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VISUAL FACTORS IN TRANSPORTATION SYSTEMS

Proceedings of Spring Meeting, 1969
NAS-NRC Committee on Vision

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FOREWORD

In the spring of 1969, a two-day meeting was held under the auspices of the NAS-NRC Committee on Vision. The meeting brought together people experienced in day-to-day operations in transportation systems with persons who are doing research in visual problems of these systems. The purpose of this juxtaposition was to encourage an exchange of information among operational people, managers of research, and research workers. It was hoped that a first-hand account of visual problems by operators would call attention to any problems that might be slighted in current research efforts and that this exchange of information might have some salutory effect on plans for future research. These papers were so greatly sought after that the Executive Council of the Committee on Vision decided to publish them as a collection representing the proceedings of the committee meeting.

VISUAL PROBLEMS OF TRUCK AND BUS DRIVERS

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The professional truck driver believes that the final responsibility for the safe operation of his truck is his alone. For this reason, he must drive defensively, that is, anticipate what the other driver will do and leave nothing to chance. Since almost all of his decisions are based on visual information, it is essential that the truck driver's visual needs be met. Let us now take a close look at the driving task to see what these needs are. A driver should have at least 20/40 vision in at least one eye with or without corrective lenses. The importance of good vision can be seen when we consider stopping distances. Under the very best road conditions, with good handling, dry pavement, clear weather, and unobstructed vision, a truck traveling 40 mph with 60,000 lb gross weight travels about 192 ft before it can be stopped and, under the same conditions, a truck traveling 50 mph would travel 264 ft.

The usual traffic sign with 5 in. letters can be read at about 280 ft by a driver with 20/20 vision. For drivers with 20/40 and 20/50 vision, distances would be 113 ft and 90 ft. Inability to read road signs soon enough may be a factor in thousands of accidents on road crossings. The driver with poor visual acuity is handicapped even more in his night driving, since 20/40 acuity decreases to 20/80 at night. Even the driver with 20/20 daytime acuity finds his acuity decreased to 20/40 after dark.

In addition to being able to see clearly at some minimum distance, a truck driver must be able to judge relative distances so that he can locate objects properly in space, and accidents happen every day because many drivers lack the ability to judge correctly the distance of approaching vehicles. The point is clear: Safe truck-driving calls for good visual acuity and good depth perception.

FIELD OF VISION

Field of vision is important because you must be able to detect a vehicle that approaches from the side or a pedestrian who may begin to cross ahead of you. The field of vision is reduced as the speed of the vehicle increases. When looking straight ahead at 30 mph, the driver's field of vision is reduced approximately 50% because of the blurring of stationary objects close to the side of the vehicle. At 60 mph this same driver is able to use only about 25% of his normal side vision. This restriction in side vision can be compensated for by proper eye movements; in fact, the alert truck driver continually moves his head from side to side, first looking in one rear-view mirror and then the other. Many times he knows just as much about what is behind him as he does in front.

In contrast with equipment of 25 years ago, today's cabs seat the driver 4-6 ft higher. This enables him to see much further; in fact, he is now able to see over and beyond any automobile that might be traveling in front of him. The cabs of trucks are much wider today, with larger windshields that greatly improve the driver's vision, and many windshields are tinted to reduce glare.

NIGHT DRIVING

More than half of all traffic fatalities occur at night, and the most dangerous hours on the highway are those just after sundown. Dusk blots as much light for drivers suffering from night blindness as late darkness does for others. This is one of the reasons why the rate of fatal accidents is three times higher at night than during the day.

Night driving demands three important visual skills: (a) the ability to see efficiently under low illumination, (b) the ability to see against glare, and (c) rapid recovery after being blinded by the glare of oncoming headlights. Truck drivers are quite vocal in their complaints about reflections from bright headlights in their rear-view mirrors, and usually they are especially careful to dim their own headlights when following other traffic at night. Laws of many states require dimming of headlights when following within 500 feet, but it should be remembered that annoying glare may be produced at a greater distance.

Ways to increase the margin of safety for night driving are: (a) watch for the glow of headlights from oncoming vehicles even if the lights themselves cannot be seen, (b) watch for the glow of headlights from vehicles approaching from side roads, (c) make use of the headlights of vehicles ahead to spot hazards that have not yet come into range of the driver's own headlights.

A clean windshield is especially important at night. Unfortunately, the inside surface of the windshield is often neglected when the windshield is cleaned, and the film that forms there causes as much blinding from headlight glare as the headlights themselves. Incidentally, smoking can be a major source of this film.

In an effort to reduce nighttime accidents, great improvements have been made in rear lighting for trucks. The visibility of the individual lights has been improved, and the number of required lights has been increased, but the benefits of these improvements can be quickly lost if trucks are operated with burned-out bulbs or lights and reflectors obscured by dirt. The truck driver must check all lights and reflectors before starting a trip, before dark, and at every nighttime stop.

BLIND SPOT

Many accidents occur because a vehicle is in the so-called blind spot, the area just to the rear of the tractor. This blind spot can be eliminated by installing a convex mirror, but, unfortunately, not all trucks are equipped with this device. This particular deficiency exemplifies a general deficiency, for all too frequently, in my experience, the design of truck cabs has not met the visual needs of the truck driver. Truck cabs are the tools of the truck driver's trade, and I feel that he has not had an adequate voice in their design.

RECOMMENDATIONS

It is my recommendation that state laws be changed so that drivers will receive a broader range of visual tests to determine whether they can see well enough to cope with modern traffic conditions. Equally important, many driver programs fail to test properly other factors related to driving: physical condition, emotional stability, motor skills, and driving knowledge. In addition, I recommend that the trucking industry agree on just what visual ability should be required of a truck driver so that it can standardize its hiring practices.

VISUAL PROBLEMS IN AUTOMOBILE DRIVING

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Each of us knows something of the visual problems of automobile driving from personal experience. At various times we encounter problems with visibility that makes us unhappy in a particular way with the vehicle we are driving. If it is our own automobile, we eventually get used to the problem and adjust ourselves to it, but if we occasionally drive unfamiliar vehicles, we are sometimes caught short by a peculiarity of that car that affects what we think should be good vision, either in an annoying way or in a hazardous way.

In discussing these problems I can do little more than mention the same types of situations that each of you as automobile drivers could also bring to mind. Many problems have, of course, been the subject of rather thorough and extensive research, but much remains to be done in putting improvements into universal practice.

The individual deficiencies important to a passenger car driver might be placed in five categories, most of which are interrelated. These are: vehicle body construction, driver limitations, lighting-equipment design, maintenance practices, and research methods.

VEHICLE BODY CONSTRUCTION

Perhaps one of the most obvious changes in vehicle construction that has improved the driver's ability to see has been the major increase in windshield area. Manufacturers have made great strides in increasing the field of view through the windshield and in attempting to change the shape, slant, or location of the windshield pillar-post so as to interfere less with visibility of traffic approaching an intersection. Many of the complaints that could have been made many years ago about insufficient field of view would not be generally valid today. Unfortunately, it seems that every change introduced to solve one problem results in another type of problem, in this case, distortion produced by the windshield glass itself.

The wave of dissatisfaction with badly distorted wrap-around windshields has receded considerably with the introduction of new windshield designs, but distortion still troubles drivers to some extent. A moderate amount of distortion on the far right side of the windshield is normally inconsequential in freeway and long-distance driving, but it suddenly becomes extremely important under conditions when poor daytime lighting, bodily discomfort, an unknown intersection, or a long stream of cross traffic make the additional distortion critical in making a good judgment as to when to make a movement either in crossing the traffic or making a left turn into the main stream. The problem seems worse when the distortion causes one eye to receive a much different image than the other eye.

Methods are available for checking distortion of sample sections of windshield glass in a laboratory, but there are no such methods for use on a complete vehicle outside of the laboratory. Since complaints of windshield distortion do not arise until the motor vehicle is in the hands of the purchaser, some portable means should be developed for measuring the degree of distortion. Only with such readings does it become possible to make an objective judgment of the severity of the condition.

Visibility of overhead traffic signals is another problem that used to be quite severe in localities that had only single overhead traffic lights at intersections. The fact that the windshield opening is not high enough for some drivers in certain automobiles has probably contributed to accidents at such intersections because of the driver's inability to see all that he should see in unfamiliar driving situations. As a result of several studies, this difficulty is well on the way to being solved. By resignedly accepting the automobile as it is, traffic engineers have done an excellent job in installing redundant signals on new highway construction so that the vertical limitation on visibility due to the design of the roofline of the vehicle does not seem to be the problem it once was.

Our traffic officers have complained about the trend toward larger rear side panels in the top of the passenger compartment. These opaque sections block the view when backing and turning simultaneously and also tend to hide vehicles passing in the righthand lane. This difficulty has been recently aggravated by wide head restraints. Our officers are also dissatisfied with the body design of patrol cars that places the bottom of the rear window quite high in combination with a trunk that slants steeply downward. Even tall officers cannot see any part of the trunk or rear of the vehicle that would allow them to judge the distance from the rear bumper to another object. There are many situations in which cautious backing until something is lightly touched by the bumper is not feasible. At times rapid backing is necessary, and adequate visibility is highly important in judging where to stop.

Bright surfaces within the vehicle reflect light either directly into the driver's eyes or onto the windshield, and these surfaces reflect both sunlight during the day and overhead luminaires at nighttime. Similar problems exist with bright sources of light located off the highway as well as improperly shielded fluorescent tubes and other lights used to illuminate highway signs when the direct light from these sources is within the driver's field of view. Many of these items might be considered merely annoying and not disabling to the driver, but there appears to be no way of preventing drivers from operating their vehicles when they are somewhat fatigued. Under such conditions, lights that normally are not only discomforting become hazardous.

DRIVER LIMITATIONS

Although almost all visual problems involve limitations of the driver in one respect or another, some are particularly difficult to solve because of variability in the height of the eyes and limitations on movement of the driver's head and eyes. For instance, visibility of the roadway in front of the vehicle depends on the angle of the driver's eyes above the hood, and visibility of dash instruments through the steering wheel is dependent upon the height of the eyes.

A prime problem of this type is deficient vision to the rear and to the sides. Despite studies conducted by independent research workers and in-house projects of car manufacturers, mirrors on present-day cars do not universally provide adequate rear and side vision for the driver even when the vehicle is equipped with right and left outside mirrors in addition to the inside mirror. Drivers of passenger vehicles in modern freeway traffic require equipment that will give them a fast and easy look at traffic on the right and left sides of the vehicle. Rapid merging from on-ramps and rapid lane-changing under freeway traffic situations are necessary with excessive head movement that would take the driver's eyes away from the vehicle immediately ahead of him. Solutions such as periscopic mirrors and segmented interior mirrors have been proposed, but no satisfactory system of this type has as yet been made part of the original equipment of a passenger car.

Readability of speedometer and other instruments also is a problem. Cars are not bought on the basis of how well the instruments can be seen, but this becomes a cause for concern once a new vehicle is purchased and the owner becomes dissatisfied because of other mechanical defects or oversights in assembly. Considerable study of factors affecting readability, visibility, and placement of instruments for day and night use has indicated what types of features detract from fast recognition and what features enhance it, but I am not aware that these factors are given priority in the installation of instruments in a vehicle when some other consideration might conflict.

LIGHTING EQUIPMENT

In addition to the aforementioned problems that depend upon a driver's adaptation, visual acuity, and understanding of symbols, illumination of the instruments on the dashboard is a factor that influences visibility. This is a twofold problem from the driver's viewpoint, although many casual drivers do not recognize it. The first effect of improper illumination at nighttime is the inability to read the instruments rapidly with the minimum diversion of vision from the highway and with the minimum time necessary to be sure what the instrument reading is. The second effect is that high brightness of instrument illumination interferes with the driver's vision in dark areas of the highway, particularly in very high-speed driving on roads having little approaching traffic. Some drivers operate their vehicles with the dashlights on full bright all the time, possibly as an unconscious remembrance of the comfort these lights gave them as children when they were riding at night in a car but more likely because it allows them to read poorly designed instruments better. They are not aware that the bright light within the passenger compartment might interfere with their adaptation to the low level of illumination outside.

Another continual problem to the automobile driver is the shape, location, and brightness of taillamps. These lamps range from being too dim on some vehicles in high-speed, two-lane traffic to being far too bright on vehicles in dense traffic under adverse weather conditions. In some instances, droplets of water on the unwiped windshield areas produce so much background light that it is difficult for the driver to see through it. The large wiped areas now required by Federal standards have brought improvements in this respect.

Detecting and locating other vehicles also presents a problem. Much to-do was made several years ago about running lights on motor vehicles, but the initial infatuation has subsided to the extent that the subject is very seldom mentioned any more. The problem of indicating the presence of another vehicle under certain daytime lighting conditions and at dusk before headlamps are turned on is still a valid one, however.

Some studies have been made on the benefits of driving with headlamps lit during the daytime and on the brightness of the light emitted by daytime running lamps on the front of a vehicle. Although none of the studies appears to have really defined the exact distribution of light that would be necessary to set a standard for such devices, work is being done in this area.

Turning on headlamps at dusk provides an indication of the presence of the vehicle to other drivers for quite a period of time before the sky is dark enough for the headlamps to be of any benefit in illuminating the roadway. Persons concerned with visibility of vehicles have proposed mandatory use of automatic, ambient light-sensing units for turning on headlamps if the driver fails to do so. A disadvantage is the continuous added cost of frequent sealed beam headlamp replacements when filaments burn out.

MAINTENANCE

The need for maintenance of a vehicle is almost too obvious to mention, so I will bring up only one point. Smearing of the windshield by the windshield wipers still seems to be a major visibility problem in bad weather. I know there are all types of homemade and patent medicine remedies for this situation, but it still plagues passenger car drivers.

RESEARCH METHODS

One of the most pressing needs that you ought to consider is the necessity for research into the ways in which research should be conducted. In many areas of automotive lighting equipment, data on the effects of changes and improvements in equipment are obtained purely by subjective evaluations of observers who know what they are evaluating and who have considerable time to make each evaluation. When more objective measurements have been sought, they usually involve threshold values to determine at what point an observer can just perceive a change or a particular effect. However, the visibility of lighting and signaling equipment in actual situations is far above threshold value by the time the driver becomes aware of the signal. Some method is needed for consistently and objectively evaluating the effectiveness of lighting equipment designed for the purpose of attracting the attention of the driver or eliciting some action from him.

Another problem that many times is overlooked in investigations is the practical effect of a given system under actual traffic conditions. For instance, in testing a stop-lamp system, the best objective research might show that under hazardous conditions the driver's attention is attracted to the signal light as soon as it comes on and that it overcomes his distractions. However, this ideal light would not necessarily function much better in traffic than present-day stop lamps, principally because drivers in heavy traffic commonly ignore the repetitive stop signals of the vehicles ahead of them until their meaning in confirmed by some other visual effect, such as a sudden decrease in distance from the vehicle ahead.

This evaluation of signals by the driver is essential because chaos might result on a freeway system if every driver automatically took some type of action each time a stop signal was exhibited on the vehicle immediately before him. I suggest that this type of situation be recognized and evaluated in research on visibility factors affecting the actions of a passenger car driver.

You might well consider establishing guidelines for new research workers. With the enormous increase in organizations entering motor vehicle research as a result of funding by the Department of Transportation, new people are suddenly confronted with an opportunity. Some will repeat the same mistakes that you have learned to avoid, and they will produce misleading reports. Also, the rapid expansion of public and private organizations has unavoidably resulted in an increased number of inexperienced people who will be using these reports in making evaluations and setting specifications, and many mistakes will be made by both groups unless they are soon given some rules of thumb.

TRANSCRIBING RESEARCH RESULTS INTO SPECIFICATIONS

It would be valuable to study the problem of writing performance specifications, since they are the practical application of the research I have been discussing. As they are stated in safety regulations, many of the automotive industry's vision-related standards incorporate many design requirements that either limit new ideas or use subjective statements that do not permit adequate enforcement.

As a simple example, consider the present Society of Automotive Engineers standard for turn-signal pilot-indicators. Both law enforcement officials and the general public have complained about ineffective turn signals and about turn signals that remain on after a change in traffic lanes has been made. The automobile manufacturers have attempted to overcome this to some extent by installing a lane-changing, spring-operated intermediate position of the turn signal switch, but for years the following unsatisfactory regulation requiring only pilot lights has remained essentially the same:

> The illuminated indicator shall consist of one or more bright lights flashing at the same frequency as the signal lamps, and shall be plainly visible to the drivers of all heights when seated in normal position in the driver's seat while driving in bright sunlight. If the illuminated indicator is located inside the vehicle, for example in the instrument cluster, it should emit a green color and have a mini-

mum area equivalent to a 3⁄16-inch diameter circle. If the illuminated indicators are located on the outside of the vehicle, for example on the front fenders, they should emit an amber color and have a minimum area of 0.1 square inch.

