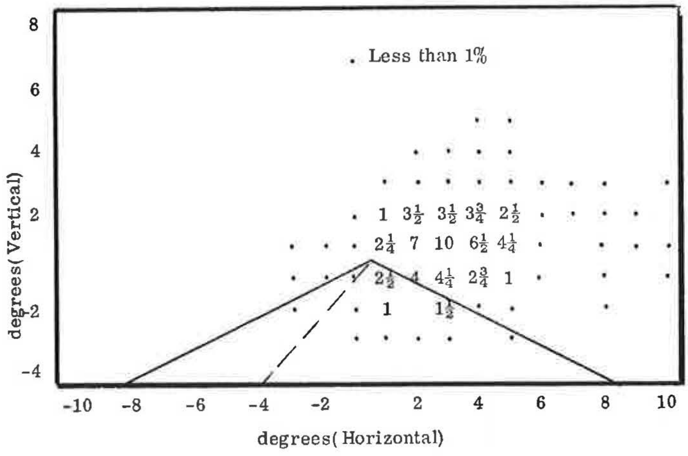
Eye-Movement Data

The analysis was conducted in 4 parts: spatial analysis of eye-movement data, temporal analysis of eye-movement data, analysis of special film segments, and microscopic analysis.

Occasionally during the filming sessions on Run 2, the subjects would become extremely drowsy. As a result, eyelids would lower and much of the corneal reflection was lost. Because this seemed to signify a finite change in state compared with the



RUN 1-Lap 1- 60-70 mph



RUN 2-Lap 1- 60-70 mph

Figure 6. Percentage of total fixation time per 1-deg square—all subjects combined.

rest of the Run 2 data, these "special" film segments were removed from the remainder of the Run 2 data and analyzed separately.

Because film sessions during Run 1 were duplicated during Run 2, paired comparisons of the eye-movement parameters were the most convenient form of analysis. The paired-t statistic was chosen as it requires neither independence nor equal variances.

Spatial Analysis of Eye-Movement Data—Figure 6 shows fixation density maps for combined subjects on lap 1, Run 1 and Run 2, under 60 to 70 mph open-road driving conditions. A fixation density map is, in reality, a 2-demensional representation of a 3-dimensional world, viewed through the windshield of an automobile. The numbers inside the 1-deg squares represent the percentage of fixation time spent in the square, and the dots designate squares that contain less than 1 percent of the total fixation time.

Longitudinal Analysis—The vertical, time-weighted, mean grid location (Fig. 7) is a measure of central tendency that indicates the relative height above the roadway or the viewing distance ahead of the vehicle. Figure 8 shows the results of this measure for combined subjects on Run 1 and Run 2 for the 3 open-road driving conditions. There is no significant difference (paired-t test, 8 degrees of freedom) between runs; however, a downward trend over both runs is evidenced. This trend indicates that, as time on the road progresses, subjects tend to look closer to the car. The trend is statistically significant for Run 2 and not for Run 1. The subjects exhibited a recovery of this measure after the rest break at the end of L3 of Run 2 (Fig. 8, L3*). A paired-t test (vertical mean at L3* - vertical mean at L3) revealed significance beyond the 99.5 percent level. This indicates that after the rest break the subjects again looked farther down the roadway.

Lateral Analysis—The horizontal, time-weighted, mean grid location (Fig. 7) is a measure of central tendency that indicates the relative location of eye fixations to the right or left of an imaginary vertical plane passing through the point of intersection of

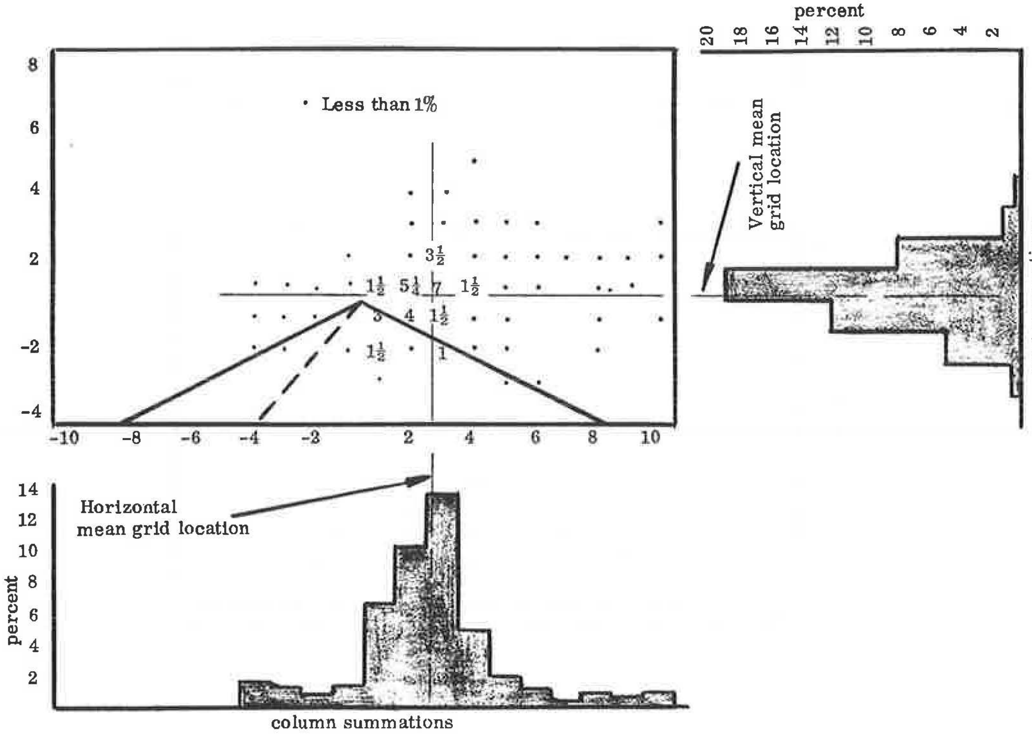


Figure 7. Mean grid location—a graphical interpretation.

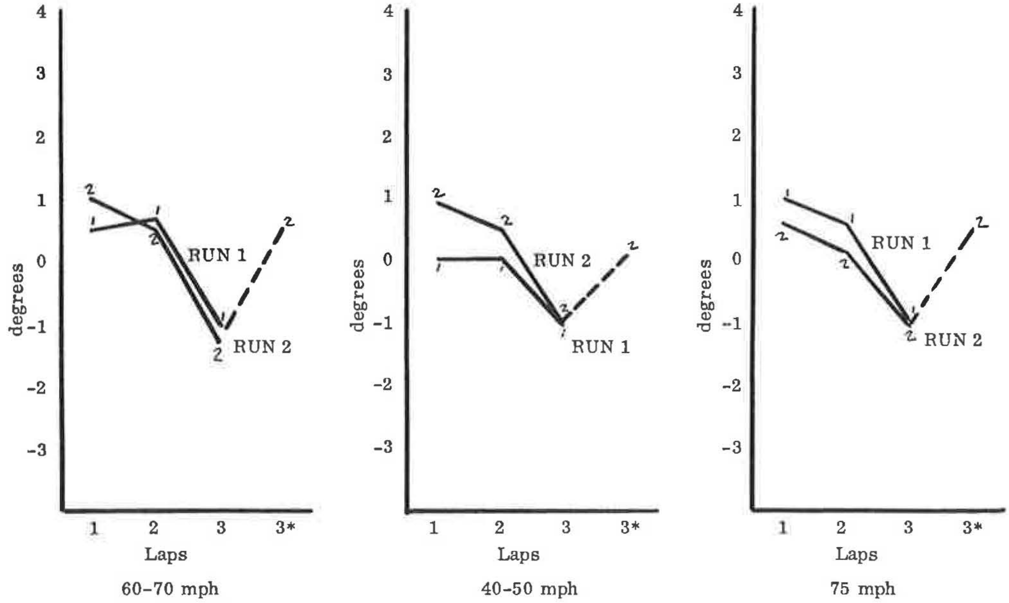


Figure 8. Vertical mean grid location—all subjects combined.