This standard is almost useless either as a guide to a design engineer or as a standard for agencies entrusted with obtaining compliance with Motor Vehicle Safety Standards. Any possible performance standard that is implied by that specification is so nebulous that is it unenforceable, and the only items that are specific are the design requirements of size and color. If an enforcement agency tries to obtain compliance with the spirit of the law by pointing out that the daytime brightness of the indicators is so low it will not attract the driver's attention, the defense has been that the signal is visible to all heights of drivers when they look directly at the signal (or move their heads slightly). Standards need to be expressed in measurable terms of performance so that everyone will know what is required. Another area of study that could be of significant importance to persons responsible for setting standards is the development of specifications based on an objective method of evaluating individual items of lighting equipment, such as turn-signal lamps, with respect to their effectiveness in sunlight. At the present time, the minimum standards for exterior lighting equipment are specified in terms of candlepower, which appears to be a reasonable unit of measurement for nighttime use or if lamps are of approximately the same luminous area. This system is not adequate for daytime use, as is readily illustrated by comparing the daytime effectiveness of various rear lamps used on present-day passenger vehicles.

A lamp that has some minimum lens area that is semirecessed into overhanging sections of the car body so that it is shaded from light coming from above gives a much more effective signal for attracting the attention of other drivers than does another lamp that has the same candlepower but a larger lens area surrounded by bright chrome trim. At nighttime the two lamps function about equally well, but in daylight, when the sun reflects from the lens and the chrome surfaces, the lamp with the bright spots produces a red signal that can only be seen by a driver who is looking at it. A specification is needed that takes these daylight conditions into account in an objective manner, that can be used by engineers in designing a lamp, and that is clear enough to serve as an enforceable standard.

Perhaps one of the most important difficulties is getting the results of research uniformly applied to the construction of vehicles. The major problem in this respect appears to me to be one of determining when and to what extent an improvement becomes economically worthwhile. We each know from driving our own cars that a driver can, after a fashion, overcome the effects of a visual defect in the construction of a vehicle because he gets used to the situation and usually corrects for it without thinking. The producers of vehicles then argue that the mere fact that a driver may have to adjust to a problem does not necessarily warrant the expenditure of the money necessary to eliminate the problem. The only way to refute this argument is to estimate how much it would cost not to make the change and to set a limit for what would be an acceptable cost.

Today's problems of automobile safety may be analogous to the problems of industrial safety years ago. In spite of long experience, some semblance of safety training, and supposed attention to their task, machine operators still frequently injured themselves severely. It was not until mechanical obstructions were placed in the operator's way so that they could not inadvertently or deliberately endanger themselves that the accident problem was relieved. Similar measures would appear to be called for in designing motor vehicles.

FACTORS IN VISIBILITY AND LEGIBILITY OF HIGHWAY SIGNS AND MARKINGS

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The problem of transmitting information to drivers on the highway has been with us since the early days of the automobile. Visual transmission by means of signs was a natural development, but early signs were varied and often difficult to read. It soon became clear, therefore, that the problems of visibility and legibility were important as highway and safety problems developed with increasing traffic.

DEFINITIONS

An early study by Forbes (1939) adopted the term "legibility" to indicate the recognizability of letters on a sign and the term "attention value" to indicate how well the sign is seen when it competes with other visual stimuli for the driver's attention. "Visilibility" as used here refers to attention-getting characteristics and does not mean detection threshold or greatest detection distance. The practical problem for the traffic engineer is whether the sign attracts enough attention to be read when it is within legible distance.

The 1939 study analyzed legibility into "pure legibility" with unlimited time for reading the sign and "glance legibility," which refers to legibility when reading time is limited.

Visibility or attention value was analyzed into "target value" or characteristics making the signs stand out against its background and "priority value," which referred to other factors, such as location along the highway and mounting position that affects the order in which signs might be read. It was shown that contrast factors affected the target value and that location, number of signs, reading habits, search procedure, and the "mental set" while looking for a road marker affected the priority value.

LEGIBILITY FACTORS

There have been many studies of factors affecting sign legibility. Factors of importance are contrast of letters, height of letters, height-width ratio, stroke-width, spacing between letters, and vertical spacing between lines.

Mills (1933) used a shutter exposure technique to test color combinations and recommended, first, black on yellow and, second, black on white or white on black, thus indicating the importance of letter contrast. Lauer (1932) summarizing work of his laboratory at Iowa State University, recommended a light yellow as best for all seasons, a letter width-to-height ratio greater than 33%, a stroke 20% of average letter width, and a spacing of 50% of average letter width. Average letter width is difficult to use, however, because of the varying widths of different letters of the alphabet.

Two later studies (Uhlaner, 1941; Kuntz and Sleight, 1950) indicated an optimum stroke-width for square block letters in the range of 15 to 25% of letter height (or width). Also, legibility increases with letter width up to a square letter as shown by several studies (Forbes and Holmes, 1939; Allen and Straub, 1955).

A series of license plate legibility studies (Berger, 1944–1952; Harrington, 1960; Hodge, 1962) confirmed this range except for bright, internally illuminated letters when a narrower stroke gave better legibility. This is easily explainable as an irradiation effect on the retina that produces an effectively wider stroke-width.

This irradiation effect plays a part in the lesser effectiveness of dark letters on a light background in comparison with light letters on a dark background that a number of studies have shown. Although they differ in detail, these studies consistently indicate the light letter to be more effective when the letter design, stroke-width, spacing, and brightness are such that a widening of the stroke produces a better balance of the letters and their internal and external spacing. For example, in a full scale outdoor legibility distance experiment, Case *et al.* (1952) found black letters better at close spacing and white letters better when spacing was wide [equal to letter height of (wide) Series E letters]. In a laboratory experiment, Allen and Straub (1955), using three different width alphabets [Bureau of Public Roads Series (narrow) A, C, and (wide) F], found internally illuminated letters on a dark background better at intermediate brightness.

Allen *et al.* (1967) found bright letters on a low transmission background more legible when seen against low and medium ambient illumination but not against a high ambient background.

Legibility distances for highway sign design—human factors engineering. Based on the information then available, designs, first, for a standard block-letter alphabet, later, for a rounded-letter alphabet, and, still later, for a lower-case alphabet were developed by the National Committee on Signs, Signals and Markings and the U. S. Bureau of Public Roads. It has been known for many years that one minute of arc represents so-called normal vision for young subjects, but this was not of much assistance to the highway sign designer. The traffic engineer and those designing highway signs needed to know how far most drivers can read a sign with a particular size and design of letters.

Accordingly, a method for determining legibility distances for a standard block letter alphabet was developed by Forbes (1939) and applied by Forbes and Holmes (1939). This was the first application of the "engineering psychology" or the "human factors engineering" approach in the highway field. Perhaps the highway field can claim a nationwide first, since most aviation psychology and military human factors engineering applications were developed in response to World War II problems shortly after this.

The Forbes and Holmes full scale outdoor observations indicated a linear relationship between height of letters and visibility distance of about 50 ft/in. in daylight for black-on-white Series D (medium wide) letters. The narrower Series B letters gave about 33 ft/in.

These were 80 percentile values from observations by 412 different people and represented 20/20 vision. Letters from 6 to 24 in. in height and six-letter place names with *one misspelling* were used for test signs. Floodlighted signs at night gave a legibility distance from 10 to 20% shorter. Results with button reflectorized signs under headlights were similar up to about 300 ft, beyond which there was little increase with letter height. This study required subjects to record all letters accurately, including the misspelling.

Comment. Legibility distance of 60 ft/in., stroke-width 20% of height, and smallest internal spacings equal to stroke-width correspond rather well with the usually accepted figure of one minute of arc for normal visual discrimination. However, most states require only 20/40 vision for a driver's license.

Lower case letters and familiarity effects. A comparison of legibility distances of lower case and capital letters using both familiar words and scrambled letters (Forbes *et al.,* 1950) showed distances similar to the Forbes and Holmes (1939) study for the scrambled letters, but familiar words gave longer distances. Legibility distances for lower case alphabets in terms of "loop height" were comparable to those with capital letters. Longer legibility distances were found with familiar names. The familiar place names shown a second time but in different orders gave slightly longer legibility distances than when first seen, even though subjects had previously seen a list of all names that might be used. White-on-black signs, the wide Series E rounded letter, and a new lower case alphabet were used. Letter heights were 6, 9 and 13 in. for capitals and 5, 8 and 12 in. "loop height" for lower case. Fifty-five observers viewed all sizes and types of test sign on foot, starting from about 2000 ft, under day and under night floodlighted conditions.

Figure 1 shows daylight distributions, medians, and 80 percentile trend lines for scrambled letters and familiar words. Figures 2 and 3 show median distance values for daylight and night conditions for capital letters and lower case. The 85 percentile represents performance of people with approximately 20/20 vision.

The shorter legibility distances of scrambled letters were quite comparable to those of the Forbes and Holmes (1939) study in which a one letter misspelling was used.

Comment. Legibility distances on the order of 70 to 80 ft and in some cases 100 ft/in. of letter height reported by Allen and Straub (1955) and by Allen *et al.* (1967) correspond well with the comparable distances of our study since they used three-letter familiar syllables.

Lower case letter height must be measured by "loop height" since this is the only constant dimension of all letters. Loop height in this

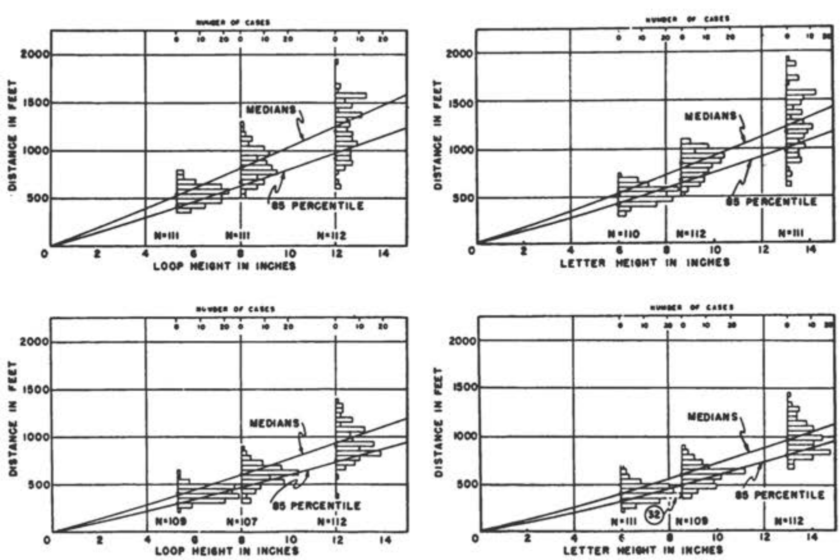

Figure 1—Daytime legibility distance distributions for lower case (loop height) and capital letters (letter height). Scrambled letters below, familiar names, first observation above. From Forbes *et al.*, 1950.

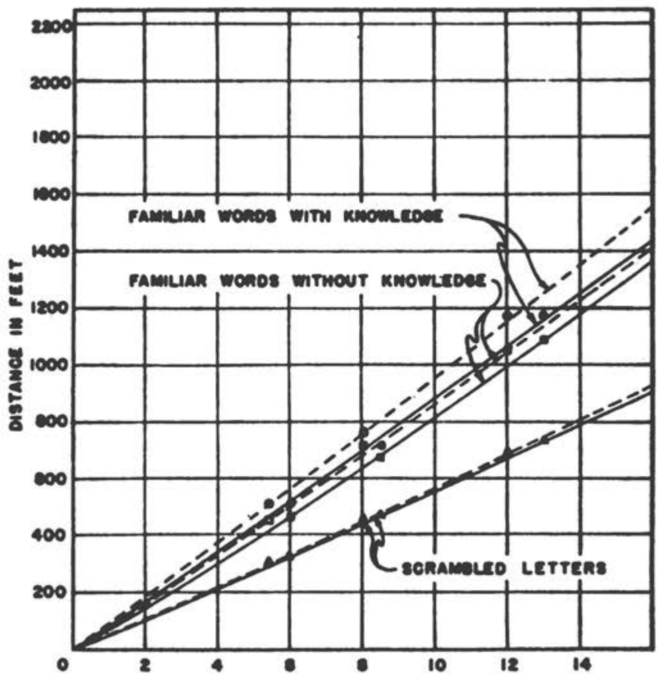

Figure 2—Effect of familiar names on lower case and capital letter legibility distance, daytime. From Forbes *et al.*, 1950.

alphabet was about three-quarters of the height of rising stems of the lower case letters. Each word began with a capital letter.

For the most effective design of signs, a larger vertical spacing between lines is required for capital letter signs compared to that for lower case signs.

Effect of brightness. The preceding two studies by Forbes and others used floodlighted signs and, therefore, constant brightness. Several other studies reported an increase of legibility distance with sign-brightness.

An increase from 50 to about 90 ft/in. of letter height was reported by Allen and Straub (1955) for wide Series F letters using three-letter familiar syllables. Luminances varied from 0.1 to 100 ftL in these laboratory tests. However, preliminary tests of 7 in. Series C letters under headlights showed increasing high beam legibility distances of only 30 to 40 ft/in. from 1.0 to 300 ftL.

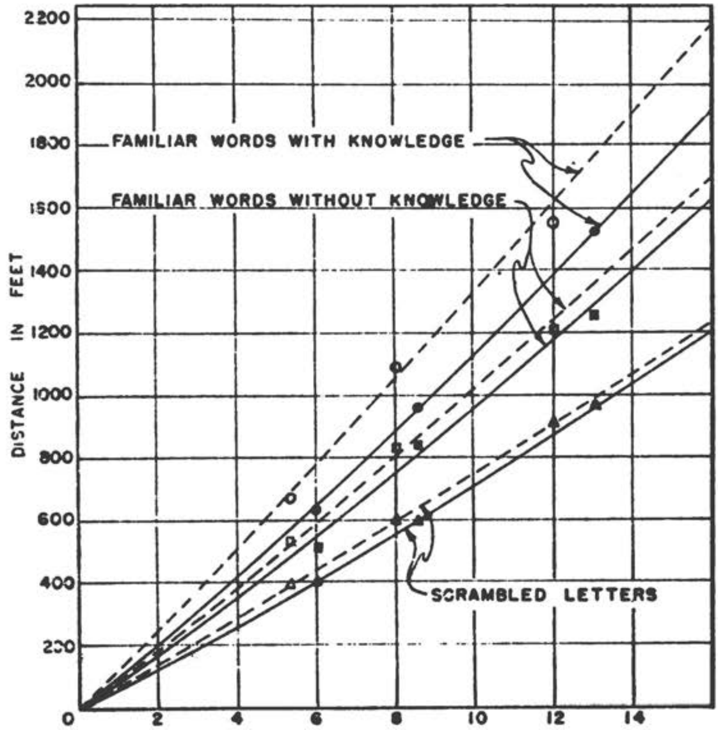

Figure 3—Effect of familiar names on lower case and capital letter legibility distance, night observations. From Forbes *et al.,* 1950.

An even greater range of legibility distances was reported by Allen *et al.* (1967) with internally illuminated bright-on-dark and dark-on-bright background signs using three-letter familiar syllables.

These were outdoor, full-scale observations using sign luminance values from 0.2 to 2000 ftL with and without headlight glare and in three different levels of ambient illumination. As would be expected, legibility distances were greatly affected by headlight glare and by ambient illumination. Here again, resulting legibility distances were generally from 40 to about 60 ft/in. of letter height in the range between 2 and 20 ftL but ranged from 12 to 65 ft/in. in glare and in high ambient illumination. From 10 to 100 ftL sign brightness for rural and for lighted areas respectively were recommended.

Comment. Allen *et al.* (1967) commented that the driver does not ordinarily observe a highly luminous sign continuously on his approach as did their subjects. This might have resulted in the high luminance values at which they obtained maximum legibility distance.

This author would also emphasize their comment that a large, very bright sign face will impair the driver's dark adaptation and his vision for low luminance objects on the road beyond the sign.

Need for contrast. The need for over 40 to 50% contrast for daytime luminance-levels and 50 to 60% contrast for nighttime luminance-levels is indicated in a study by Richards (1966). He was measuring ability to discriminate letters rather than sign legibility distances. He found a greater need for high contrast targets by older subjects.

Tradeoffs between letter height, width, and letter spacing. As seen above, increased letter height, width and letter spacing all give increased legibility distance. When either width or height available for a sign is limited, a different combination may be needed for maximum legibility. Solomon (1956) in outdoor measurements with 10 in. letters found that legibility distance increased up to a letter-spacing 40% above "normal" for both narrow and wide letter alphabets. He noted that, for an overhead sign with vertical distance limited but horizontal space available, a square letter with wide spacing may be advantageous. The reverse might be needed for a sign on the side of the road, of course.

Whether lower case or capital letters are more efficient for a given area of sign depends on combinations of letter size, width and spacing used (Forbes *et al.*, 1950; Christie and Rutley, 1961).

Glance legibility. When time to view signs is limited to a short glance of about one second, as in much seeing by drivers on the highway, the legibility distances are reduced by 10 or 15%, and about three to four short familiar words can be recognized. This was shown by Forbes (1939), and the limit for familiar words with about one-second exposure was confirmed in a study by Hurd (1946).

Thus, not more than three to four familiar words should be used on each sign at locations along a highway to require minimum reading by the motorist (Forbes, 1941).

Calculation of necessary letter sizes. A method for calculating required letter size for a given highway design speed and warning distance was suggested by Mitchell and Forbes (1942) in the United States and in England by Odescalchi *et al.* (1962) and Moore and Christie (1963). To accomplish this, time to read signs and warning time needed for stopping or other maneuvers must be known or assumed.

Mitchell and Forbes (1942) used a one-second glance for each three-word sign and a one-second safety factor. Average perception response time of 1.5 sec was assumed on the basis of previous experiments. Odescalchi (1962) measured "distraction time" for three, six, and nine name signs when a subject in a car interrupted an auxiliary task to find a given place name on a map sign. The subject "cancelled" four small lamps with one switch and pushed a button when he found the required place-name.

The results differed somewhat from the assumptions of the Mitchell and Forbes (1942) study but not to an unexpected degree, considering the variability of this type of measurement. Their equations were more complete in that they included distance of sign from driver's path. Either calculation can be applied to a given situation.

Legibility summary. It has been demonstrated that legibility distance increases with the various parameters of letter height, width, spacing, contrast, and brightness, but there are interaction effects. Familiar words are seen at longer distances. Scrambled letter determinations give better control of guessing, better reliability, and shorter distances, which are probably more representative of the 20/40 vision of many drivers. Relatively high sign luminance is needed against high ambient backgrounds but usually not for ordinary rural roads.

From the data available, sign design requirements for legibility can be predicted for a given combination of design speed and surrounding environmental requirements. Mitchell and Forbes (1942) and Odescalchi *et al.* (1962) have published methods of calculating needed sign letter size.

VISIBILITY FACTORS

In addition to being legible, a sign must be seen by the motorist to be effective. Thus, suprathreshold visibility factors contributing attention value of the type previously called "target value" are of great importance (Forbes, 1939). These become even more important as greater volume and speed of traffic is encountered.

Attention value analyzed. An early study (Forbes, 1939) analyzed "attention value" in "target value" * and "priority value" as noted previously. Subjects drove and called out signs on rural highways. Signs that contrasted with background terrain were seen at much greater distances than others, but no equipment was available to measure brightness and contrast of these high "target value" signs. At intersections, signs were called in obvious relation to (a) route sign being followed, (b) placement along the highway, and (c) reading order from top to bottom and left to right in multiple name signs. The effect of such factors was called "priority value."

* The author was indebted to Mr. Guy Kelcey for suggesting this term in discussion of sign characteristics. "Conspicuity" has been used by other investigators more recently.

Conspicuity of sign panels. Odescalchi (1960) had observers rate various sizes of white signs, seen against open field and shaded backgrounds, for "conspicuity" at 150 to 500 yd in a paired comparison presentation. He used different sizes of white panels to determine detectability while fixating a gray panel between them. Five colors were more effective the greater their luminance, with one reversal.

Effect of reflective sign background. A study of arrow signs with and without a reflective sign background (Powers, 1965) was inconclusive. It analyzed turn errors by a group of drivers following a route indicated by the experimental signs, but the number of drivers and erroneous turns was too small for reliable statistical evaluation.

Measurement of suprathreshold visibility or "attention value." This suprathreshold visibility or attention value of signs differs from the threshold of detection and is much more difficult to measure. Data on visibility factors in suprathreshold conditions, therefore, are needed, but relatively few studies have been conducted (Forbes *et al.,* 1965). A four-year study of such factors was recently reported (Forbes *et al.,* 1968).

Several methods of measurement were tried. The most satisfactory and consistent proved to be measuring the immediate subjective response of subjects in the laboratory when presented with a one-second view of four simulated signs while simultaneously carrying on an auxiliary task.

In a series of 14 experiments, from 19 to 25 subjects viewed different combinations of signs and backgrounds under day and night conditions. Simulation by means of projected highway scenes with colored slides in a completely dark laboratory allowed control of the important variables. Results from the laboratory experiment were checked by outdoor observations later.

Procedure. The subject was first adapted to a projected highway scene, then, at unpredictable intervals, simulated signs were superimposed for one second on the highway scene while the subject fixated on a matrix of small red lights in the foreground. One to four lights in this matrix were programmed to extinguish at random, and the subject had to relight them by pressing one of four buttons under his left hand. The subject responded with one of four buttons under his right hand to indicate his immediate, quick impression as to which of four signs was "seen first and best." A number of different highway backgrounds were used; they were typical of day, night, summer and winter backgrounds in different parts of the country. Most of the experiments used simulated signs approximating the interstate green, but one experiment used seven colors in pairs.

Rectangular simulated signs were cut from colored photographic material. Overlays of neutral film of different densities were used to obtain brightness differences. Colored slides were then made by placing the simulated signs on a colored print of the highway scene and photographing them in color. Considerable care was needed to obtain proper exposure for the most accurate color relationships both in making these slides and later in taking pictures of the outdoor signs used for day observations in the full-scale observations. Also, projection in a completely darkened laboratory was required to reproduce accurate color relationships. Luminance measurements were made from the projected pictures by means of a Pritchard-Spectra photometer.

Results of the Laboratory Study: Mathematical models based on certain assumptions were tested against the laboratory results. Showing the best fit was a model based on brightness ratios of sign-to-background and letter-to-sign that were additive. These were modified by a factor for relative legend area and relative size, and this modification resulted in Equation 1.

$$P = \frac{BR_{S_iB_i} + BR_{L_iS_i}}{\sum_{i}^{n}\left(BR_{SB} + BR_{LS}\right)} \times AR_{LS} \times SF \times 100, \qquad (1)$$

where

P = percent "seen first,"
B_B = background brightness,
B_{Si} and B_{Li} = sign and letter brightness respectively for sign i,
A_{Li} and A_{Si} = area of legend and of sign i,
A_{Si} and $A_{Si\text{-}1}$ = area of sign i and of next smallest sign i-1.

Brightness ratios:

$$BR_{SB} = \frac{B_S}{B_B} \text{ if } B_S > B_B$$

$$BR_{SB} = \frac{B_B}{B_S} \text{ if } B_B > B_S$$

$$BR_{LS} = \frac{B_L}{B_S}.$$

Legend-to-sign-area ratio:

$$AR_{LS} = \frac{A_{Li}}{A_{Si}} \text{ expressed as percent of largest ratio.}$$

Size factor:

$$SF_1 = \frac{A_{Si}}{A_{Si} + A_{Si-1}}$$

$$SF_2 = (1 - SF_1)\,\frac{A_{Si-1}}{A_{Si-1} + A_{Si-2}}.$$

The model giving second best fit for laboratory results used contrast rather than brightness ratio.

Sign-to-background percent contrast:

$$C_{SB} = \frac{B_S - B_B}{B_S} \times 100 \text{ if } B_S > B_B$$

$$C_{SB} = \frac{B_B - B_S}{B_B} \times 100 \text{ if } B_B > B_S.$$

Similarly, letter-to-sign percent contrast:

$$C_{LS} = \frac{B_L - B_S}{B_L} \times 100 \text{ or } \frac{B_S - B_L}{B_S} \times 100.$$

This second model was based on additive percent contrasts for sign-to-background and letter-to-sign, also modified by the relative legend area and relative size factors (Equation 2).

Then, percent "seen first":

$$P = \frac{C_{SiBi} + C_{LiSi}}{\sum_{i}^{n}\left(C_{SB} + C_{LS}\right)} \times AR_{LS} \times SF \times 100. \qquad (2)$$

Equation 2 reduces to Equation 3 for a single sign in which the legend usually covers about one-half of the area. This equation was used to calculate distances predicted for the outdoor observations, and these calculated distances were compared with the actual observations. As applied to outdoor results, the average distance seen was calculated by the following model:

$$D = \frac{C_{SB} + C_{LS}}{2} \times ER, \qquad (3)$$

where ER = expected recognition distance* (small dimension of sign in feet × 1200) or clear sight distance, whichever is smaller.

* Assuming twice legibility distance of 50 ft/in.

Mounting Position of Signs. In preliminary experiments, it was found that the sign placed over the highway was seen first more often than the sign placed beside the highway in the simulated sign presentations. To equalize the factor of mounting position, all presentations in the later experiments were in the over-the-highway position. These overhead positions were also balanced out from right to left in the experimental design.

This appears to disagree with results of Straub and Allen (1956) where mounting position 5 ft to the right and 8 ft above the pavement was indicated as most effective and the overhead position least effective. However, their conclusions were from brightness measurements with headlights based on luminance levels. With floodlighted signs, of course, both side-mounted and overhead signs would be approximately equal in brightness.

Essential Results of Experiments. Figures 4, 5 and 6 show the observed laboratory results for the green signs against different backgrounds and calculated values for the mathematical model giving the best fit. The fit is not exact but better for all the various conditions than any of the other models that was tried. Figure 7 shows calculated and observed values for the outdoor observations. The predictions calculated by means of Equation 3 were better for the night observations than for the day observations. This was probably due to greater variability of conditions during the day, such transient conditions as cloud shadows, for example. Since this variability would also influence measurements, it was necessary to freeze conditions by color photography. From a series of exposures the truest photographs of test sign locations were selected, and these were projected and measured by a Pritchard photometer. Night contrast factors were determined from reflective characteristics of sign materials and data published by Straub and Allen (1956) and by Powers (1965). On the whole, the calculated values were close enough to the observed values to indicate fair validity for the laboratory results. This percent contrast calculation method was suggested for estimating sign visibility against various backgrounds for traffic engineering purposes. Details can be found in Forbes *et al.* (1968).

Effectiveness of colored signs. The fourteenth experiment presented seven different colors of simulated signs against various backgrounds. Figure 8 shows that the paired comparison presentation gave visibility ratings clearly related to brightness of the sign colors. There was also, however, an effect of contrast with the background as shown by the individual curves. The luminance determination for red was probably low due to sensitivity characteristics of the photometer, it was later found.

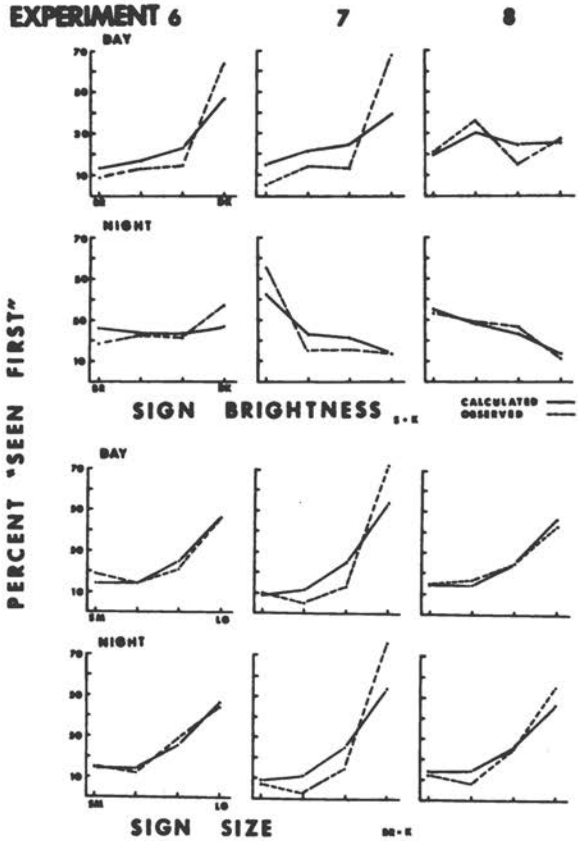

Figure 4—Visibility effects of brightness (upper) and size (lower) of simulated green signs, observed (dotted) and calculated values. (Day and night alternately from top). Experiments, 6, bright letters; 7, blank; 8, letter brightness reduced on darker signs. From Forbes *et al.*, 1968.

These results with colors are somewhat similar to those of Odescalchi (1960) mentioned earlier. He had observers rate color panels according to size adequate for visibility, and the panels were rated an approximately the same order as their luminance.

Brightness ratio and brightness level. Pain (1969), using Munsell gray chips of different value, analyzed brightness ratio and brightness level using both an eye movement camera and subjective responses. He also found the latter a more consistent measure and confirmed brightness ratio as a primary factor. Brightness level showed an interacting effect adding to the brightness ratio effect in the case of negative contrast.

Importance of Backgrounds. Hanson and Woltman (1967) reported the wide range of backgrounds against which highway signs are seen in different parts of the country. Dark green trees, bright sky and highway bridges furnished 23, 19 and 16% of the backgrounds. In winter, of course, snow backgrounds are common.

SUMMARY

Studies of sign legibility factors have indicated greater legibility for wide letters, stroke-width from 14 to 25% of letter height, wider letter spacing and brightness contrast in the range of 50% or better. Legibility distances for block letter signs under daylight conditions may be taken to be about 50 ft/in. of letter height. Under night conditions, legibility distances of

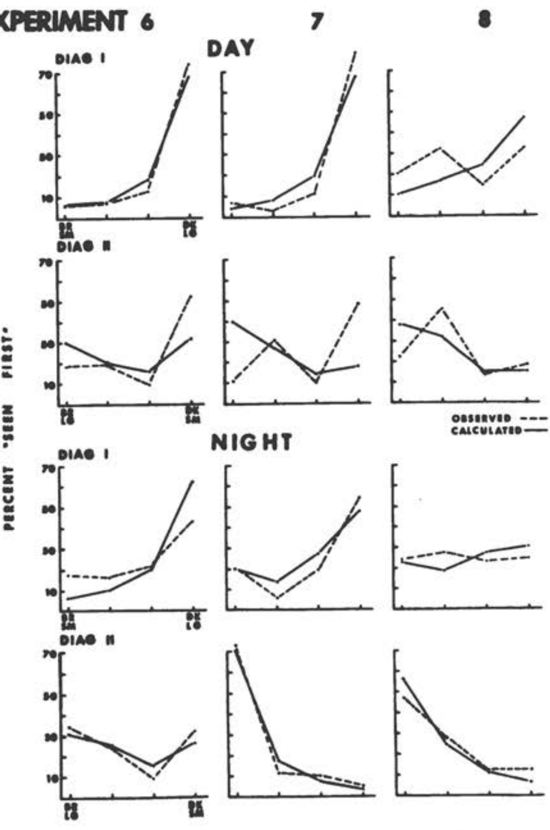

Figure 5—Visibility effects of size and brightness varied together (top) and oppositely (second row). Observed (dotted) and calculated. From Forbes *et al.*, 1968.

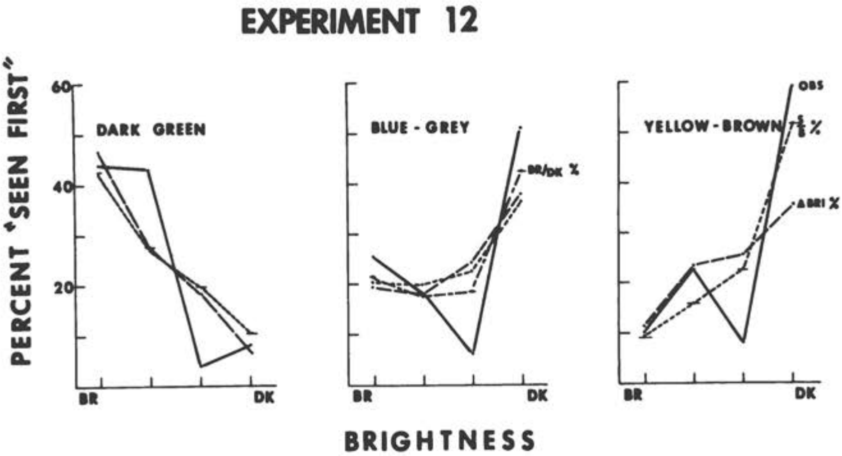

Figure 6—Visibility of green simulated signs seen against different colored backgrounds. Solid lines observed, broken lines calculated values.

33 ft/in. of letter height determined with scrambled letters and constant illumination represent a conservative value for estimation purposes.

Although *familiar* words gave 65 ft or more of legibility distance per inch of letter height in various studies, these longer distances should be discounted because of the effect of the familiar test words and better than normal vision of observers in most of the studies. Most state laws and regulations require drivers to pass visual tests for 20/40 vision only.

Methods of calculating sign letter size for certain speed and warning distance have been published. Legibility distance increases with letter height, letter width, and with brightness level up to a certain optimum brightness. It is reduced by glare and high ambient illumination from the surroundings. Therefore, an urban area may require higher brightness levels for signs than dark rural conditions. For high illumination, floodlighted signs may be needed, but, for most rural highway signing, brightness levels from reflective materials will produce sufficient legibility distance.

Attention-gaining visibility characteristics of highway signs at suprathreshold levels are important when highway signs compete with other signs and visual stimuli. A four-year laboratory study indicated that brightness ratio of sign-to-background and legend-to-sign were additive and, together with relative size, largely determined this type of attention-getting visibility characteristics. Average percent contrast was used to estimate outdoor visibility distances obtained in both night and day observations with sufficient accuracy for estimation purposes.

Other factors such as chromatic contrast and illumination-level should be studied for more refined evaluation of sign effectiveness. However, the sum of percent contrast of sign-to-background and letter-to-sign applied to the maximum expected visibility distance gave usable estimates.