the horizon and roadway. Figure 9 shows the results of this measure for combined subjects on Run 1 and Run 2 for the 3 open-road driving conditions. The horizontal mean for Run 2 is significantly greater than that for Run 1 for the 60 to 70 mph and 40 to 50 mph open-road conditions. Statistically, this is significant beyond the 97.5 percent level (paired-t test, 8 degrees of freedom). This indicates a shift in the eye-movement patterns away from the center of the roadway to the right side of the road. Although numerically in the same direction, the shift for the 75 mph, velocity production, open-road condition is not significant.

As with the vertical mean, the subjects exhibited a recovery of the horizontal mean grid location after the rest break at the end of L3 of Run 2 (Fig. 9, L3*). A paired-t test (horizontal mean at L3 - horizontal mean at L3*) was significant at the 99 percent level. This indicates that, after the rest break, the subjects' eye-movement patterns shifted away from the extreme right side of the roadway back toward the center of the roadway.

As was indicated earlier, the area of minimal angular velocity is along the line of direction of the vehicle. In order to determine the amount of time the subjects spent fixating in these minimal angular velocity areas, the percentage of total time they spent fixating in the 2 center grid columns was calculated. These 2 columns contain the road straight ahead and the intersection point of the road and the horizon. Figure 10 shows these calculations for combined subjects on Run 1 and Run 2 for the 3 open-road driving conditions. Under the 60 to 70 and 40 to 50 mph open-road conditions, the paired-t tests (8 degrees of freedom) indicate that the amount of time spent in the 2 center grid columns during Run 1 is significantly greater than that for Run 2. These values are significant at the 99.5 and 95 percent levels respectively. The results for the 75 mph condition were not significant, although again the shift occurred in the same direction. This finding indicates that during Run 2, the subjects devoted significantly more of their total fixation time to areas containing greater angular velocity information.

A paired-t test revealed a recovery of this measure, significant beyond the 95 percent level, following the rest break. Therefore, after the break, the subjects again spent a lesser percentage of time fixating in the areas with maximal angular velocity information.

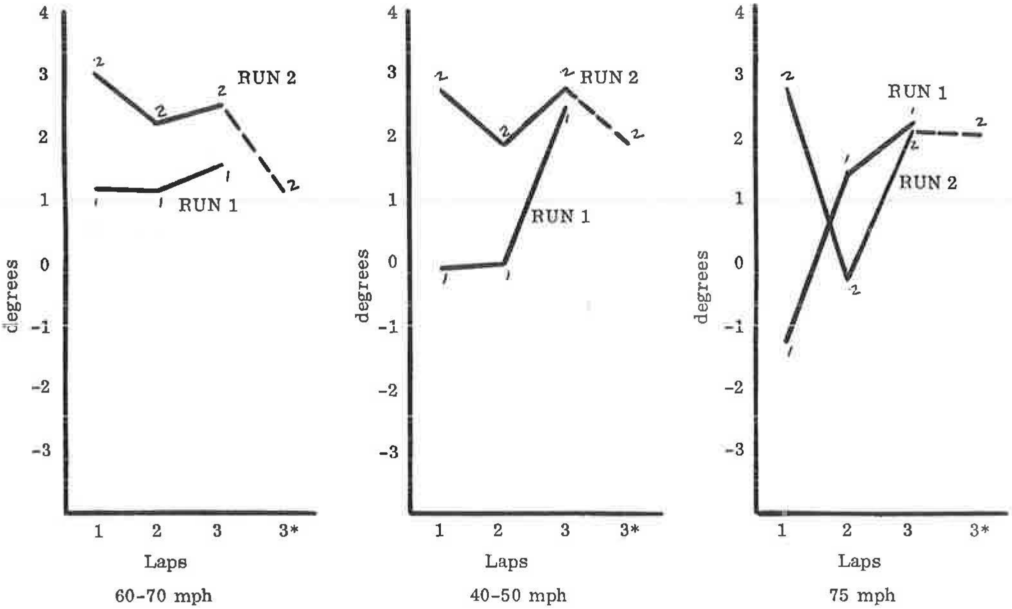


Figure 9. Horizontal mean grid location—all subjects combined.

Additional Analysis—In order to measure the dispersion of the fixation density diagrams in the vertical and horizontal direction simultaneously, Belt (1) developed the concentration index ratio (CIR):

$$\text{CIR} = \frac{\text{total fixation time outside the most densely populated 3- by 3-deg square}}{\text{total fixation time over the entire grid}} \times 100 \text{ percent}$$

Because this measure seeks the most densely populated area, the effects of vertical or horizontal shifts in the density maps are neutralized.

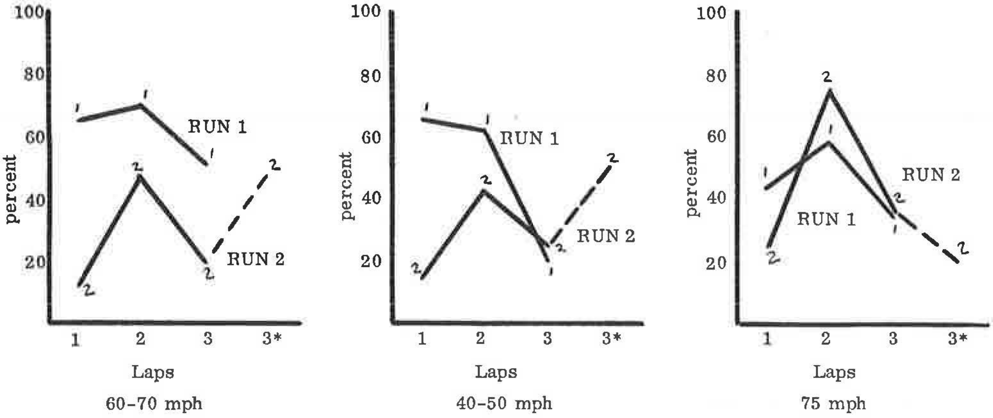


Figure 10. Percentage of fixation time in 2 center grid columns—all subjects combined.