EXPERIMENT 13

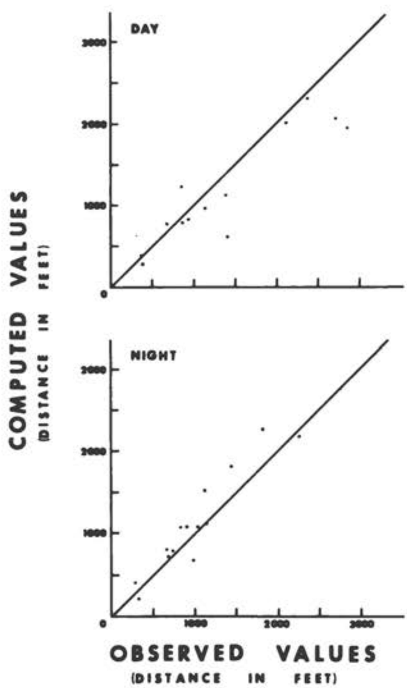

Figure 7—Outdoor observations and calculated distance values. Day (above) and night. From Forbes *et al.*, 1968.

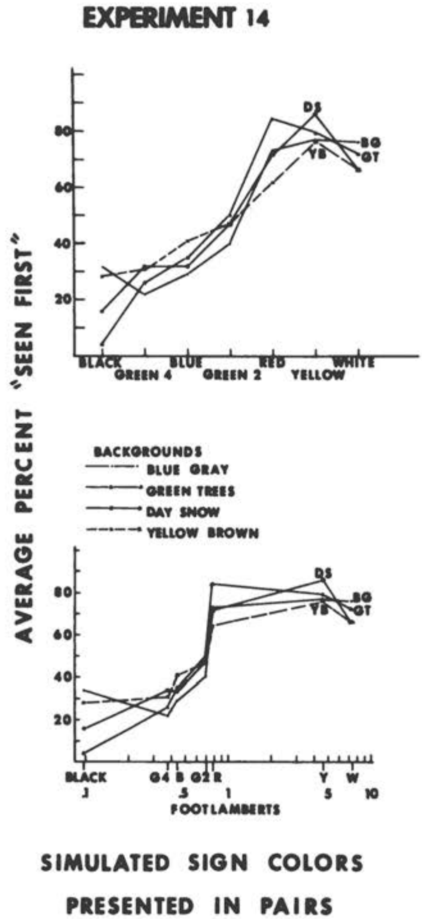

Figure 8—Colored simulated signs seen against four backgrounds. By colors (above) and brightness (below). From Forbes *et al.*, 1968.

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REQUIREMENTS FOR AUTOMOBILE EXTERIOR LIGHTING

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There are two fundamental requirements that vehicle exterior lighting must satisfy. The first of these involves the provision of adequate illumination for the driver at night so that he will be able to guide his vehicle and to see hazardous objects. The second is to provide illumination from the vehicle itself so that it will be seen and its driver's intentions become known to other drivers. These requirements mean that the vehicle must be equipped with headlights and a marking and signaling system.

Although trucks and multipurpose passenger vehicles are an important part of our highway traffic, I propose to deal mainly with passenger cars. It is probably safe to say that whatever recommendations may be made for passenger vehicles would apply to some extent to other classes of vehicles, except motorcycles and special purpose vehicles.

HEADLIGHTING

The present quad-lamp headlighting system was introduced in 1957 and provides some advantages over the previous sealed beam, two-lamp system. The SAE recommended practice J579a, revised in August of 1965, details the performance for sealed beam headlamps in the United States. The lower beam, which is provided by two type-2 units in the four-headlamp system, is designed as a meeting beam to provide a compromise between visibility and discomfort and disability glare, particularly on two-lane roads. The aim and candlepower distribution of such a beam is shown in Figure 1. As is well known to motorists through their driving experience, the lower beam is the one that is used most of the time (Hare and Hemion, 1969). For this reason, the low beam has to satisfy a great many diverse driving needs. The low beam is used in city streets and freeways, two-lane and multi-lane rural roads, and largely used on interstate and rural expressways. It is obvious that visibility requirements vary greatly under these diverse conditions.

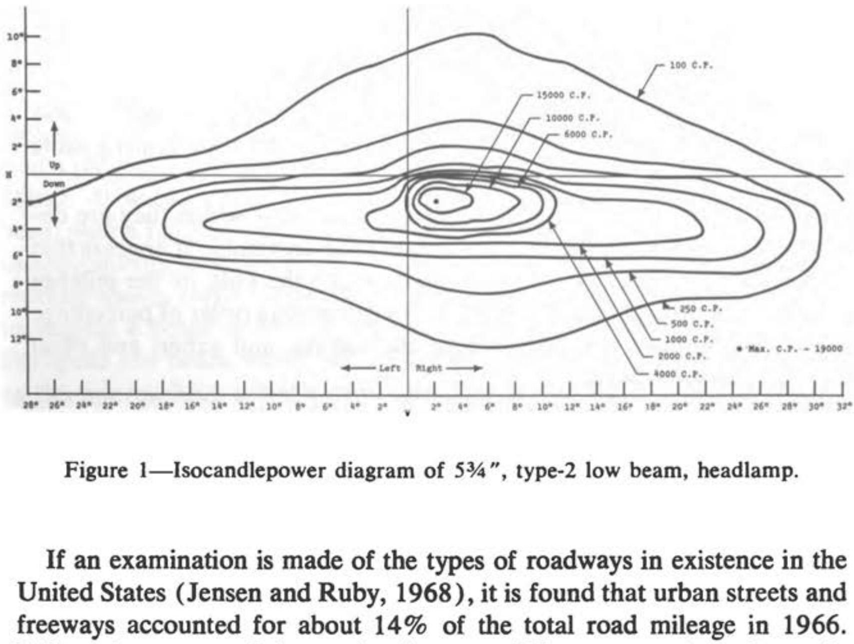

Figure 1—Isocandlepower diagram of 5¾", type-2 low beam, headlamp.

If an examination is made of the types of roadways in existence in the United States (Jensen and Ruby, 1968), it is found that urban streets and freeways accounted for about 14% of the total road mileage in 1966. Eighty-six percent of the road mileage could be accounted for by main and local rural roads (Bureau of Public Roads, 1966). Urban and rural freeways and interstates accounted for less than 1% of the total mileage (Table 1).

Although the bulk of the mileage is in a rural environment, it has been estimated (Bureau of Public Roads, 1967) that urban freeways are used for 8% and urban streets for 41% of the miles driven. Similarly, eventhough rural freeways are only a small fraction of the total mileage, they are used for a total of 9% of the total vehicle miles, whereas the local and main rural roads carried a disproportionately low 42% of the vehicle miles. Furthermore, in spite of the relatively low mileage available in the form of freeways or interstates, it has been projected that such roads will be used for about 28% of the miles to be driven by U.S. motorists in

TABLE 1. Percent Road Mileage and Use by Type and Location of Road—1966.

Location of Road	Type of Road	Existing Miles	Traveled Miles
Urban	Street	14	41
	Freeway	< 1	8
Rural	Main/Local	86	42
	Freeway	< 1	9

Total Miles: 3.7 million
Total Travel: 752 thousand

1975. An approximately equal proportion of the mileage (30%) will be driven on city streets and the remainder (42%) on rural roads (Table 2).

The geometry of such roadways and the speeds for which they are designed clearly influence the driver's visibility requirements. It appears that there are three classes of roadways upon which the bulk of the mileage will be driven through the next decade. In descending order of percentage of total miles, these are rural roads, city streets, and urban and rural freeways and interstates.

Bearing in mind this information, it seems that there may be a need for three distinct types of vehicle forward lighting to provide adequate visibility under each of these three major conditions.

City streets. The illumination required of the headlights in city driving depends on the ambient illumination-level provided by the fixed luminaire lighting system. Street lighting practice varies considerably, and this factor introduced additional difficulties into the specification of headlighting requirements for city use. In England vehicles use only parking lights when driving within city limits. Studies carried out by the Road Research Laboratory have indicated that the use of headlamps in cities provides no benefit in accident reduction when the fixed lighting is relatively good but did reduce accidents where street lighting was non-existent or of poor quality (Newby, 1963). The British feel that when

TABLE 2. Percent Road Use by Type—Projected 1975.

Type	Use
Freeway/Interstate	28
Urban Street	30
Rural Main/Local	42

street lighting is good the headlights do not add to visibility but are a source of glare, particularly in inclement weather. Under good street lighting the major requirement for vehicle lighting is to provide warning to pedestrians and other drivers of the presence of a vehicle. A recommendation was made by the Road Research Laboratory for a so-called "dim-dip" system which involves the use of the vehicle headlights at reduced intensity (Jehu, 1965).

Whether or not street lighting practice in the United States is as effective as that used in England is debatable, but lighting in the United States probably provides lower levels of illumination (Ministry of Transportation, 1967). For this reason the use of city driving lights that provide better visibility than those accepted in England may be required. Nonetheless, the British studies and practice do suggest a trend that could indicate a potential change in the performance of driving lights in the United States. It would appear desirable for a city driving light to provide a beam with a fairly sharp vertical cutoff so as to considerably reduce glare to approaching drivers while providing forward visibility adequate for the reduced speeds used on city streets. In many respects it may be desirable to suggest a beam similar to that which was used until recently as the European low beam, which had a flat top and thus cast little light as high as the approaching driver's eyes. Because of the large angles that are used in maneuvering vehicles in city driving, the possible approach angle of headlights in these conditions is large, and, for this reason, the only way to reduce glare is to ensure that high intensity portions of the beam are kept below the driver's eyes. This has the disadvantage of making it more difficult to read route signs and street names.

Rural roads. Rural main and local road driving is done at night without fixed luminaire illumination and at higher speeds than on city streets. Opportunities to use the high beam are probably greatest on this class of roads since they account for the largest proportion of the road mileage and carry the least amount of traffic per mile. On the other hand, when meeting approaching cars, the situation is probably more critical than that found in other driving conditions because of the small lateral separations between the vehicles. The design of the meeting beam to provide adequate driver visibility at posted speeds of 50-60 mph provides a real problem for lighting engineers. The present low beam system provides a sight distance of about 400 ft when there is no other car approaching. This may be reduced to about 150-300 ft in a dry road meeting due to the glare from the approaching vehicle's headllights. If it is considered that a distance of over 300 ft is required to stop a car from 50 mph (AASHO, 1965), it would seem that the visibility distance provided by the present meeting beam is inadequate. Obviously there are many factors that interact to affect visibility, such as, the transmission of the atmosphere, the reflectance of the roadway, the road delineation, and many driver and vehicle factors.

The SAE recommended practice J579a, which is used in Federal Motor Vehicle Safety Standard No. 108 issued by the Department of Transportation in January 1969, specifies that the maximum intensity to be found at the test point located half a degree down and two degrees to the right (1/2 D-2R) from the longitudinal axis of the lamp is 15,000 cp. The fact that what was formerly a recommended practice has now been incorporated into a federal standard could lead to a restriction on headlighting design. It is obvious that additional visibility is needed in a two-lane highway meeting, and one way to attain this is to increase candlepower, thereby increasing illumination down the road. For this reason, it may be found desirable to increase the maximum candlepower permitted at the critical 1/2 D-2R point. In fact, some data (Roper and Meese, 1964)have shown that on a straight, two-lane road a lamp that projected 20,000 cp at this point was capable of increasing visibility compared to lamps that projected 6,000 and 10,000 cp as shown in Figure 2. These results also held for meetings on a curved road. The data were obtained using 16 in. square targets having a reflectance of 7% placed at the right edge of the road. Not surprisingly, visibility increased as the candlepower aimed toward the targets was increased, although there was also some increase in the glare.

Other data for a specific headlight system (Roper and Meese, 1952) indicate that there is a logarithmic relation between glare illumination from approaching headlights and the concomitant visibility distance. Figure 3 shows that low levels of glare illumination have a relatively large

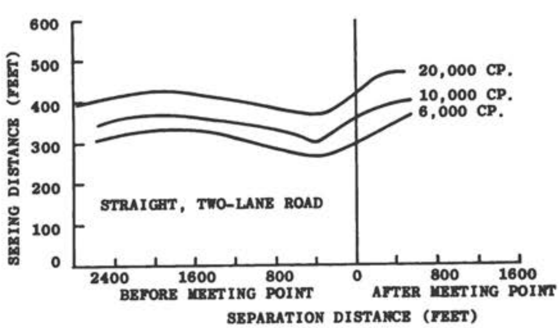

Figure 2—Visibility distance in a two-lane road meeting as a function of candlepower at ½°D-2°R. (Data from Roper and Meese, 1964.)

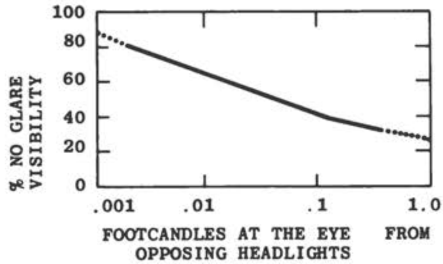

Figure 3—The effect of glaring illuminance upon visibility. (Data from Roper and Meese, 1952.)

adverse effect on visibility compared to succeeding increases in glare illumination. This is shown by the linearity of the function. These data and those reported elsewhere (Road Research Laboratory, 1963) indicate that if low levels of glare cannot be avoided, as is the case with present systems, then advantages should accrue from increasing illuminating intensities even if accompanied by proportional increases in glaring intensities. However, it should be possible in practice to obtain greater increments in illuminating intensity than glaring intensity values in many road conditions so that considerable improvements in visibility should result. The data shown in Figure 2 attest to this fact, as do other data (Meese, 1966), including those obtained by simulation procedures (Mortimer, 1965). There is, however, one important caution that should be added; the previously mentioned data were collected under good atmospheric conditions. It would be dangerous to generalize these findings to inclement weather, particularly rain, which will reduce the amount of light returned from the road and also cause potentially large increases in discomfort and disability glare by the light-scattering action of water on the windshield.

It would appear, therefore, that for rural roads a beam could be added to the presently used low beam to provide a much higher intensity toward the right edge of the roadway, which is an important stimulus for tracking the roadway (Gordon, 1966). This beam would be aimed about 400 ft ahead of the vehicle and could result in substantial increases in visibility.

In order to test this hypothesis as well as to obtain better insight regarding improved methods of evaluating headlamp beams, a spot lamp was added to the low beam system. The aim and beam distribution of this lamp are shown in Figure 4, which indicates a very high concentration of light centered at the 1/2 D-4R point on the aiming chart. An initial test was carried out to determine whether a beam configuration of this type added to the present low beam would cause undue glare to approach-

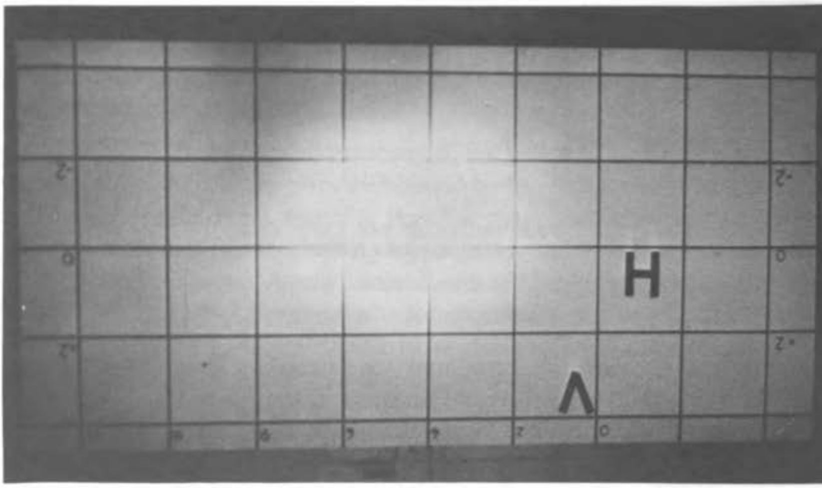

Figure 4—Aim and light distribution of the spot-lamp beam.

ing drivers. The tests were run on a two-lane road that had no street lighting. The road was curved and quite undulating. Measurements were taken of the number of vehicles that passed in the opposite lane and the frequency with which they indicated discomfort glare by flashing their headlamps. It was found that in 400 meetings with approaching traffic only one car flashed its headlights when the spot lamp was in use with the low beams, whereas 15% of 40 vehicles flashed their lights when the high beams were used. This method would appear to be quite effective and safe to use for evaluation of beam configurations to determine glare acceptability under actual driving conditions. It would appear that the configuration used, with some modification, such as by a reduction in the intensities that are found above the horizontal, could produce an acceptable beam pattern. An attempt was made to show the visibility given by the low beam and the low beam augmented by the spot lamp in Figures 5 and 6. It would be desirable to obtain data indicating visibility distance in simulated meetings using a method such as that proposed by Roper and Meese (1964). The results are shown here to indicate a tentative method and potential benefits that could accrue from increasing illumination with relatively small increases in glare.