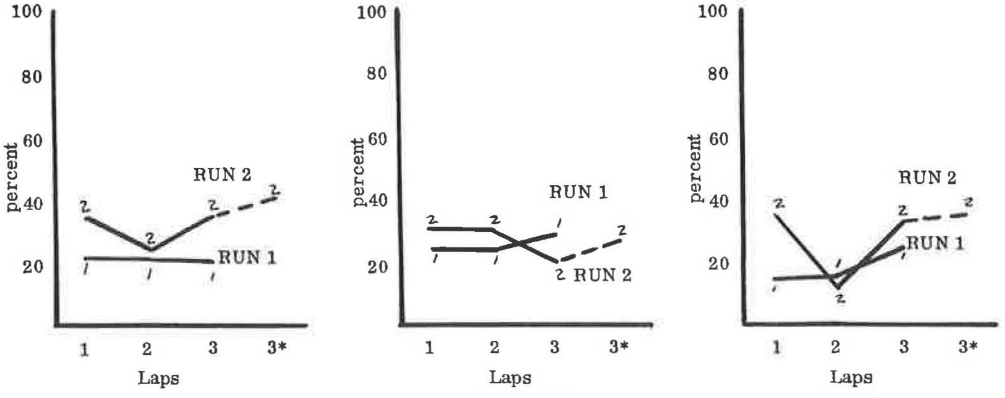


Figure 11. Percentage of total fixation time outside the most densely populated 3- by 3-deg grid square—all subjects combined.

Figure 11 shows the results of this measure. For the 60 to 70 mph open-road driving condition, the paired-t analysis revealed an increase from Run 1 to Run 2 significant beyond the 99 percent level. For the 75 mph open-road condition, the increase was significant beyond the 90 percent level. For the 40 to 50 mph condition the observed shift was also positive. However, because of subject variability, this shift was not statistically significant. These analyses for the 3 open-road conditions are interpreted to indicate that the dispersion of fixation durations increases between Run 1 and Run 2.

A paired-t analysis of these data between L3 and L3* shows (Fig. 11) that no significant changes occurred after the rest break. It appears from the spatial analysis, for the 3 subjects tested, that the eye patterns shifted to the right between Run 1 and Run 2 and shifted downward over the course of both Run 1 and Run 2. Also, after the rest break at the end of L3 of Run 2, the eye patterns moved back toward the left and upward. While the mean shifted between Run 1 and Run 2, the eye patterns also enlarged with respect to their 2-dimensional representation. Also, the amount of time spent fixating outside the areas containing minimal angular velocity information increased from Run 1 to Run 2 and decreased after the rest break at the end of L3 and Run 2.

Temporal Analysis of Eye-Movement Data—Analysis of the amount of time subjects spent foveally pursuing environmental features was revealing. Because of the rarity of pursuit of eye movements in driving, the data were combined for the various open-road driving conditions to obtain large enough samples to test for significance. Figure 12 shows mean pursuit eye-movement time for all subjects combined on Run 1 and Run 2. The increase in mean pursuit duration from Run 1 to Run 2 is significant beyond the 99 percent level (paired-t test, 8 degrees of freedom).

Figure 13 shows the percentage of total film time due to pursuit eye movements for all subjects combined on Run 1 and Run 2. The increase in this measure from Run 1 to Run 2 is significant beyond the 97.5 percent level (paired-t test, 8 degree of freedom). Interestingly, this percentage increased after the rest break (Fig. 13, L3*, for each subject). However, because of the lack of paired samples, one for each subject, this was not tested statistically. For the 3 subjects tested, it appears that the tendency to make more and longer following eye movements increases from Run 1 to Run 2.

Table 1 gives the environmental feature that the following eye movements intersected. Scenery on the right included poles, guardrails, trees, or any feature in that area that could not be determined from the film. Category "other" included the left edge marker, bridges, center of subject's own lane, and scenery on the left. Most important from this figure is that at no time during the film sessions of Run 1 did any of the subjects make a pursuit eye movement in the area of the scenery on the right.

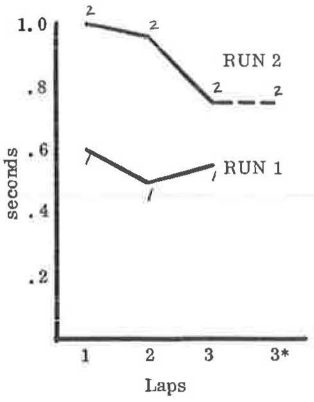


Figure 12. Duration of mean pursuit eye movements—all subjects and maneuvers combined.

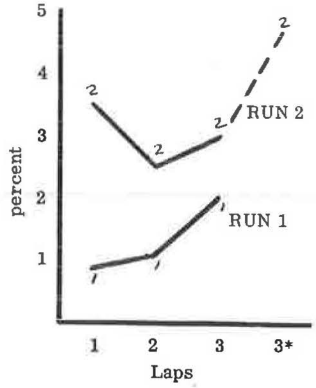


Figure 13. Percentage of total film time due to pursuit eye movements—all subjects and maneuvers combined.

TABLE 1

PRINCIPAL FEATURES INTERSECTED BY PURSUIT EYE MOVEMENTS

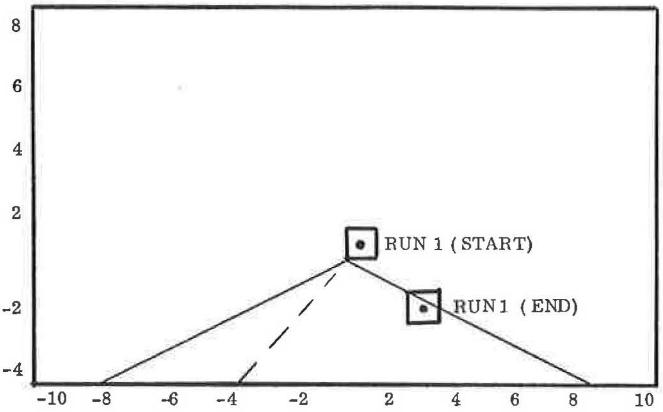
Subject	Run	Mean Pursuit Time					Percent of Total Pursuit Time				
		Center Lane Marker	Road Sign	Scenery on the Right	Right Edge Marker	Other	Center Lane Marker	Road Sign	Scenery on the Right	Right Edge Marker	Other
1	1	0.450	0.719	—	0.625	—	57.7	36.9	0.0	5.4	0.0
	2	0.438	1.056	0.786	0.688	—	1.4	64.0	30.1	4.5	0.0
2	1	0.552	0.799	—	0.500	—	34.7	58.7	0.0	2.6	4.0
	2	0.435	0.988	1.593	0.813	—	31.7	42.6	8.6	4.4	12.7
3	1	0.493	0.524	—	0.915	—	41.4	37.6	0.0	11.0	10.0
	2	—	1.076	0.992	0.313	—	0.0	48.7	39.9	1.6	9.8

DISCUSSION OF RESULTS

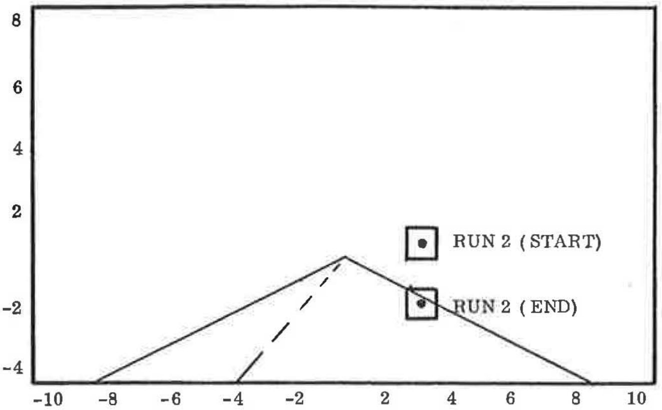
The spatial analysis of the eye-movement data yielded several measurable results. In general, the mean locus of the eye-movement patterns shifted to the right (Fig. 9) and down (Fig. 8) approximately 2 deg in each direction over the course of Run 1. During Run 2 the vertical shift repeated its pattern, while the horizontal tended to remain approximately 2 deg to the right over the course of the run. Therefore, regardless of the amount of sleep, the subjects exhibited the same downward shift over "time behind the wheel." The shift to the right occurs over time behind the wheel for Run 1, but the effect of no sleep, Run 2, causes the shift to the right at the outset of Run 2.

Figure 14 shows the shifts in terms of roadway geometry. The shift does not seem large when expressed in degrees. In terms of margin of safety, however, time to overtake the "higher" point is approximately 5 or more seconds; time to overtake the "lower" point is approximately 2 or less seconds.

The analysis of the amount of time the subjects spent viewing in the 2 center columns (Fig. 10) helps to confirm that fact that the eye-movement patterns had shifted to the right. Figure 14 shows the center columns in relation to the roadway. For the 60 to 70 and 40 to 50 mph maneuvers, the amount of time spent viewing in the 2 columns was significantly less for Run 2. The difference, although not significant, was in the same direction for the 75 mph velocity production task.



ALL SUBJECTS & ALL MANEUVERS COMBINED-
RUN 1



ALL SUBJECTS & ALL MANEUVERS COMBINED
RUN 2

Figure 14. Approximate position of locus points at the start and the end of Run 1 and Run 2.

Analysis of the eye-movement data from lap 3* of Run 2 revealed that the locus point had returned to its Run 1 position following the rest break. At this point it appears that, with respect to eye movements, the subjects had successfully revived.

The concentration density graphs (Fig. 11) reveal that on the average the eye-movement patterns were less concentrated during Run 2. Therefore, it appears that more foveal viewing time was allocated to areas normally monitored primarily by the peripheral retina. This implies that some decrement in peripheral sensitivity had occurred.

In Mackworth's static laboratory setting (5), impairment resulted in a tighter foveal concentration (i.e., fixations were more central). In the dynamic freeway setting, the change in the observed fixation pattern was the opposite of Mackworth's findings.

Earlier it was argued that drivers sense velocity by stimulation from the peripheral fields. According to both Yarbus and Senders (17, 10), then, sensitivity decrement to the peripheral retina, coupled with a need to sense velocity, should result in more foveal excursions to areas of greater angular velocity. This would predict greater dispersion in the eye-movement patterns. Furthermore, it would explain the overall drift of the eye-movement patterns to the right and down (Fig. 14). Such a shift is toward an area of greater angular velocity information. It is thus suggested that this effect is consistent with the principle of perceptual narrowing.

When combined with the experimental results reported by Jarboe (3), these findings provide special insight into a possible cause of open-road accidents. Jarboe showed that an additional effect of fatigue in driving is an increase in the speed the subject maintains when denied use of a speedometer. The increased speed and reduced viewing distance ahead of the car combine to make it extremely difficult or impossible for the driver to take the actions necessary to maintain complete control of his vehicle.

Shifting and increased dispersion of the eye patterns were, in fact, evident in this study. Under the strict control exercised during the filming sessions, the measures appear to be reasonable and valid. However, changes in traffic patterns or roadway environment could substantially change these observed phenomena. Therefore, another measure of impaired driver performance, which might be appropriate to a wider variety of traffic patterns and roadway environment, was sought.

In the results previously cited (Figs. 12 and 13), both the mean pursuit duration and the percentage of total film time due to pursuit eye movements (volume of pursuit movements) were significantly larger for Run 2. Because spatial analysis revealed that the eye-movement patterns had shifted to an area where the angular velocity of environment features was greater, it is suggested that the tendency to fixate on faster moving objects might result in more pursuit movements (16). Analysis of the lap 3* data, after the rest break, revealed the locus of the eye-movement patterns had shifted back to the Run 1 position, while the mean pursuit time remained the same and the percentage of total film time due to pursuit movements actually increased. Therefore, for the 3 subjects tested, it appears that, regardless of whether the locus of eye-movement patterns is near areas of large angular velocity, the tendency to make more and longer pursuit eye movements is affected by sleep deprivation.

To probe this phenomenon in detail, the area to the right (categorized as scenery on the right for reduction purposes) was examined. The data given in Table 1 reveal that no pursuit eye movements in that area were found for any of the subjects over Run 1. For Run 2, however, a large percentage of the total volume of pursuit movements for each subject was found in this area. Rested subjects made no pursuit eye movements in this area of large angular velocity, although they did fixate in that area occasionally. This implies that a rested subject is capable of obtaining the necessary information from a moving roadside feature without having to pursue that feature by making the appropriate pursuit eye movement.

At this point it appears that the increase in pursuit eye movements are induced by sleep deprivation. It is possible that the effect is due to either sensory impairment or a regression of learning. In order to examine this dilemma, eye-movement film from Zell's study (18) was examined. Film of the 4 inexperienced subjects for the 60 to 70 and 40 to 50 mph open-road conditions on the first test were reexamined. These film samples theoretically depict the condition of least experience. The combined pursuit eye movements from these 2 maneuvers were contrasted to the combined pursuit movements from the 2 maneuvers for 2 experienced drivers. Table 2 gives the individual values obtained.

Salvatore (9) argued that, in driving, the foveal area is allocated the task of detection and discrimination, while the periphery is allocated the task of motion

TABLE 2

COMPARISON OF PURSUIT EYE MOVEMENTS OF EXPERIENCED AND INEXPERIENCED SUBJECTS

Subject	Mean Pursuit Duration	Volume of Pursuit Eye Movements (percent)
Inexperienced		
S1	0.30	7.6
S2	0.52	4.0
S3	0.43	1.3
S4	0.71	3.7
Avg	0.49	4.15
Experienced		
SA	0.47	2.1
SB	0.42	0.006
Avg	0.45	1.05

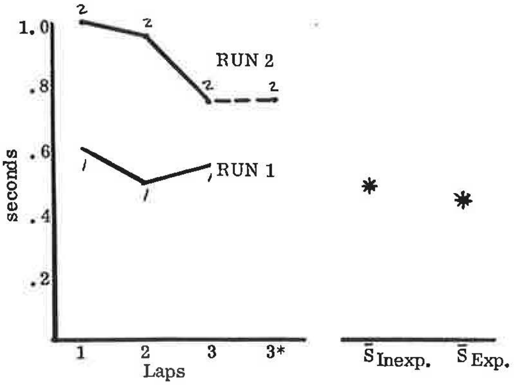


Figure 15. Duration of mean pursuit eye movements and comparison of experienced and inexperienced subjects—all subjects and maneuvers combined.

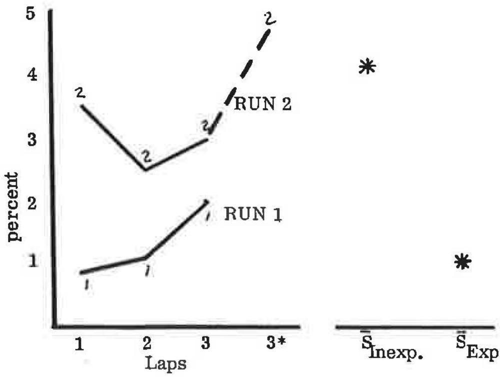


Figure 16. Percentage of total film time due to pursuit eye movements and comparison of experienced and inexperienced subjects—all subjects and maneuvers combined.

perception. This represents a rather sophisticated time-sharing task in the information processing chain, especially in the context of single channel theory. It appears that at least three out of four of Zell's inexperienced subjects had not yet learned the time-sharing task. However, as their experience increased, their eye-movement patterns became more like those of the experienced driver.