Probably more satisfactory would be an adaptive headlighting system that can take account of the location of approaching vehicles and adjust the beam pattern accordingly to maintain glaring intensities at acceptable levels while still providing good roadway illumination. A system that may have this capability is under development by Joseph Lucas Industries

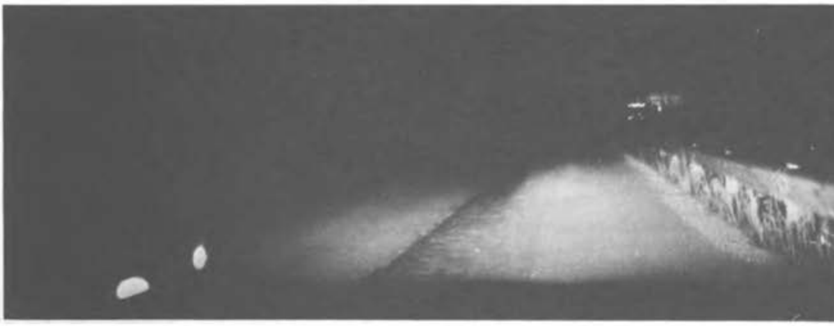

Figure 5—Visibility along an expressway shoulder with low beams.

in England. The operation of the Lucas "Autosensa" driving lamp is shown in Figure 7 (SAE, 1969).

Freeways and interstate highways. Interstate roads and roads that have substantial medians are carrying an increasing amount of traffic. In addition, the speed limit on these types of highways is generally not less than 65 mph, and for this reason minimum visibility distances of the order of 500 ft should be provided. The principal requirement is that the beam should adequately illuminate the lane on which the vehicle is traveling and the right edge of the highway. This can be accomplished by a high intensity beam aimed so that its sharp vertical cutoff is at about the horizontal axis of the lamp and with a sharp horizontal cut-off close to the vertical line. This will insure that glaring intensities caused by light thrown to the left of the traveled lane are low and that a swath of light is provided along the traveled lane and to the right. Light above the horizontal should also be minimized to reduce the possibility of light entering the eyes of approaching drivers on curves as well as to reduce back lighting of rear view mirrors of vehicles being followed.

Figure 6—Visibility with low beams and spot-lamp.

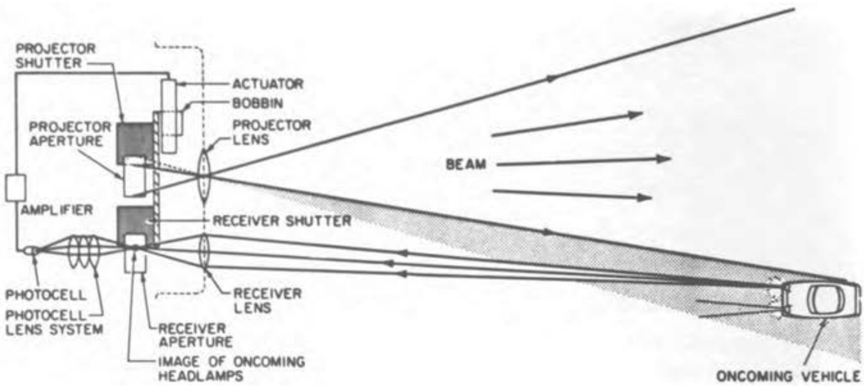

Figure 7—The Lucas "Autosensa" headlamp. (Reproduced from the SAE Journal, Feb. 1969 by permission of the Editor, Joseph Lucas (Electrical) Ltd., and Mr. M. Platt (London).

Experiments have shown that the use of the present high beam system on divided highways in clear weather conditions leads to improvements in visibility (Webster and Yeatman, 1968). While this is undoubtedly true, it would appear that discomfort glare and possibly also disability glare could be substantial unless the medians are quite wide. For this reason, special lighting devices are needed and have been developed for use on divided highways where the medians are of moderate size. A recent study reported by Meese (1966), in which he evaluated a prototype turnpike beam, showed that visibility could be increased by about 50% compared to the low beam system. It is of interest to note that a turnpike beam is available as an optional extra on at least one 1969 automobile. The beam pattern and aim of this lamp are shown in Figure 8 and the candlepower distribution curves in Figure 9.

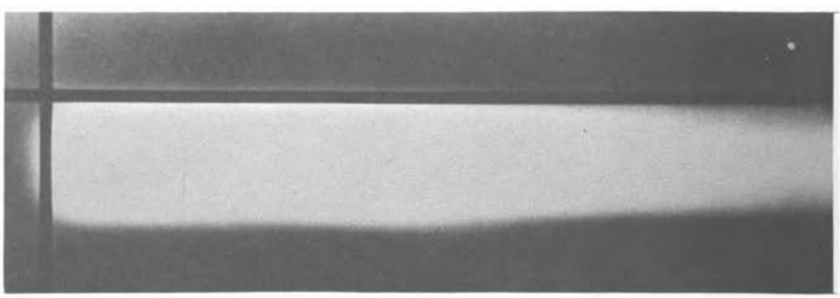

Figure 8—Aim and light distribution of the Super-Lite beam. (Photograph reproduced from Dodge Public Relations brochure "Super-Lite," by permission.)

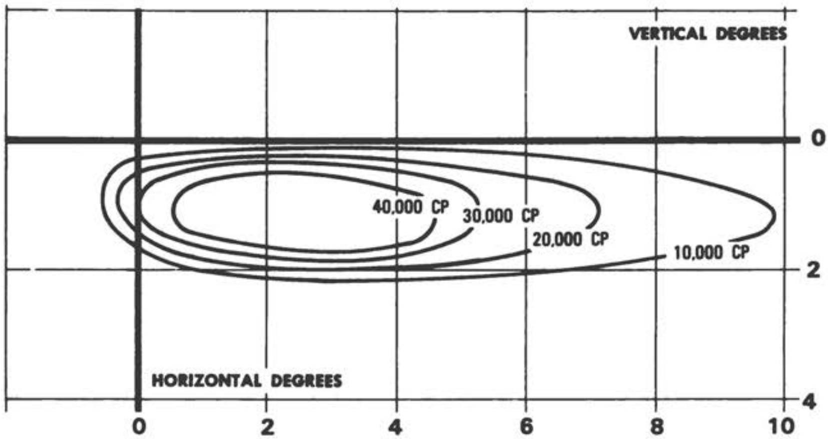

Figure 9—Candlepower distribution of the Super-Lite beam. (Reproduced from Dodge Public Relations brochure "Super-Lite," by permission.)

Developments in light sources and headlight aiming. New light sources that can provide high intensity illumination with relatively low current consumption, such as quartz-halogen bulbs, are of considerable interest. They are coming into extensive use in European lighting systems and form a component of the turnpike beam developed by Chrysler Corporation and Sylvania Electric Products, Inc. Quartz-halogen bulbs are a particularly important development for European headlamp designers. Because of their desire to achieve a meeting beam having a sharp vertical cut-off, they throw away about half the light that is produced by their bulbs. Previously this has resulted in lamps providing considerably lower intensities than comparable United States or British sealed beam units, and, in general, visibility has not been as good. The use of new high intensity sources should remedy this situation and provide improvements in visibility for the European systems.

A major problem associated with conventional lighting systems is the mis-aim that is frequently found in the vehicle population, for headlamp mis-aim increases glare and reduces visibility. Developments have been reported recently for on-board headlamp aiming systems (Oyler *et al.*, 1968), and systems manually adjusted from the driver's seat are presently available on at least two French vehicles. Citroën cars have already introduced an automatic load compensating system. In this respect some developments by Bendix (France) of a relatively inexpensive headlamp leveling system could have an important impact upon improvement in vehicle headlighting aim (SAE, 1969).

Polarized headlighting. Since Land (1948) introduced the idea of polarization as a method for eliminating headlight glare, the approach has had continuing appeal to headlighting engineers. No completely successful application has yet been developed, but, recently, increasing emphasis has been given to polarization by headlighting research workers. These studies (Hemion, 1969; Webster and Yeatman, 1968; Johansson and Rumar, 1968) have all reported distinct improvements over the present system in visibility under most test conditions when polarization headlighting systems were used. There does not appear, at the present time, to be an entirely satisfactory way in which a polarized system could be introduced into existing vehicles, nor could new vehicles with a polarized system be introduced without putting either drivers of the existing vehicles or drivers of the newly introduced vehicles at a disadvantage. Additional research is required, in any event, to consider the effects of depolarization under various weather conditions, effects upon pedestrians and other road users not using the polarized analyzers, the effect of headlight reflection by rear view mirrors, the effect of analyzers upon the visibility of vehicle rear lighting systems and other related effects. Further research in this area is needed to evolve a practical and economically feasible system. There is little doubt that with further effort this can be achieved because some of the problems that plagued the concept twenty years ago no longer exist. Whether the best overall systems payoff will come from the use of a polarized headlighting system or from improvements in the design of conventional lighting systems is not clear at this time. Additional study of both types of improvement is needed.

Deriving a visibility transfer function. There has been a great deal of field and simulation testing in which aspects of vehicle headlighting performance have been investigated to determine the requirements for headlights. In view of the extent of the work that has been done and that is undoubtedly still required to be carried out before significant improvements in vehicle forward lighting will be achieved, it appears timely to consider the possibility of carrying out much of this work on an analytical basis. It seems entirely reasonable to suppose that, with our present knowledge of human visual functions, a computer simulation of nighttime meetings could be carried out. A start on this type of activity was made by Jehu (1955), who was able to derive visibility curves as a function of the separation distances between vehicles, the beam patterns that were used, and the characteristics of the target, including its location. Jehu utilized the Stiles and Holladay equation that predicts the effect of a glare source from values of the glaring intensities and their location relative to the fixation point of the eye (Stiles, 1929; Holladay, 1927). Since that time additional work concerned with the effects of glare have been carried out by Hartmann (1963), Fry (1964), Schober (1965), and Adrian (1968) so that further useful information is available.

Table 3 shows the major elements that would enter into the model used to compute an index of visibility. The main factors are those relating to the driver's vision; the characteristics of the lamp or lamps that are used; the area, reflectance, location, and background contrast of the target; the environment; vehicle factors, which include the location of the lighting systems as well as their type; and roadway factors that affect visibility.

The model used by Jehu is not able to predict visibility adequately after the vehicles have passed each other at the meeting point. This is because this formulation takes no account of changes in visual adaptation during and following the meeting. In view of the fact that his quite simple model appears to have been reasonably well confirmed by field tests, there is every reason to suppose that further effort in this direction could be successful in developing a more sophisticated transfer function that would be able to characterize more of the factors associated with night driving visibility and the role of the lighting system.

Obviously, the development of such a model could substantially reduce the time needed to develop improved forward lighting systems and ultimately permit developments to be made with much greater economy. It should be noted that the model itself could be used to provide the best compromise for lamp performance to maximize visibility in night driving conditions.

TABLE 3. Elements of the Headlight-Driver Visibility Model.

Driver Factors	*Lamp Factors*	*Target Factors*
Adaptation level	Beam distribution	Area
Visual acuity	Intensity	Reflectance
Contrast sensitivity		Location
Readaptation rate		Background
Seated eye height		
Environment Factors	*Vehicle Factors*	*Road Factors*
Clear	Lamp location	Reflectance
Fog	Number of lamps	(dry, wet)
Ambient illumination	Windshield transmittance	Geometry
	Analyzer transmittance	Median width
	H-Point height	
	Inter-car separate distance	
	Opposing vehicle density	
	Velocity	

VEHICLE MARKING AND SIGNALING

The purpose of vehicle marking is to provide an indication of the presence of the vehicle, its location on the roadway, and its orientation. With the recent introduction of side marker lights, vehicles are now visible from any angle at night. Headlights adequately delineate an approaching vehicle, whereas the red rear lights clearly indicate the back of a vehicle because the intensities are different and red is not easily confused with white (Holmes, 1941; Hill, 1947). The ability to identify the orientation of the vehicle in the daytime may not be as simple as at night. For this reason and to make the vehicle more conspicuous, it has been proposed from time to time (Allen and Clark, 1964) that running lights should be used at the front of the vehicle. Evaluations of the use of headlights or running lights with regard to accident reduction in daytime have not found significant beneficial effects (Allen and Clark, 1964). However, a recent study (Cantilli, 1969) carried out by the Port of New York Authority suggested that there were reductions in the number and severity of accidents associated with vehicles that were driven during the daytime with parking lights turned on. In addition, rear-end accidents were reduced in frequency and severity. It might be interesting to determine if the difference in accidents occurred during the hours of dawn and dusk since under normal, bright day conditions the parking and taillight intensities are not sufficiently great to be adequately visible.

Most United States manufacturers have now adopted the principle that parking lights should be turned on with the headlights. This enables the full width of the vehicle to be seen in the event that one of the low beam headlamps is burnt out. Therefore, there is now a fail-safe forward marking indication for the "one-eyed" car, which poses a definite hazard on two-lane highways. It might be recommended, however, that front parking lights be white rather than amber in order to provide uniformity in coding, namely, that white indicate the front of a vehicle. The combination of parking lights with the front turn signals has also undoubtedly resulted in some reduction in the effectiveness of the front turn signals at night. It may be noted that certain European cars separate the front parking-lights, which are white, from the amber front turn signals. In the case of the front parking and signaling system, the parking lights and separated amber turn signals would require little physical separation in order to retain turn signal effectiveness because of their intensity and color differences. Front turn signals should be located away from the bumper and the headlamp. If this is not feasible, then a location closer to the headlamp is preferred for an amber signal (Mortimer and Olson, 1966).

There has been an increased amount of research in rear lighting of automobiles during the last few years. This work is concerned with the nature of the messages that should be transmitted as well as determining means for coding them. For example, utilizing a stream of vehicles equipped with deceleration (coasting)signals in actual driving conditions, the effectiveness of this signal was subjectively evaluated and found to be undesirable (Connolly, 1962). Experiments have been conducted to evaluate the effect of providing drivers with signals for acceleration/deceleration or a combination of headway and relative velocity information (Rockwell and Banasik, 1967) and have shown that these kinds of information can be utilized by drivers in maintaining constant headways. Other data have suggested that a form of velocity display provided useful information in car-following (Nickerson *et al.,* 1968).

It would appear that an appraisal of accident records, as well as a closer look at the nature of the driving task, may assist in determining the requirements for the message content of rear lighting systems.

Before doing this, it is worth noting that there is little information to indicate that the rear lighting system is important in reducing accidents. In one study carried out in Great Britain comparing frequency of rear-end accidents of post World War II vehicles with pre-war cars, which had lower intensity taillighting, it was found that the post-war vehicles were relatively underinvolved. Many British pre-war and post-war automobiles only had one taillight, which gave the driver a poor cue to use in making judgments of headway. By increasing taillight intensity and placing one taillight at each side of the car, rear-end accidents were reduced (Moore and Ruffel Smith, 1966). Recently the HSRI accident data file was searched for rear-end accidents in Ann Arbor incurred by one group of vehicles that were known to have had problems with the brake light switch. The analysis tended to show that these vehicles were overinvolved in being struck in the rear compared to other accidents. While this initial analysis is based on a small sample of accidents, the data give an indication that brake lights do provide useful information to drivers. Therefore, if stop and other important signals could be shown in a more effective manner so that following drivers become readily aware of them and their meaning, rear-end-type accidents could be reduced.

At least two studies (Solomon, 1964; Munden, 1967) have found that there is a U-shaped relationship between the probability of accidents and the speed of vehicles. In other words, vehicles that are traveling either considerably slower or faster than the average are more likely to have an accident. Figure 10, which is based upon Solomon's data, shows that when the deviation from the average speed exceeds 20 mph the relative

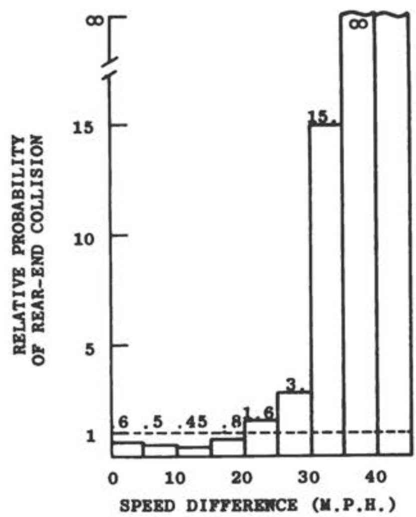

Figure 10—The effect of relative velocity upon rear-end collision probability.

rear-end accident probability becomes almost infinitely large. These data serve to support the suggestion that a rear lighting system should augment the driver's ability to perceive relative velocity. This information, combined with knowledge of the headway between his car and the one ahead and the speed at which he is traveling, would aid a driver to avoid a rear-end collision. Drivers are provided with speed information and can directly estimate headway from the visual cues of the rear of the vehicle ahead in the day or the taillights at night. Relative velocity information is not directly available but is derived from changes in the headway.

Although it is not possible to display relative velocity without intermediate electronic sensors, knowledge of the speed of the car being followed could give the driver the necessary information. This information could be visually displayed in a number of ways, and research is required to determine adequate methods. However, it is likely that a discrete form of speed display would be desirable and adequate rather than a continuous format. In this way a configuration of lights could be used to indicate a certain speed range. It is probable that a maximum of four such ranges would be required, including the stopped-vehicle condition. A hypothetical arrangement is shown in Figure 11.

In order to improve the detectability of signals that are given from the rear lighting system of automobiles, various coding techniques have been evaluated.