Figure 15 shows the average value of Zell's subjects for mean pursuit duration compared with the previously cited results of this study. Figure 16 shows the average value of Zell's subjects for volume of pursuit movements plotted next to the comparable results from this study. The data in Table 2 suggest that mean pursuit duration may be an index of impairment independent of experience. Figure 16 suggests that the volume of pursuit eye movements is an index of impairment that shows a regression toward behavior characteristic of inexperienced subjects. This conclusion is based on the observation that sleep-deprived subjects and inexperienced subjects exhibit similar behavior. The possibility of using pursuit eye movements as correlates of performance is suggested here for the first time. Additional research will be necessary to confirm their validity and suitability as performance indexes in driving research.

SUMMARY

The intent of this research was to investigate the changes in eye-movement patterns that occur under conditions of prolonged driving and sleep deprivation. The eye-movement data were examined spatially and temporally. The major results are listed as follows:

1. The mean locus of the eye-movement patterns shifted 2 deg to the right and 2 deg down over the course of Run 1. At the outset of Run 2, after sleep deprivation, the horizontal mean had already shifted approximately 2 deg to the right. The vertical mean exhibited the same downward shift over time that had been observed during Run 1. In terms of time-headway, subjects would overtake the locus of the "fatigued" eye pattern approximately 3 sec sooner than they would overtake the "rested" patterns.
2. On the average, the patterns were less concentrated during Run 2. This finding in conjunction with the discovery of the mean locus shift indicates that more foveal viewing time was allocated to areas normally monitored peripherally. This finding is consistent with the expected behavior in a dynamic control situation and indicates a decrement in peripheral sensitivity, i.e., perceptual narrowing.

3. Both the mean pursuit eye-movement duration and the volume of pursuit eye movements (the percentage of total film time due to pursuit eye movements) were significantly larger for Run 2. Thus, the tendency to make more and longer pursuit eye movements is affected by sleep deprivation.
4. Comparison with eye movements of inexperienced and experienced drivers indicates that mean pursuit duration may be an index of sensory impairment, and that volume of pursuit eye movements may be an index of regression toward behavior that is characteristic of inexperienced subjects.
5. There were no discernible differences in any of the significant measures due to differences in velocity.

ACKNOWLEDGMENT

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An Evaluation of the Priorities Associated With the Provision of Traffic Information in Real Time

KENNETH W. HEATHINGTON, Purdue University;
RICHARD D. WORRALL, Peat, Marwick, Mitchell and Company; and
GERALD D. HOFF, Chicago Area Expressway Surveillance Project

A structured questionnaire was administered to 732 drivers residing in the Chicago metropolitan area. The responses were used as a basis for developing priorities for scheduling improvements in the highway system. Specifically, the priority of providing traffic information in real time relative to that of making any other improvement in the highway system was evaluated. In general, it was found that the drivers interviewed were quite concerned with the condition of the pavement surfaces on both expressways and city streets in the Chicago area. The respondents having a lower income, having a lower educational level, and living in the southern part of Chicago were more concerned with improving the pavement conditions than were their counterparts. Information on traffic conditions seemed to be relatively important to expressway drivers but unimportant to city street drivers. The provision of motorist-aid phones was generally desired for expressways but not for city streets. The provision of additional radio traffic reports had very low priority.

•THE DECISION-MAKER must establish priorities for scheduling improvement in the areas of his responsibility. He must decide on the allocation of resources to the ongoing projects that compete for expenditures as well as for new projects that are to be initiated. In the private sector, his decisions primarily affect his company and his employees; in the public sector, his decisions affect more than just one definable entity. Many times the decision-maker evaluates engineering projects solely from engineering recommendations that generally consider only the proposed costs and user benefits. Often he does not have access to meaningful public attitudes toward specified projects.

This research is directed toward formulating a basis for allocating resources to an information system that would provide traffic information in real time to expressway drivers. This research forms the basis from which priorities can be established for improving information to drivers relative to other improvements in the highway system. The results of this research are applicable to the Chicago metropolitan area.

A structured questionnaire administered to 732 drivers in the Chicago metropolitan area was used to measure driver attitudes. The subjects used in the survey owned a car, made a regularly scheduled automobile trip such as to a place of employment or to school, and resided in Cook County. This method of data collection was selected because of its combination of simplicity, economy, and reliability. The portion of the questionnaire dealt with in this presentation centered around the attitudes of drivers toward improvements in information items relative to selected improvements in the highway system. Money in the form of a budget allocation was used as a surrogate for the importance attached to information items. Each respondent was asked to allocate \$100 of "play money" to 10 items connected with expressways; 3 items were for information, 6 were of a general nature, and 1 could be written in by the respondent. Each

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respondent could allocate $100 in any amount desired to any number of items. This portion of the questionnaire was administered to the respondents before any reference was made to information items appearing in the survey. This was done to prevent any undue influencing of the driver by material appearing in the questionnaire.

Each respondent was furnished 10 envelopes, 9 of which had predetermined descriptors listed on them and one structured so that the respondent could write in an additional descriptor not listed on the other 9. (The descriptors used in this study were first selected by the staff working on the project. A pretest was then administered to respondents in the Chicago area. A final selection was then made from the response to the "preselected" descriptors and those that were most frequently recorded in the open-ended part of the question.) The envelopes were given to each respondent in a random order. Each respondent was given $100 in play money in $5 denominations and instructed to spend (or budget) the money in any manner he wished on any or all of the descriptors. Denominations smaller than $5 were given the respondent on request. (The respondents were instructed to disregard any apparent differences in perceived costs of descriptors.)

RESEARCH FINDINGS RELATING TO EXPRESSWAYS

Driver Preferences For Improvements

Table 1 gives the mean value and standard deviation of expenditures of all drivers and the number and corresponding percentage of the respondents who allocated some money to a descriptor. The largest average value of expenditures was for repair of pavement damages such as holes and bumps. More people allocated funds to this descriptor than to any other; more than 65 percent (481) of the respondents interviewed felt that the quality of the pavement surface needed improvement. A large number of respondents allocated money to descriptors 6 and 9. The mean value of expenditure for descriptor 6, increase enforcement of regulations, was $16.22. The mean value for descriptor 9, provide signs that can be electronically changed to furnish information about traffic conditions on the expressway ahead, was $15.47. Descriptors 2, 3, and 9 were considered to be information items. It is interesting to note that descriptor 9 ranked second by number of respondents allocating funds and third by the mean value of money allocated. The provision of motorist-aid phones ranked sixth with an average expenditure of $8.54. Radio traffic reports received a mean value of expenditure of $2.82 and ranked ninth.

The descriptors for expressways were ranked according to those most and least preferred by the respondents. These rankings are given in Table 2 by the respondent's maximum and minimum expenditure for a descriptor. In some cases, a respondent spent an equal maximum or minimum amount on more than 1 descriptor. For example, a respondent may have spent $20 on each of 2 descriptors, with the remaining $60 being spent in less than $20 increments on the remaining descriptors. Consequently, the columns in Table 2 do not necessarily add up to the total respondents. The reverse of this process was used to determine those items least preferred.

Data given in Table 2 can be interpreted in the following manner. Suppose that the respondents were making a budget for expenditures and were considering only the specified descriptors. In this budget, 270 respondents or 37.04 percent of the sample gave descriptor 1, improve repair of pavement damages, top priority. This does not mean that these 270 did not consider some other descriptor to have equal priority. But it does indicate that they gave descriptor 1 top priority second to no other item. Descriptor 6 was given top priority, second to no other item, by 191 respondents, and 157 respondents gave the highest consideration to descriptor 9. Only 2.61 percent of the respondents gave top priority to the provision of additional radio traffic reports; however, 10.56 percent gave top priority to the provision of motorist-aid phones. In general, the respondents interviewed had a preference for information descriptors.

Evaluating the descriptors least preferred, one finds that 638 respondents allocated the least amount of money to reducing the number of entrance ramps. For these 638 respondents, other descriptors may have a priority as low but none will have one lower. Relatively few respondents preferred to give the information descriptors, 6 and 9, the lowest priority. However, providing additional radio traffic reports received the lowest priority by 77.78 percent of the respondents.

The data given in Table 3 show that 76 respondents (10.43 percent) spent all of their money on 1 descriptor. Also, 87 respondents spent all their money on 2 descriptors, 134 respondents on 3 descriptors, and so on. For those people spending all of their money on 1 descriptor, 14 (1.92 percent) chose to spend the entire amount on descriptor 1. Likewise, 15 respondents (2.06 percent) chose to spend all of their money on descriptor 6. For those who spent all their money on 3 descriptors, descriptor 1 was

TABLE 1

EXPENDITURES FOR TRANSPORTATION IMPROVEMENTS ON EXPRESSWAYS

Descriptor	Mean Expenditure		Standard Deviation	Respondents Spending Money on Item	
	Amount ($)	Order		Number	Percent
1. Improve repair of pavement damages such as holes and bumps	20.84	1	22.53	481	65.98
2. Provide along the route free telephones that are only connected to the highway or police departments and can be used by the motorist to call for assistance	8.54	6	12.43	369	50.62
3. Provide additional radio traffic reports	2.82	9	6.61	165	22.63
4. Remove completely from the expressway stalled vehicles and vehicles involved in accidents	10.49	5	14.99	384	52.67
5. Reduce the number of entrance ramps	2.28	10	7.27	92	12.62
6. Increase enforcement of regulations such as those concerning shoulder riding, lane changing, and driving speed (minimum and maximum)	16.22	2	20.51	445	61.04
7. Improve maintenance of painted lines on pavement that separate lanes	8.06	7	12.51	324	44.44
8. Construct more entrance ramps	3.79	8	11.76	131	17.97
9. Provide signs that can be electronically changed to furnish information about traffic conditions on the expressway ahead	15.47	3	18.35	466	63.92
10. Other (please specify)	11.49	4	24.77	190	26.06

Note: Total respondents = 729.

TABLE 2

RANKING OF DESCRIPTORS FOR EXPRESSWAYS

Descriptor	Respondents Most Preferring Descriptor			Respondents Least Preferring Descriptor		
	Number	Percent	Order	Number	Percent	Order
1	270	34.04	1	249	34.16	10
2	77	10.56	6	361	49.52	6
3	19	2.61	10	567	77.78	3
4	107	14.68	5	345	47.33	7
5	20	2.74	9	638	87.52	1
6	191	26.20	2	286	39.23	8
7	77	10.56	6	405	55.56	5
8	40	5.49	8	600	82.30	2
9	157	21.54	3	264	36.21	9
10	125	17.15	4	541	74.21	4

Note: Total respondents = 729.

TABLE 3

DESCRIPTORS CHOSEN BY RESPONDENTS TO RECEIVE TOTAL EXPENDITURES FOR EXPRESSWAYS

Descriptor Chosen	Respondents by the Number of Descriptors Chosen to Receive Total Expenditures																			
	1		2		3		4		5		6		7		8		9		10	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
1	14	1.92	43	5.90	73	10.01	89	12.21	81	11.11	73	10.01	58	7.96	30	4.12	16	2.19	4	0.55
2	1	0.14	21	2.88	36	4.94	71	9.74	69	9.47	65	8.92	57	7.82	29	3.98	16	2.19	4	0.55
3	0	0	1	0.14	13	1.78	16	2.19	24	3.29	27	3.70	38	5.21	26	3.57	16	2.19	4	0.55
4	5	0.69	14	1.92	45	6.17	73	10.01	75	10.29	67	9.19	56	7.68	29	3.98	16	2.19	4	0.55
5	0	0	3	0.41	16	2.19	14	1.92	9	1.23	11	1.51	12	1.65	12	1.65	11	1.51	4	0.55
6	15	2.06	23	3.16	73	10.01	88	12.07	82	11.25	60	8.23	56	7.68	29	3.98	15	2.06	4	0.55
7	2	0.27	17	2.33	35	4.80	49	6.72	57	7.82	61	8.37	54	7.41	29	3.98	16	2.19	4	0.55
8	5	0.69	2	0.27	11	1.51	23	3.16	19	2.61	22	3.02	16	2.19	14	1.92	15	2.06	4	0.55
9	9	1.23	35	4.80	66	9.05	97	13.31	79	10.84	74	10.15	56	7.68	30	4.12	16	2.19	4	0.55
10	25	3.43	15	2.06	34	4.66	28	3.84	35	4.80	20	2.74	10	1.37	12	1.65	7	0.96	4	0.55
Total	76	10.43	87	11.93	134	18.38	137	18.79	106	14.54	80	10.97	59	8.09	30	4.12	16	2.19	4	0.55

chosen by 73 respondents (10.01 percent) as 1 of 3 choices for expenditures. Likewise, there were 73 respondents (10.01 percent) choosing descriptor 6 as 1 of their 3 choices and 66 respondents (9.05 percent) chosing descriptor 9 as 1 of their 3 expenditures.

By looking at Table 3, one can begin to visualize the dominant descriptors. When respondents chose to spend all of the $100 on only one descriptor, 3 descriptors seem to dominate: 6, 1, and 9. This is neglecting descriptor 10, which was written in by the individual respondents. The response to this descriptor will be discussed later in this paper, but this response generally indicates an extreme dissatisfaction with some specific rather than general existing condition. When the respondents chose to allocate money on 2 descriptors, 3 descriptors appear to dominate: 1,6, and 9. When the allocation of money is for 3 descriptors, again descriptors 1, 6, and 9 are dominant with descriptors 2, 4, and 7 gaining in preference. This analysis can be continued until 7 descriptors are shown to be dominant. Descriptors 1, 6, and 9 seem to be preferred out of the 7 dominating descriptors. Only descriptors 5, 8, and 10 never seem to be dominant.

The write-in descriptors could not be categorized in any meaningful manner. Of 729 respondents, 204 chose to write in a descriptor but these did not exhibit any trends. Some respondents wanted all toll facilities eliminated. Others preferred to restrict buses and trucks to certain facilities at specific times of the day. Public rapid transit on the expressways was a choice of some, while others simply asked that traffic flow be increased. Many respondents allocated some of their money to remedy a specific thing located at a specific place. The write-in descriptors did not show any pattern to be representative of a large portion of the respondents.

Analysis of Priorities by Subgroups

The respondents were divided into various subgroups, and tabulations were made for each subgroup in the same manner as for the total sample. The subgroups were the following: male and female, expressway and nonexpressway user on journey to work, income, mileage driven in Chicago area, age, geographical area, and education.