In these tests, consideration has been given to variations in the num-

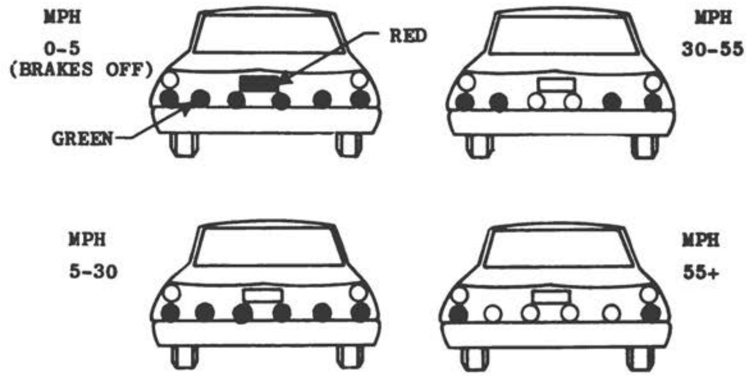

Figure 11—Hypothetical rear lighting velocity display.

ber of lights, functional separation of lamps, and the use of color as codes, in addition to flashing and intensity changes that are used in the present rear lighting system. The studies have shown that when lamps are separated according to function the attention-getting quality of signals is improved. Figure 12 shows three of the lighting systems that were evaluated in a static simulation. In these tests (Mortimer, 1969b) the reaction

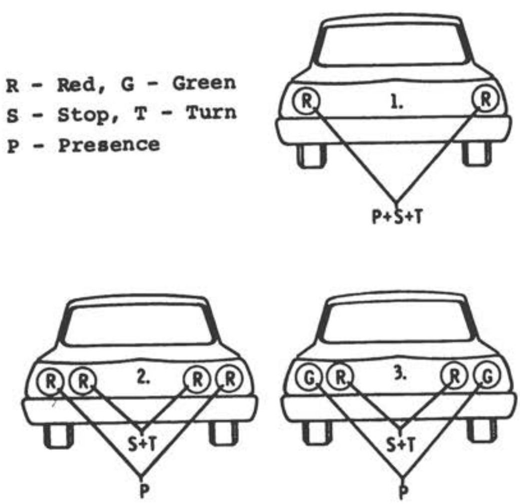

Figure 12—Three rear lighting arrangements.

times of observers, who carried out a time-shared signal detection task, to stop and turn signals given by these lighting configurations were measured. It was found (Figure 13) that when signal lights were separated from taillights there was an improvement in performance and this improvement increased when the taillights were of a different color (green-blue) from the signal lights (red). Studies carried out at The University of Michigan in which vehicles were driven both on city streets and on an expressway have supported the static simulation findings by showing that when taillights, turn signals, and stop lights are given by different lamps that are physically separated from each other and when they are each color coded, maximum reduction in driver response time was obtained (Mortimer, 1969a). It should also be noted that the performance of the system that represented current practice was generally poorest compared to experimental rear lighting configurations.

At the present time we are continuing our research in rear lighting systems. In one study, we are concerned with finding the location that will

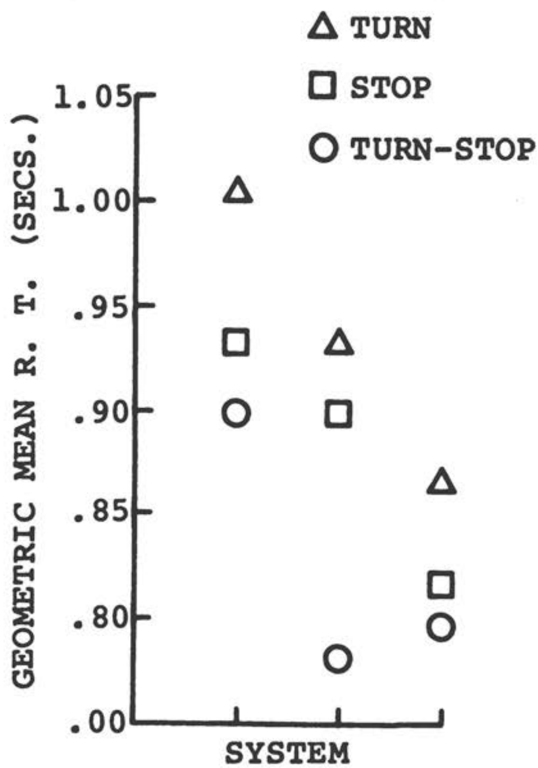

Figure 13—Mean reaction time to three signal modes.

maximize the visibility of rear turn signals to following drivers. The analysis has tentatively revealed that a repeater signal should be mounted as far forward on the vehicle as possible at a minimum height of about 33 inches. The photometric requirements for such a signal are currently being determined in psychophysical tests. A signal of this type may assist in avoiding side-swipe accidents resulting from changing lanes. There may be other benefits that could accrue to drivers from being able to see the repeater light mounted forward on the vehicle since it could provide them with better feedback of the operation of their turn signals and should result in a reduction in the frequency with which the signals are inadvertently left on.

Other work is continuing at Highway Safety Research Institute with the evaluation of various taillighting configurations to provide information of relative velocity and closure with a leading vehicle. Simulation is one technique being used in these evaluations. Results to date have indicated that an array of four lights, one at each corner of a square as shown in Figure 14, may provide a reduction in threshold of closure compared to a two-light horizontal array. The threshold to detect a change in headway was greatest for the single light, as would be expected (Parker *et al.,* 1964).

We are carrying out additional work concerned with the intensity requirements of marker and signal lights to take into account changes in the ambient illumination from night to day and the intensity requirements for visibility in fog. Finch (1968) has recommended intensity ratios of 1:10:100 in these conditions. It is certainly true that large increases in intensity are required in order to provide marking of the vehicle in fog (Moore and Ruffel Smith, 1966; Finch, 1968), but there is relatively little difference in the visibility of red and green-blue lights (Mortimer, 1969b), as shown in Figure 15. Other studies are concerned with the evaluation of a deceleration (coasting) signal, signal lamp location, and the information requirements of rear lighting systems.

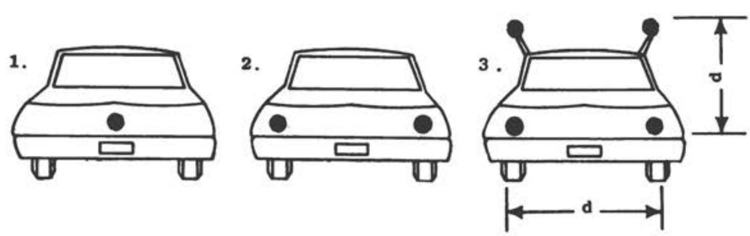

Figure 14—The taillight arrays evaluated for closure threshold.

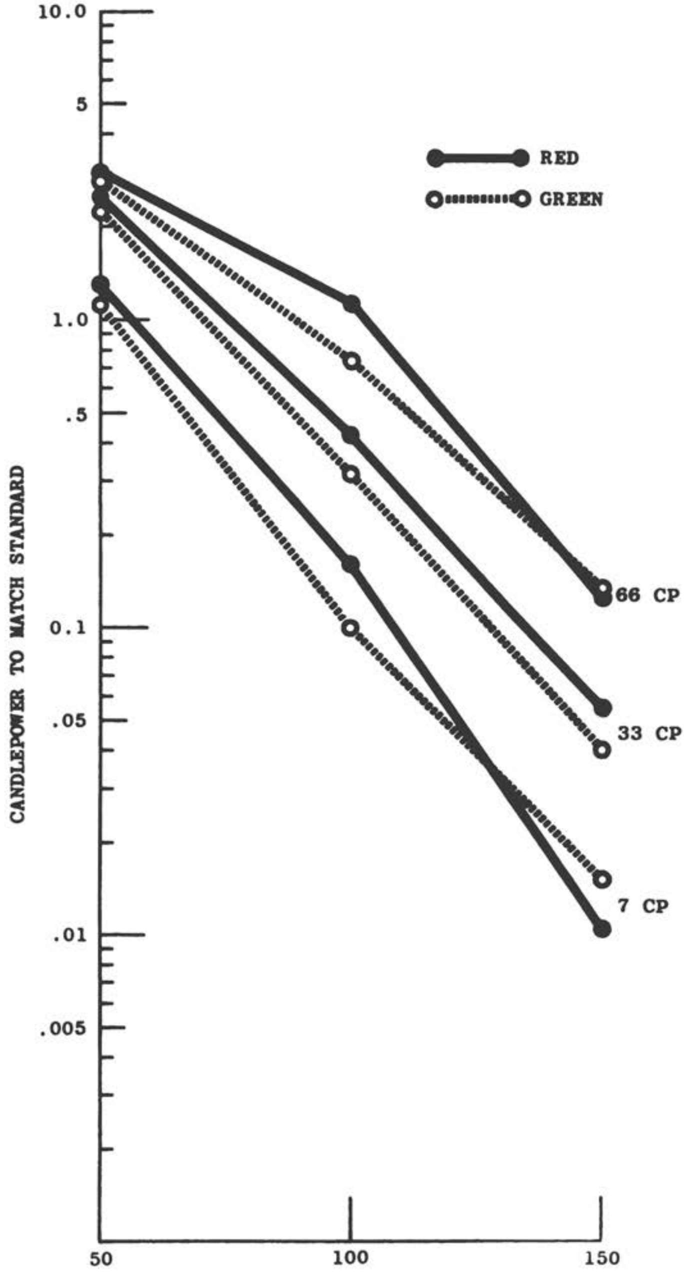

Figure 15—Perceived intensities of red and green-blue lights at three distances in a 200′ night fog.

CONCLUSIONS

On the basis of the foregoing analysis and the research and development work that has been carried out over the last 60 years, it is clear that many advances in forward and rear lighting systems have been made and that further improvements are needed.

Forward lighting systems could benefit from changes in beam configurations specifically designed to meet the performance requirements of the driving conditions that are now encountered and that will characterize roadways of the future. The development of more efficient light sources, adaptive lighting systems, better manual or automatic headlamp aiming, as well as renewed interest in polarized headlighting suggest that improvements in forward lighting can be expected.

At the same time progressive changes have been made by vehicle and lighting equipment manufacturers to provide more effective marking combined with improved reliability and fail-safe features. Nonetheless, improvements in the performance of the rear signaling system of vehicles is entirely feasible by taking more account of the driver's visual and perceptual characteristics, and these improvements can be achieved by separation of the functions of lamps as well as by the use of other coding techniques, such as color. Present indications are that a change from red taillights to green-blue could be beneficial when a number of problems associated with green-blue taillights have been resolved. Included among these problems is choosing a green-blue filter to give color recognition to dichromats by the addition of sufficient blue to the green taillight and the addition of more yellow to the present red signal light. It is anticipated that color coding would result in a real benefit to color-blind drivers, not just color normals. Our research program is concerned with this question. An improved marking and signaling system will require differential intensities for day, night, and fog conditions. We are studying these requirements, but it seems probable that at least 200 cp in daytime and about 70 cp at night are adequate for signal lights depending upon system coding, e.g., functional separation. Higher values would be needed in day or night fog. Separation of signal lights from taillights, besides improving driver response, could have particular advantages in fog conditions by providing increased versatility in the design of the rear lighting system to meet performance requirements. Further research is required to define the information content of rear lighting systems and to ensure that introduction of new systems would be compatible with those presently in existence.

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FACTORS IN HIGHWAY LIGHTING

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The basis for highway lighting has been changing recently and, I hope, changing for the better. There are now Federal legislative requirements relating to highway safety, and the concept of highway safety has been expanded to include, among other things, standards for highway lighting. So now there is the possibility of taking a good hard look at highway lighting to see if something better than current practice—the techniques that have evolved over the past 35-40 years—can be used as a standard.

Justification for present work is largely safety, but there are other benefits that must also be considered, for example, driver orientation and guidance, the general traffic control problem, driver comfort and convenience, increased operating efficiency of the entire highway system, better enforcement of regulations, and the rather difficult but important aspects of aesthetics. Lighting is installed, of course, to provide better seeing conditions, and some light is usually better than no light. It has generally been assumed that the amount of light incident on a surface will give a measure of performance of a lighting system, but this does not take into account the type of highway or the condition of the highway that the light is falling on. This has been the technique that has been applied and is the current basis for specification of lighting. I submit that it is not adequate.

The current highway system has, however, developed over a fairly long period of time, and, by practice and experience, schemes have evolved that are reasonably acceptable. The range of improvements in the efficiency of lighting units has been substantial, and, as a result, the technical and economic limitations are not nearly as severe as they once were.

What are the warrants for lighting? Presently, the Highway Research Board, sponsored by the National Cooperative Highway Research Program has requested proposals to determine warrants for highway lighting. Why do we need such warrants? Is it not obvious that certain things need to be lighted? One would think so, but when you examine the situation, you find that this is not the case. For example, the American Association of State Highway Officials has a roadway lighting guide that is used by administrators nationwide to determine warranting conditions. In the case of freeways, these warranting conditions say something like this: If someone has already installed lighting somewhere in the area, then it is all right to put lighting on the freeway. Other statements are similar and equally vague. For example, continuous freeway lighting is considered to be warranted when local governmental agencies find sufficient benefits of convenience, safety, policing, community promotion, and public relations to pay an appreciable part of the cost. These warrants say, in effect, that lighting need not be installed on a freeway unless it has been installed on adjacent city streets, and if you look at the warrants for city streets, you will find them equally vague.

One of the most important objectives of the research to be sponsored by the Highway Research Board is developing requirements for a suitable visual environment resulting from fixed roadway lighting. In other words, what is the proper visual environment that one needs to drive a car, walk down the street, or apprehend criminals? I believe this is the area that will be productive in the future, and I would like to give a resume of what appears to be the driver's visual requirements and some of the unanswered questions.

The San Mateo bridge is a good example of a new concept in bridge design, one in which aesthetics played a dominant part. It is a design with a more or less continuous beam going across and with adequate clearance for ships without any drawbridge mechanism. One of the design concepts was the elimination of poles, and this gave me the opportunity to design low-mounted, continuous luminairs. These luminairs provide uniform illumination that provides a good indication of detail on the roadway, guidance and orientation information, and excellent visibility in bad weather.

Lighting should be designed for the field of view of the driver. If you are designing for an automobile driver, then you should look at his field of view. This field is limited, about 20 degrees up, about 10 degrees down, but much wider horizontally. Of course, there are many other designs for vehicles. Motorcycles, sports cars, and trucks would have different fields of view, but whatever it is, we need to know what it is and design for it.

There are techniques in addition to putting light on the roadway, and one of these is the delineation technique. Self-luminous delineators were installed about 3 years ago on a section of road in Oakland, and they have operated very satisfactorily. This installation was one of the early experimental attempts to use lighting to provide the same kinds of information at night that are present in daylight; in other words, lines stretching out ahead that give run-of-the-road and orientation guidance. In many instances, it is not necessary to put high levels of illumination on the road, but, rather, what is needed is to provide the driver with this guidance information.

Current roadway lighting generally uses what is called the "forest of poles" technique. This technique creates serious problems in avoiding glare and getting adequate distribution of luminance on the roadway. There is a canopy of lights above the roadway, but the roadway itself is spotty and low in luminance. This technique meets all current design requirements for illumination, but it does not take into account the really important thing, the pattern of luminance in the field of view.

The Manahawkin Bridge was one of the first to use low-mounted luminaires in the United States. It was a good first attempt, but the lights are mounted with intermittent spacing that results in pools of ligh on the roadway. The San Mateo Bridge also uses low-mounted luminaires. These are considerably lower, about 30 inches above the roadway, than the ones on the Manahawkin Bridge, and they are essentially continuous. The lighting is not quite continuous since there are eight-foot lamps inside a ten-foot luminaire. The lighting should be absolutely continuous, for if you are driving a sports car in the inside lane and you are driving rapidly, there will be a noticeable, disturbing flicker. It would be a better installation without the flicker. The accident records are beginning to show that this installation is as safe at night as it is in the daytime. This is noteworthy because people frequently drive 100 mph on this stretch of road.

Glare can be studied by dividing a scene into discrete quantities of luminance. One-degree grid areas are assigned a location, and the magnitude of the luminance in each of these areas is measured. Computers are used to synthesize this information into an overall glare analysis, and I believe this technique can be applied to roadways.

The directional reflectance characteristics of the pavement should also be considered when designing a roadway. One finds a single number given for reflectances of materials, for example 30 percent for concrete and 15 percent for black top, but a single number is not adequate. Samples of pavement have very complex and unique characteristics. In our laboratory, we use the following technique. A sample of pavement is mounted at the center of rotation of light on a boom, and this light is moved to simulate changes in vertical and horizontal angle. If a photometer is placed at an angle of view approximating that of a motorist, then you begin to get the kind of reflectance information necessary for designing studies of pavement luminance.

I think we are beginning to get somewhere. If we can begin to think of this problem from the motorist's point of view rather than thinking only of hardware and installation problems, we shall be making progress.