Contingency tables were used to test for any significant difference within subgroups for 3 categories: (a) proportion of respondents allocating some money for a descriptor, (b) proportion of respondents most preferring a descriptor, and (c) proportion of respondents least preferring a descriptor (1, 2).

The results of the tests for significant difference within subgroups of those respondents who allocated some money for a descriptor on expressways are given in Table 4. There is no significant difference at the 0.05 level within any of the groups. The results of the tests for significant difference within subgroups for descriptors most preferred for expressways are given in Table 5. There is a significant difference within the subgroups of education, income, and geographical area. The data indicated that generally, as the educational level increased, the percentage preferring descriptor 1 decreased, while the percentage preferring descriptors 9 and 10 increased. As the income level increased, the frequency with which descriptor 1 was most preferred decreased, while the frequency of descriptor 10 as the most preferred increased. The frequency for which descriptor 1 was most preferred was quite high for respondents in the geographical area in the southern portion of Cook County, which includes the Calumet Expressway. There is considerable pavement damage on this expressway. Descriptor 1 had a relatively low frequency of preference by respondents in the geographical area that lies between and incorporates the Eisenhower and Stevenson Expressways. It is noted that these data were collected prior to the latest resurfacing of the Eisenhower Expressway. Descriptor 1 was the only descriptor in which there was a large range of frequencies exhibited by respondents in the various geographical areas.

The groups of lower income, lower education, and southern geographical areas placed the repair of pavement damages as a top priority more often than did other levels within these subgroups. In the Chicago metropolitan area, these particular levels of the 3 subgroups generally coincide.

The results of the tests for significant difference within groups for descriptors least preferred for expressways are given in Table 6. At the 0.05 level of significance, there was no significant difference within any of the subgroups.

Regression Analysis

An attempt was made to develop a model by linear regression analysis that would predict the amount of expenditure for a given descriptor by a respondent exhibiting specified characteristics (4). Stepwise regression techniques were used to develop a relationship of the form

$$y = a + b_1x_1 + b_2x_2 + \ldots + b_nx_n$$

where y = the amount of money allocated by a respondent for a given descriptor. Thus 10 different sets of equations were attempted, one for each descriptor.

The independent variables considered in each regression analysis were number of routes used to go to work; number of days the preferred route was used in a 4-week period; usual time the respondent left home to drive to work; variation in leaving times for work; importance of arriving at the place of employment on time; frequency with which a respondent decided on the route to use to go to work before he left home; frequency with which a respondent changed routes because of congestion on his journey to work; frequency with which a respondent thought he improved his travel time by changing routes during the trip to work; importance of knowing the traffic conditions in help-

TABLE 4

RESULTS OF TESTS FOR SIGNIFICANT DIFFERENCE WITHIN SUBGROUPS FOR CATEGORY OF THOSE RESPONDENTS ALLOCATING SOME MONEY FOR A DESCRIPTOR ON EXPRESSWAYS

Subgroup	Degrees of Freedom	Chi-Square Calculated	Chi-Square 0.05	Significant Difference
Male versus female	9	9.59	16.92	No
Expressway versus nonexpressway users	9	7.65	16.92	No
Age	27	21.65	40.11	No
Mileage	36	19.53	52.53[a]	No
Education	45	38.90	62.73[a]	No
Income	27	35.15	40.11	No
Geographical area	45	31.20	62.73[a]	No

[a] Interpolated value.

TABLE 5

RESULTS OF TESTS FOR SIGNIFICANT DIFFERENCE WITHIN SUBGROUPS FOR CATEGORY OF DESCRIPTORS MOST PREFERRED FOR EXPRESSWAYS

Subgroup	Degrees of Freedom	Chi-Square Calculated	Chi-Square 0.05	Significant Difference
Male versus female	7	10.67	14.07	No
Expressway versus nonexpressway users	9	13.55	16.92	No
Age	24	32.57	36.42	No
Mileage	24	22.35	36.42	No
Education	25	51.25	37.65	Yes
Income	12	29.63	21.03	Yes
Geographical area	30	52.03	43.77	Yes

TABLE 6

RESULTS OF TESTS FOR SIGNIFICANT DIFFERENCE WITHIN SUBGROUPS FOR CATEGORY OF DESCRIPTORS LEAST PREFERRED FOR EXPRESSWAYS

Subgroup	Degrees of Freedom	Chi-Square Calculated	Chi-Square 0.05	Significant Difference
Male versus female	9	10.98	16.92	No
Expressway versus nonexpressway users	9	8.91	16.92	No
Age	36	18.13	52.53[a]	No
Mileage	45	27.42	62.73[a]	No
Education	45	25.49	62.73[a]	No
Income	36	23.72	52.53[a]	No
Geographical area	45	35.25	62.73[a]	No

[a] Interpolated value.

ing to decide which route to take to work; importance of knowing the traffic conditions in helping to decide the time to leave for work; importance of knowing the road conditions in helping to decide which route to take to work; importance of knowing the road conditions in helping to decide the time to leave for work; frequency with which a respondent listened to radio traffic reports before leaving for work; frequency with which a respondent diverted to another route if the radio traffic report indicates that there is heavy congestion on his route while driving to work; frequency with which a respondent diverted to another route if the radio traffic report indicates that there has been an accident ahead while driving to work; frequency with which a respondent would contact an information center about traffic conditions before leaving to drive to work; length of time respondent had lived at his present address; length of time respondent had lived in the Chicago metropolitan area; length of time respondent had lived in a metropolitan area with a population of 500,000 or more; number of cars the respondent's household had available for use; respondent's age; respondent's sex; mileage driven in Chicago area per year; respondent's educational level; and respondent's family income. These variables were obtained in other portions of the questionnaire.

The independent variables of sex, income, and education were treated as dummy variables. The correlation matrix did not indicate any significant correlation between dependent and independent variables. The stepwise regression analysis did not indicate that a meaningful linear equation could be developed to predict the amount of expenditures for a given descriptor. The coefficient of determination at each step of the regression analysis was quite low. Only about 10 percent of the variation in the dependent variable could be explained by the model developed at each step.

RESEARCH FINDINGS RELATING TO CITY STREETS

Table 7 gives the mean value and standard deviation of expenditures of all drivers and the number and corresponding percentage of the respondents that allocated some money to descriptor. The highest mean value of expenditure is for descriptor 6, improve repair of pavement damages. There were 566 respondents (77.64 percent) allocating some money to descriptor 6, making it the descriptor for which money was most frequently allocated. Descriptor 3, provide more left-turn lanes at signalized intersections, ranks second with a mean value of $17.78. Descriptor 3 was also frequently selected for expenditures; 520 respondents (71.33 percent) spent some money on it. Descriptor 1, improve enforcement of no parking regulations during the rush hours, received the third largest mean expenditure and received consideration for expenditure by 63.24 percent of those interviewed.