SELECTED VISUAL PROBLEMS OF AN AIR LINE PILOT

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Barron (1965) summarized many of the factors that contribute to unreliability in visual perception:

> Under usual conditions, man uses his eyes most consistently to relate to his environment. These are his most reliable sensors, and he believes what he sees. Unfortunately, his interpretation of the visual image is affected by many factors. The eyes of a six-month-old baby perceive the same visual stimuli as those of the sixteen-year-old boy or the sixty-year-old man, but the interpretation of what is seen depends upon such variables at training, association, memory, and recent and past experiences. Vision is easily altered in aviation by hypoxia, acceleration, aeroembolism, glare, haze, heat, smoke, toxins, fumes, aircraft structure, personal equipment, disease, drugs, circulatory disturbances, fears, emotions, aging, and other stressors.

His list of the factors that can alter vision is rather formidable, and, while many of them are very real to air line pilots, I am pleased that I, at least, do not recognize all of them as creating major problems. However, it is clear that Dr. Barron has not overstated the importance of visual cues. These cues provide the pilot's most reliable information, and they are becoming increasingly important.

Currently, the Federal Aviation Administration requires air line pilots to be examined by one of its designated Aviation Medical Examiners, examined semiannually if he is a captain and annually if he is a copilot or flight engineer. The basic visual standards require that he have a natural or corrected distant and near visual acuity of 20/20. The latter is read at 18 inches, and I should like to talk about this test later. There are also requirements for normal color vision, normal fields of vision, absence of acute or chronic pathological conditions that might interfere with proper function or be aggravated by flying, and "bifoveal fixation and vergencephoria relationship to prevent a break in fusion under conditions that may reasonably occur in performing airman duties."

If we look at the ages of the 26,700 active members of the Air Line Pilots Association (1968), we find: (a) an average age of 38, (b) a bi-modal distribution with modes of ages 31 and 47, and (c) 32.6% of these pilots in their fifth decade, 11.5% in their sixth.

This last category is especially interesting since it includes more than 3,000 pilots between the ages of 50 and 60, which is the FAA mandatory retirement age. The number of sixth decade pilots will gradually increase to somewhat over 7,000 by 1974 and continue at least at that level for the next 20 years as the numbers that enter this age bracket from below more than equal those who retire at age 60. For the first time, and for the foreseeable future in our industry, we shall have relatively large numbers of pilots in their sixth decade.

These statistics are related to the subject of visual problems, primarily because of the presbyopia, or loss of accommodation, associated with middle age. It also has broader significance. I firmly believe the emergence of a large and permanent block of pilots in this age bracket is a basic fact that must be recognized by everyone seriously involved in air transport operations (Orlady, 1966). This fact is relevant whether they are designing or operating airplanes, investigating accidents, revising medical standards, promulgating operational rules or procedures, or are involved in any other aspect of this business. Certainly, we must have a system that works well with the people in it, and any rational human factors approach will both take advantage of their strengths and, to the extent possible, compensate for their weaknesses.

To get back to visual problems, we find that regardless of whether he is looking inside or outside the cockpit an air line pilot wants to be able to do two things: one is to remain a safe distance from objects that are a hazard to him, such as terrain, other aircraft, and some weather phenomena; the other is to arrive and depart to and from a specific piece of terrain in a very precise fashion. Here the requirements involved are becoming increasingly demanding, and they are, I believe, a major reason why we have seen a significant change in the distribution of tasks in air line cockpits. This change is to place increasing reliance on cockpit instruments to insure proper operation of our airplanes during all phases of flight. It has been an evolutionary and increasing change—a product of the increasingly stringent demands of the traffic system, the fundamental limitations of the human sensory system, and the response characteristics and operational tolerance limitations of today's airplanes.

Until recently, there has been very little precise information dealing with distribution of tasks in air line cockpits. However, data are now available from a study (UAL-ALPA, 1968) that included a work sample analysis taken by a research observer every 20 seconds during climb and descent in short-haul jet operations using a two-man crew. Data were taken from 386 climb and 389 descent segments into 32 different airports during regular line operations. The average flight segment was 126 nautical miles and lasted 25 minutes, 76% of which was spent in either climb or descent. Slightly over six minutes was spent at cruise on an average flight.

There was a very little difference in task distribution between climb and descent, and, if we look at the descent data in five broad categories, we find:

1. That 53% of total crew time was devoted to flight path control, i.e., anything required to move the airplane along its desired course, including engine and flight control, and scanning of flight, navigation, and engine instruments;
2. That the next largest category was external vigilance; this occupied 22% of total crew time measured by this method and involved looking outside the airplane for other aircraft, approach lights, the landing runway, and other objects;
3. That communications and navigation took 12%; the latter was restricted to tuning or operating navigational radios;
4. That the seemingly inevitable "other" or "miscellaneous" category took 11% of total time;
5. That systems operation of such things as air conditioning, pressurization, hydraulics, anti-ice, and the electrical systems took only about 2%.

The last point is a considerable tribute to design improvements and is another reason why we are seeing changing task distributions and an increasing need for re-examination of traditional allocation of duties concepts (Scucchi and Sells, 1969). On the average, these crews spent slightly less than ⅘ of their total time inside the cockpit and slightly more than ⅕ of their total time looking outside.

In addition, we find that the pilot flying the airplane spent about 70% of his time in flight control activities and about 15% in external vigilance. The non-flying pilot, in contrast, spent almost 35% in vigilance, over twice the percentage of his partner. He also spent a somewhat surprising 25% in flight control activities, about 16% in communications, and almost 10% tuning or operating navigational radios and reading charts and approach plates.

This distribution has surprised many people, particularly because of the relatively small amount of time (22%) recorded for external vigilance. It is, of course, possible that the results were skewed by the recording technique and that it was not sensitive enough to pick up short-term glances for conflicting traffic or airport and runway identification. Mitigating that sort of objection, however, is the large sample in both climb and descent phases, the large number of 20 second observations made, and the overall consistency of the observations recorded. At the very least, it does seem clear that a considerable amount of time and attention by both pilots is required inside the cockpit and that serious doubts have been raised as to the validity of the unsubstantiated assumption that we can have at least one pilot looking out all of the time.

This brings us to the first of the specific problems I should like to discuss. It is the problem of avoiding other aircraft in visual flight conditions.

If we look at the record, we find that since 1938, we have had: six collisions between air carriers, eight collisions between air carrier and the military, and twenty-four collisions between air carrier and general aviation aircraft, a total of thirty-eight of all types of in-flight collisions involving air carriers. Furthermore, eight of these collisions have occured in the last three years, seven between an air carrier and a general aviation aircraft, one between two air carrier aircraft.

The actual number of near-collisions is important and unknown. In an effort to get more information regarding them, the FAA has sponsored an anonymous near-collision reporting program. Data for the first year of operation have not yet been published in final form, although a preliminary report was given to the industry a few weeks ago. This project can make a major contribution to our understanding of near-collisions.

Air traffic control (ATC) procedures require that radar controllers advise aircraft under their control of potentially hazardous traffic seen on their radar scope if doing so would not interfere with the controller's primary job of providing separation of Instrument Flight Rules (IFR) traffic in their sector. They do this by identifying possible targets by distance, clock position and, if pertinent, relative speed. For example: "slow-moving and converging traffic, 10 o'clock—3 miles." Air traffic control radar gives range and azimuth information but not altitude. Therefore, targets called out are not always potentially hazardous traffic because the airplanes may be flying at different altitudes.

In a previously mentioned study (UAL-ALPA, 1968), all ATC-called traffic on 944 flight segments was recorded by a research observer in terms of its range and clock position. The observations comprised approximately 1500 calls. These data are particularly interesting because they represent the judgment of experienced and professional observers regarding potential collision hazards. The distribution by clock position was nearly symmetrical with 3.3% and 3.1% of the total called traffic at the 9 o'clock and 3 o'clock positions, 10.6% at both 10 o'clock and

2 o'clock, 17% and 17.3% at the 11 o'clock and 1 o'clock positions, and 36.5% at 12 o'clock. The remaining 1.7% was not specified.

Approximately 58% of this ATC-called traffic was not seen by the flight crews. The distribution of percentage of aircraft detected among clock positions was about the same as the distribution of undetected aircraft. In fact, even when non-ATC-called traffic was sighted, there was virtually no change in this basic distribution of 3%, 11%, 17%, and 36% in the forward quadrants (UAL-ALPA, 1969). Frequently this is critical traffic and not called by ATC only because the controller's primary workload was too heavy.

There are several reasons why the flight crews saw only 42% of the ATC-called traffic. For example, some of it can be in, above, or below an intervening cloud deck. The research observer attributed approximately 10% of the traffic not seen to the weather conditions. Another reason, particularly applicable under periods of high workload, is that pilots frequently do not scan the entire potential altitude segment involved but simply attempt to clear their own altitude. Characteristic narrowing of perception during high levels of concentration also seems to be related. An additional complication is the variation in conspicuity of the other aircraft.

Even under the best conditions, aircraft appear as rather small objects at the distance at which they must be detected in order to have time to avoid them. Ends (1967) has stated that a fighter-size aircraft can be seen only 0.7 of a mile before collision if it is 10° off the pilot's line of sight. Detection is made even more difficult because there is no relative change in bearing or apparent motion between two objects on a collision course other than the increase in apparent size as they approach each other. Motion cues and peripheral vision are simply not much help in identifying traffic in which you are most interested. Nor are the airplanes themselves any better. This is perhaps understandable, for any exterior color scheme that would provide effective conspicuity against the wide variety of backgrounds to which airplanes are exposed almost certainly would be considered an aesthetic monstrosity by the people who would have to make large additional expenditures to achieve it. At night the background of city lights adds confusion and, frequently, irrelevant motion distraction to an already confusing scene.

If one looks at all of the adverse factors involved—including the fact that we are putting more and more airplanes in the same airspace, flying them faster, and keeping the people who fly them busier—one is hard-pressed to discover why the record is not even poorer. Lederer (1967), former Technical Director of the Flight Safety Foundation and now NASA's Director of Aerospace Safety, has put the problem in perspective. A few years ago, he commented: "Mid-air collisions are remarkably rare. The combination of a well-organized, well-managed air traffic control system, a large sky, alert flight crews and luck have resulted in a livable collision record. Mid-air collisions between air lines now occur about once every three years in the United States, or one in about twelve million flights. This is better than the acceptable level of aviation risk, which is one accident per ten million flights or hours. Nevertheless it is not good enough."

It may not be good enough in the era of the SST and the Jumbo Jets, and it is certainly not good enough if we can improve it. Consequently, it may be worth spending a few more minutes reviewing some of the things we know.

Despite advances in air traffic control methods and technology, all segments of the industry still depend on the see-and-be-seen concept to avoid one of those rare "aluminum storms" that can spoil a pilot's whole day. I can furnish no better examples than excerpts from the report of the National Transportation Safety Board (1968) regarding the collision of an air carrier twin engine jet and a general aviation aircraft flying under Visual Flight Rules (VFR) that occurred near Urbana, Ohio slightly over two years ago. The Board stated:

> The lack of positive control over aircraft operations conducted in terminal areas under the present day air traffic control is not satisfactory. Had the Beechcraft been under control of an air traffic controller the accident could have been avoided because the controller could have arranged to sequence the two aircraft in such a manner as to avoid any converging of their flight paths. The Board is aware, however, that present day air traffic control facilities are not adequate to handle the workload which would be created by requiring positive control of all aircraft operating in terminal areas. Until such time as the air traffic control system is able to provide positive separation between aircraft at all times, *or some other system to achieve the safe separation of aircraft is available,* some version of the "see and be seen" concept will have to be used by all airlines operating in VFR flight Conditions [italics supplied].
>
> In operating in a "see and be seen" environment, particularly in the vicinity of terminal areas, constant vigilance must be maintained by all pilots and controllers, both in handling aircraft under positive control and in furnishing radar advisories concerning uncontrolled traffic. This is especially critical in terminal areas where there is a mix of large high speed aircraft and small relatively low speed aircraft which presents a high potential for hazard.
>
> The Board recognizes that the operating of high speed aircraft with accelerated closure rates; frequent, but necessary, diversion of attention to cockpit duties; and current conspicuity problems, places a difficult burden upon flight crews. Nevertheless, maximum vigilance must be maintained in terminal areas when operating in a "see and be seen" environment.

Among the thirty-two separate findings in its conclusion the Board stated:

11. There was no way the Beechcraft pilot could have been warned of the fact that his intended flight path would intersect that of the DC-9.
12. The DC-9 was operating on an IFR flight plan under radar control of the FAA throughout the flight.
15. The RAPCON controller advised the DC-9 crew of the presence of a slow speed target at 12:30, 1 mile. This warning was acknowledged approximately 14 seconds before the collision.
18. Approximately five seconds should have been sufficient to detect the target and initiate a change in direction of the DC-9.
19. The aircraft response time would have been approximately three seconds.
20. There is no evidence of any attempted evasive action by either crew.

As to the "Probable Cause" of this accident, the Board stated:

> The board determines the probable cause of this accident was the failure of the DC-9 crew to see and avoid the Beechcraft. Contributing to this cause were physiological and environmental conditions and the excessive speed of the DC-9 which reduced visual detection capabilities under an air traffic control system which was not designed or equipped to separate a mixture of controlled and uncontrolled traffic.

In this accident, the DC-9 crew had something between six and nine seconds to see the Beechcraft in time to avoid it. The last words on the Cockpit Voice Recorder—transcribed four seconds before it ended—were from the copilot who announced, "Ready on the checklist, Cap'n." This, of course, represented an operational diversion requiring attention inside the cockpit. One feels slightly uncomfortable contemplating any system so critical that cannot occasionally tolerate a nine-second diversion of attention. In fact, it suggests we may be truly operating on borrowed time with continued reliance on the see-and-be-seen concept as we know it and as it is subordinated to other demands in the flight system.

Industry concern is demonstrated by the very large sums of money being spent to develop an electronic collision avoidance system that will not depend upon see-and-be-seen. Such expenditures include a currently sponsored $3 million evaluation, and, on just one air line, a budget allocation of $50 million has been made for procurement and installation of an acceptable system. Unfortunately, the most promising of the systems being developed have not yet been service tested, let alone installed on air carrier and general aviation aircraft. If such a system is effective only between air carriers, it treats with a very minor part of the problem. Some estimate it to be less than 5%, and remember that in the air even a rowboat can sink a "Queen Elizabeth." In the meantime, we have no choice but to continue to rely on increased external vigilance among all crew-members and the development of procedures that maximize the effectiveness of their vigilance.

Sincere, respected individuals and organizations have stated that the third crew-member's contribution in traffic detection is small at best and that both his position in the cockpit and his duties prevent his being an effective observer. Here again, little factual data were available before the study (UAL-ALPA, 1968) of a short-haul jet transport operation utilized research observers to record first detection of ATC-called and non-ATC-called traffic with both two- and three-man operating crews. Control data from a three-engine jet operated with three crew-members in a high density traffic area and from a twin-engine turbo-prop being operated by two crew-members were also collected.

The data showed:

1. No essential difference in rates of detection of ATC-called traffic for the two- and three-man crews;

2. A considerable difference with non-ATC-called traffic; the rates of detection of this critical traffic (for example, the Urbana crash) were 37% greater on the twin-engine jet when it had a three-man operating crew; there was no essential difference between the two-man crew turbo-prop and the twin-engine jet when it was being operated with two men;

3. The third crew member first saw approximately ⅓ of the total traffic detected in both the two- and three-engine jets; the actual distribution is shown in the following table.

Initial detection of total traffic (ATC-called and non-ATC-called).

Crew Member	Two-Engine Jet (3 Man Crew)	Three-Engine Jet
Captain	37.4%	38.2%
F/O	28.6%	30.3%
3 CM	33.0%	31.4%
Other	1.0%	0.1%

The distribution of traffic detected when the twin-engine jet was being operated with a three-man crew is remarkably consistent with the three-engine jet control data and helps clarify the external vigilance role of the third crew-member in today's air traffic environment. It is greater than many had expected because of the third crew-member's traditional duties and because his set position between and behind the two pilots clearly provides a more restricted view. For example, a well-known study (AIAA, 1967) stated that the third crew-member could see only 8.9%

of the total airspace visible to the Captain and First Officer and that even a large amount of head movement would result in only a small increase in the amount of airspace he could view.

While the reasons for the unexpectedly large number of a third crew-member's visual detections are not entirely clear, at least two theories have been suggested to explain it. One is that his restricted view is actually an advantage because it confines the third crew-member's outside view to the most critical airspace. Probably more important is his relatively smaller workload, particularly during climb and descent, which are the most critical phases of flight. This smaller workload gives him more time to look out than the other two pilots have and also permits his "look-out" to be more efficient because he is not preoccupied with or distracted by other duties. Objective re-examination of existing allocation of duties is again suggested. The argument in favor of unburdening the two crew-members with the best view in order to achieve most effective overall external vigilance is compelling.

This latter concept is supported by another interesting bit of data. When the third crew-member was not present, the pilot *not* flying detected about two-thirds of the total traffic. He did this while spending slightly more than twice the amount of time looking out as did his flying partner, who spent almost 75% of his time in flight control activities (UAL-ALPA, 1968). Cockpit demands are changing.

Glare causes another kind of visual problem for pilots. It degrades their visual effectiveness and can be a source of considerable discomfort from long periods of either looking directly into the sun or from exposure to high light levels reflected from the tops of clouds.