The ranking of the descriptors for city streets with regard to those most and least preferred given in Table 8. Descriptor 6 was given top priority by 332 respondents

TABLE 7

EXPENDITURES FOR TRANSPORTATION IMPROVEMENTS ON CITY STREETS

Descriptor	Mean Expenditure		Standard Deviation	Respondents Spending Money on Item	
	Amount ($)	Order		Number	Percent
1. Improve enforcement of no parking regulations during rush hours	13.21	3	16.07	461	63.24
2. Improve signing of street names	8.10	5	11.96	355	48.70
3. Provide more left-turn lanes at signalized intersections	17.78	2	17.32	520	71.33
4. Improve maintenance of painted lines on pavement that separate lanes	6.44	7	9.33	320	43.90
5. Provide along the route free telephones that are only connected to the highway or police departments and can be used by the motorist to call for assistance	4.93	9	8.73	257	35.25
6. Improve repair of pavement damages such as holes and bumps	22.09	1	20.06	566	77.64
7. Provide information about the traffic conditions on any nearby expressways	4.89	10	9.08	251	34.43
8. Provide signs that tell the motorist the speed to drive for which the traffic signals are set	9.33	4	11.94	395	54.18
9. Provide more street lighting	5.84	8	10.54	267	36.63
10. Other (please specify)	7.39	6	19.47	136	18.66

Note: Total respondents = 729.

TABLE 8

RANKING OF DESCRIPTORS FOR CITY STREETS

Descriptor	Respondents Most Preferring Descriptor			Respondents Least Preferring Descriptor		
	Number	Percent	Order	Number	Percent	Order
1	144	19.75	3	270	37.04	8
2	86	11.80	6	376	51.58	6
3	254	34.84	2	209	28.67	9
4	59	8.09	9	410	56.24	5
5	60	8.23	8	476	65.29	3
6	332	45.54	1	163	22.36	10
7	41	5.62	10	480	65.84	2
8	94	12.89	4	336	46.09	7
9	66	9.05	7	464	63.65	4
10	92	12.62	5	594	81.48	1

Note: Total respondents = 729.

representing 45.54 percent of the sample. This same descriptor was also given top priority for expressways. It would seem that the pavement condition in the Chicago area, both on city streets and expressways, is of major concern to a fairly large group of those respondents inverviewed. Descriptor 3 was given top priority by 34.84 percent of those interviewed.

Reviewing those descriptors least preferred, one finds that descriptor 7, provide information about the traffic conditions on any nearby expressway, was placed as the lowest item considered for expenditures by 65.84 percent of those interviewed. Descriptor 5, provide motorist-aid phones, was given the lowest priority by 65.29 percent of those interviewed. Information was a desirable feature on expressways; however, the 2 information descriptors, 7 and 5, for city streets were not of major concern to the respondents. With the exception of the write-in descriptors, 2 information descriptors are given the lowest of priorities by a majority of those interviewed.

Data given in Table 9 show that the largest percentage of the respondents allocated their $100 to 4 descriptors. Only 6.86 percent of the sample spent all their money on 1 descriptor. The more dominant descriptors can be visualized in Table 9 as they were in Table 3. Descriptor 10, which is written in by each respondent, is again omitted and discussed later. Descriptors 6 and 1 are dominant among those respondents allocating all of their money to a single descriptor. When respondents chose to allocate their money to 2 descriptors, then descriptors 6, 3, and 1 become dominant. Descriptors 6, 3, 1, and 8 exhibit dominance when money is allocated for 3 descriptors. In general, there are 4 descriptors that appear to dominate: 1, 3, 6, and 8. After the number of descriptors chosen for expenditures becomes 8 or more, the magnitude of separation between descriptors is not so pronounced; however, the preference characteristics are still there.

Descriptor 10, which was written in by the respondents, indicated much of the same randomness for city streets as for expressways. Some respondents allocated their

TABLE 9

DESCRIPTORS CHOSEN BY RESPONDENTS TO RECEIVE TOTAL EXPENDITURES FOR CITY STREETS

Descriptor Chosen	Respondents by the Number of Descriptors Chosen to Receive Total Expenditures																			
	1		2		3		4		5		6		7		8		9		10	
	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
1	8	1.10	17	2.33	47	6.45	71	9.74	77	10.56	75	10.29	67	9.19	48	6.58	47	6.45	4	0.55
2	3	0.41	4	0.55	26	3.57	56	7.68	51	7.00	62	8.50	56	7.68	46	6.31	47	6.45	4	0.55
3	5	0.69	34	4.66	59	8.09	99	13.58	87	11.93	73	10.01	64	8.78	48	6.58	47	6.45	4	0.55
4	0	0	1	0.14	24	3.29	47	6.45	50	6.86	51	7.00	55	7.54	42	5.76	46	6.31	4	0.55
5	0	0	1	0.14	8	1.10	35	4.80	36	4.94	42	5.76	45	6.17	40	5.49	46	6.31	4	0.55
6	14	1.92	31	4.25	61	8.37	110	15.09	89	12.21	88	12.07	70	9.60	52	7.13	47	6.45	4	0.55
7	1	0.14	3	0.41	14	1.92	28	3.84	26	3.57	44	6.04	46	6.31	42	5.76	43	5.90	4	0.55
8	2	0.27	8	1.10	39	5.35	69	9.47	56	7.68	66	9.05	57	7.82	48	6.58	46	6.31	4	0.55
9	2	0.27	8	1.10	8	1.10	29	3.98	40	5.49	42	5.76	46	6.31	43	5.90	45	6.17	4	0.55
10	15	2.06	13	1.78	17	2.33	16	2.19	28	3.84	15	2.06	12	1.65	7	0.96	9	1.23	4	0.55
Total	50	6.86	60	8.23	101	13.85	140	19.20	108	14.81	93	12.76	74	10.15	52	7.13	47	6.45	4	0.55

TABLE 10

RESULTS OF TESTS FOR SIGNIFICANT DIFFERENCE WITHIN SUBGROUPS FOR CATEGORY OF THOSE RESPONDENTS ALLOCATING SOME MONEY FOR A DESCRIPTOR ON CITY STREETS

Subgroup	Degrees of Freedom	Chi-Square Calculated	Chi-Square 0.05	Significant Difference
Male versus female	9	6.65	16.92	No
Expressway versus nonexpressway users	9	9.02	16.92	No
Age	36	20.26	52.53[a]	No
Mileage	45	33.88	62.73[a]	No
Education	45	34.90	62.73[a]	No
Income	36	21.69	52.53[a]	No
Geographical area	45	49.11	62.73[a]	No

[a] Interpolated value.

money for a specific thing located at a specific place. Other respondents indicated very vague descriptors such as better electronic control of traffic. Again, no meaningful categorizing of the responses could be made.

The responses to the question on city streets were divided into 6 subgroups for further analysis as was done for the question on expressways. Contingency tables were used to test for any significant difference within subgroups for those respondents allocating some money for a descriptor on city streets. The results of these tests are given in Table 10. There was no significant difference at the 0.05 level within subgroups for the frequency of allocating some money to a descriptor.

SUMMARY

The drivers interviewed strongly preferred a smooth-riding pavement whether it was on an expressway or a city street. The respondents having a lower income, having a lower educational level, and living in the southern part of Chicago were more concerned with improving the pavement conditions than were their counterparts.

Information on the traffic conditions seemed to be relatively important while driving on an expressway but unimportant while driving on a city street. The provision of traffic information in real time on expressways received the third largest mean expenditure and received some allocation of funds by the second largest group of respondents. The provision of motorist-aid phones received the sixth largest mean expenditure and was fifth in group size allocating money to it. However, these 2 corresponding descriptors were given the lowest of priorities when placed in relation to selected improvements for city streets. The provision of additional radio traffic reports was given very low priority. When considering the selected improvements on expressways, the respondents clearly indicated a desire for motorist-aid phones and for information on the traffic conditions.

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