Most modern air transports provide movable plastic sun visors to reduce glare. They are useful in long-range cruise, particularly on west-bound flights. Large portions of these flights are spent looking directly into the sun because the speed of the airplane moving westward with the sun considerably prolongs its time above the horizon. However, if the visors were dark enough to provide comfort under these conditions, they would be nearly opaque, which would make them unacceptable. Therefore, they are relatively ineffective by themselves, but if combined with ordinary sun glasses they work quite well. In this case you obviously cannot see very much directly through them, so traffic detection is provided by having pilots cross-monitor each other's blind spots. The alternative of not using both the shields and sun glasses is virtually not to be able to see at all. Fortunately, all traffic at these altitudes is under positive ATC control, which provides traffic separation and our primary collision protection. The visors are seldom used in any phase of flight that requires maneuvering because the continual adjustment required makes them more of a nuisance than a help.

Another high altitude cruise problem is the high contrast between light levels inside and outside the cockpit (Whiteside, 1957). Flight instruments are frequently too dark to read without using supplemental cockpit lighting. A rather ingenious solution to this problem was the development of special sun glasses that consist of only the top half of the lens, a reverse of the Ben Franklin type. They work very well during most conditions but not when you are getting a large amount of reflected side glare from the top of a cloud deck. The problem here is the reversal of normal light distribution, the major source of light coming from below rather than from above. Under these conditions wrap-around sun glasses seem to work best because they also provide protection from the side and below. One of my aeromedical friends has commented that this really would not be a problem if we could only find enough pilots with eyebrows on their cheek bones.

Recognition of other aircraft at high altitudes is complicated by difficulty in focusing in an empty visual field. Under these conditions the eye normally focuses at between one and two meters (Whiteside, 1957). This phenomenon is frequently illustrated by the suddenness with which targets appear. Even when relative bearing and altitude are known, the other airplane does not gradually become visible but, once seen, appears with remarkable clarity in an area that seemed empty the previous moment.

We are again fortunate that positive control of all traffic at these altitudes has virtually eliminated this collision hazard. Without it there would be very real problems, for even after aircraft are identified it is nearly impossible to determine their altitudes accurately. For example, an airplane approaching head-on and 2,000 ft below your altitude frequently appears to be above you at first, seems to gradually descend through your altitude, and then is clearly below when it passes. If one depended only on his visual perception, his immediate reaction would be to dive to avoid such an aircraft, which, of course, is exactly what should not be done in that situation. I am not aware of similar illusions in the horizontal plane and have assumed that this one is a product of cockpit deck angles and angular distance to the apparent horizon.

At lower altitudes a similar illusion is found with swept-wing aircraft circling in a holding stack with 1,000 foot vertical separation. When these aircraft are placed in a 25° bank (normal in a holding pattern), the cockpit deck angle changes considerably more than it did with straight-wing piston airplanes. This angle is great enough to create the illusion of making airplanes separated by 1,000 ft appear at or very near the same altitude.

Two fatal airline accidents have resulted from the illusion that the airplanes were on a collision course. One of them resulted in an actual collision as the pilot, thinking he was avoiding the other airplane, maneuvered into it. The other crashed after loss of control in a sharp maneuver that was not necessary but was made to avoid an imagined collision course (Lederer, 1967).

The preventative, of course, is for the pilot to stay on and trust his instruments and to depend upon his ATC clearances. However, in a mix of IFR and VFR traffic this is not good enough either, for we still depend upon the see-and-be-seen concept, and the pilot ultimately has to believe what he sees.

For the past several years, there has been a major effort in the industry to develop hardware and procedures permitting safe operation under continually decreasing landing minimums. A great many visual problems are involved, and they are principally associated with approach and runway lighting, runway and taxiway marking, cockpit instrumentation and lighting, and transition from inside to outside the cockpit with minimal external visual cues and very little time to identify and interpret them.

Head-up displays, which transfer guidance symbology from the instrument panel to the pilot's line of vision through the cockpit window, seem very promising. Superimposing instrumented landing cues over the real world outside saves the pilot at least the three or four seconds lost in transition from visual reference in the cockpit to visual reference outside and makes it possible to go back on instruments almost instantly in variable weather conditions. In spite of the importance of these devices, I shall not spend any more time on them. Not only would it require more than my remaining time, but these problems are well-recognized and a great deal of work is being done on them by a variety of private, governmental, and industrial committees. What we really need is a committee to obtain enough money to permit compliance with their recommendations.

Instead, I should like to turn to basic visual requirements in air line cockpits, portions of which, almost inexplicably, have received very little attention. Earlier I mentioned the near-vision licensing standards that stipulate measurement and correction, if required, at 18 in. However, with the exception of the overhead panel, pilots really don't have to see very much at 18 in. It is, however, extremely important for them to see well at 30 to 35 in., which is their instrument panel distance.

Because there is a predictable and inevitable loss of accommodation among pilots after the age of 40, this problem of near and intermediate vision is becoming increasingly serious. Beginning three years ago in one of the first attempts to do anything constructive about it, studies among the senior pilots of a major U.S. air line showed that 46% of the pilots tested stated that the panel was sharp and clear without accommodative aid, although 90% demonstrated less than 20/20 vision acuity at panel distance (Harper, *et al.*, 1966; Harper and Kidera, 1968). A later study, (Watkins, 1969) found that 52 (26%) of 198 air line pilots wearing a near-correction were wearing the wrong correction in the opinion of an aeromedically oriented ophthalmologist.

The conditions described in the following paragraph are not unique to Australian pilots:

> In-flight observations have shown that almost every possible method of near correction is used by Australian pilots. There are examples of single-vision reading glasses, bifocals with near correction for widely varying distances, "look-over" lenses, hinged additions to flip down when required, trifocals (including several pairs with segments at the top for the DC-9 overhead panel), and there is even a case of a presbyopic myope who wears his distance correction during take-off and landing but takes this off during flight!

Fortunately, this part of the problem is now well-recognized, and there is considerable hope that the revised visual standards and the corrections prescribed will be responsive to the pilot's actual task. Equally important, information regarding the advantage of individualized evaluation and task-related corrections is being disseminated among the pilots who need them.

Aeromedical specialists and ophthalmologists, however, are not the only groups with a legitimate interest in these problems. Aircraft designers and operators are also involved. There is no better example than the overhead instrument panels they have designed and approved with apparently little attention given to the visual demands they create. These panels contain increasing numbers of gauges, instruments, and switches accompanied by smaller labels and dial markings. In some aircraft, streamlined fuselage design and the tendency to place the cockpit as far forward as possible in order to preserve fuselage cubic area for payload has lowered the cockpit ceiling and brought the upper panel even closer to the pilot's head. Visual distance for this panel varies from about 13 to 20 in. Even when it is well lighted, real problems are created for a large number of pilots.

At the present time, the only practical answer for a pilot who requires correction for near vision is some sort of a trifocal arrangement. One currently popular with many pilots utilizes a hinged flip-down lens attached to the frame of ordinary bifocals corrected for instrument panel in the lower segment with the remainder of the bifocal corrected for distant acuity. The flip-down lens has its near correction in the upper segment and is used for viewing the upper panel, which has only occasional or intermittent viewing requirements. This device preserves safe segments for distant vision and instrument scan should an emergency arise even while the hinged lens is in the flipped-down position. It was devised by Harper (Harper and Kidera, 1968) and is being used by an increasing number of pilots.

There have been several other approaches. One uses four separate segments in a single pair of glasses. A very small portion of the lower segment has a near correction for reading manuals and approach plates, and the remainder of the lower segment is corrected for the instrument panel; most of the remainder of the lens is for distant vision with an additional very small segment for near vision at the top for viewing the overhead panel. Another solution used by some pilots is to take off their bifocals and invert them for the upper panel. Perhaps most ingenious is the solution devised by a pilot who needed near and intermediate vision corrections, but none for distance. He bought two pair of "Ben Franklin" glasses—one corrected for near and the other for the instrument panel—inverted the glasses with the near correction and then cemented them to his other pair. In spite of the fact that they look like something designed by Rube Goldberg, he has a good correction for his instrument panel, a nice wide open segment for distance viewing outside the airplane, and a large near-corrected lens at the top so that he can cover the entire upper panel with a fairly small head movement. His lower intermediate correction is adequate for manuals and approach plates at about lap distance, so he has none of the distraction or annoyance caused by very small viewing segments.

When we realize that we are talking about professional pilots in charge of sophisticated multi-million dollar airplanes, much of this seems slightly incongruous. With present knowledge and acceptance of human factors and total systems approaches, it seems virtually inexcusable to make trifocals a design requirement for a majority of the Captains who will fly our most modern transports. Hanks (1961) has an explanation:

> The manner in which an aircraft or weapons system is developed affects significantly the application of human-factors concepts to the system. The manufacture of aircraft is a highly competitive business in which the customer is in a position to dictate the choice of subsidiary systems so that, far from being a homogenous effort, the ultimate design and installation may be subject to many wills and opinions, operational and administrative demands and philosophies, and, in the opinion of some, just pure cussedness. Thus, cost or weight factors may overshadow important human operational considerations, especially if competency in human-factors analysis is lacking on the part of the customer, the subsidiary, or the prime contractor.

Those same general comments apply to chart lighting and chart legibility. Task requirements are changing in air line cockpits, and, as more attention is required inside the cockpit, these changes are accompanied by an increased need to refer to charts and instrument approach plates. We need useable chart holders and chart lights that are white, variable in brightness and diection, and do not cause distraction to either pilot. This distraction is a basic problem with most ceiling-mounted spotlights currently in use.

The charts themselves are a major problem. The medical director (Flight Safety Foundation, 1968) of a European air line has recently commented:

> Even more important than intensity of chart lights is the size of the print used on charts, let-down diagrams and technical publications. Again, our middle-aged presbyopic pilot may have difficulty in reading these, and if the print is too small, he finds his arms not long enough! Correcting lenses, however, will deal with this problem adequately. The size of the print and type-settings used are of immense importance in ensuring that pilots read the information correctly.
> Regarding charts, why are they still printed in rather washed-out blue color? This is about the worst possible color to use for reading in artificial lighting. . . . I don't want to raise the question of legibility of charts, maps, and flight information, but it is a big human factors problem and one on which we have spent a considerable amount of time and effort.

It seems clear that we can do better than this and I believe we must. One obvious approach to the problem of both the upper instrument panel and chart legibility is the development of effective compulsory standards, and we may have to sue them as undesirable as that approach is.

This concludes my discussion of some of the typical visual problems of air line pilots. The problems identified were illustrative rather than exhaustive, and they are not necessarily the most critical. However, it is clear that flying faster, heavier, and more sophisticated airplanes to gradually lowering weather minimums in an increasingly complex environment will continue to result in decreased tolerances of all types and that improved visual cues will be a basic operational requirement. It also seems clear that maximum and integrated contributions from all relevant disciplines will be required if we are to continue to improve levels of safety under these conditions. Individuals making final decisions can no longer afford the luxury of ignoring state-of-the-art human factors knowledge in the broadest sense, including the precise identification of problem areas. Equally important will be a willingness to re-examine original premises and take positive action if it is suggested.

This point is stressed because another comment made several years ago by Hanks (1961) is still pertinent:

> These [human factors] considerations demonstrate the need for a greater coordination of effort in dealing with human factors as the jet age advances, proceeding from air crew selection through aircraft and component-system design and operation and governmental regulations. While some accomplishment has been made, one is reminded of the story in which the agricultural expert was sent out to teach modern farming. As he explained his program to one marginal operator, the farmer commented "T'won't do no good mister. I don't farm as good as I know how now." One suspects that, in the interests of flight safety, we're not operating as well as we know how now.

This attitude will not be good enough in the future and we shall need your help to change it.

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VISUAL PROBLEMS OF THE AIR TRAFFIC CONTROLLER

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At the present time, extensive planning and evaluation of future air traffic control equipment is in progress at the National Aviation Facility Experimental Center. The impact of automation on air traffic control tasks and procedures is being felt in current systems and in the formulation of a system for the future. Current air traffic control in the United States has been dealing with increasing traffic loads during the past five years, and the traffic is expected to increase at a rapid rate for many years to come. The future air traffic control system must, therefore, be able to handle higher densities of traffic than the current system. It also must handle more varied types of traffic. Most types of subsonic aircraft will remain with us, but the advent of supersonic aircraft and the increase in small executive and general aviation aircraft will extend the range of types of traffic that the air traffic control system will have to deal with effectively.

The visual problems of the air traffic controller can be divided into four categories: (a) medical, (b) equipment, (c) atmospheric phenomena, and (d) environmental.

MEDICAL

The air traffic controller is required by the Federal Aviation Administration (FAA), to take a comprehensive annual medical examination that includes chest X-rays, EKG, glaucoma and optic examinations, and audiometric and psychological testing, but the most frequent medical reason for disqualification of controllers is visual deficiency.

EQUIPMENT

The primary visual tool for air traffic control is radar, and there are five types of displays currently in use: Direct View Surveillance Radar, Radar Brite Display Equipment, Large Screen Display, Airport Surface Detection Equipment, and Precision Approach Radar.

At one time radar displays were always located in a dark operating area, for this location provided the controller with the best raw radar presentation. Radar indicators were later placed in the busiest control towers as an aid to the local controller for issuing a landing sequence to a pilot flying under Visual Flight Rules. This meant that on a bright or hazy day the local controller would stick his head into a funnel placed over the raw radar display in order to block out the bright light. This funnel enabled him to see the traffic on the radar display and the controller had to use it hundreds of times a day. I am happy to say that in the last year the FAA has installed Brite I Displays in the towers. The Brite I Display is a television-type display that can be viewed with no difficulty, and this superior display has been a tremendous aid to the tower controller, for he can use it day or night without excessive eyestrain. Unfortunately, the controller in the Instrument Flight Rules (IFR) room at a majority of locations works all day in darkness, and these dark surroundings contribute to fatigue and eyestrain.

At most major radar facilities, the FAA is using Radar Brite Display Equipment. This not only lets the controller work in daylight or office-light surroundings but provides a display that can accommodate an automated tracking system or systems. When aircraft are properly equipped with radar beacon equipment, the computer can automatically track and read out the aircraft's identification and altitude and display them adjacent to the radar target on the controller's scope.

In the New York Common IFR Room, we now have a Large Screen Display. This is an Ediphor Projector System fed by a scan converter. We have found that the display tends to deteriorate, unnoticed by the busy controller, after thirty or forty minutes. The screen is out of focus but the operator only realizes this after looking away, at which time he notices how sharp all other objects seem, and when he looks back at the screen, it seems blurred. Controllers working for long periods on this screen have complained of headaches and dizziness. When not concentrating on the screen but using it as a reference, it seems good, but when you must concentrate on it, you realize the targets are not sharp. This type of display has a definite role to play in the air traffic control system of the future, and it is operational in the Common IFR Room in New York.

Another piece of equipment is the Airport Surface Detection Equipment in use at the Kennedy tower. This has proven to be very valuable because the traffic flow at the airport moves at the same speed when visibility is ½ mile as it does when it is 3 or 4 miles. The tower ground controller, who controls all traffic taxiing on the airport, must switch from looking out the window to looking at a radar display so that he can follow aircraft under his control as they move from ramps, via the taxiways, to the departure runway. At large airports, this is no simple task when thirty-five or forty aircraft an hour are landing and a comparable number are taxiing out for takeoff. But a major visual problem is produced by the blower that cools the radar console. It sucks in air from the back of the console and blows the warm, dry air out through the front. After a few minutes of looking directly into this equipment, your eyes feel as though they are going to dry up and fall out of your head.

The Precision Radar (GCA) display utilizes what amount to a height-finding radar with a two-dimensional display showing altitude above ground and distance from a surface reference. The azimuth display for GCA shows the narrow segment of ground surface underlying the zone scan by the height-finding radar. Thus a target in three dimensions of space requires the controller to perform some visual integration, for the display enables the controller to provide the pilot with accurate glide path information and guidance to the runway.

We have two 1218 UNIVAC computers that will aid the controller in tracking aircraft. Our 1218's receive from the air route traffic control center in New York computerized flight plans, automatically printed out and displayed on the controller's scope ten minutes before he works the aircraft. The biggest problem here is the inability to adjust the size of the automated letters on the display. This type of equipment will be commissioned in June of this year in the New York Common IFR room, and this installation will be the first step toward complete automation. With the start of the stored program alpha numerics (SPAN), the controller is now adjusting to automatic displays of the aircraft identification and altitude readout. The use of digitized radar will be another big step forward for the controller and the system in years to come.

We have clocks, wind equipment, runway visual range equipment, runway visibility value equipment, and altimeters, and all are used and read to the pilot at approximately the same time, yet they all have different size numbers, ranging from 1 inch to ¼ inch in size. The type of letter and size of numbers should be standardized. For example, we look at a runway visibility meter, the face of which is the size of a Big Ben alarm clock, but the numerals that you must read are obscured by the needle pointing to the number. The controller is still reading weather information from an electrowriter machine, and this display is only as legible as the handwriting of the person who is feeding the information into it. When the controller is reading the weather to the pilot in instrument weather conditions, there is no time to waste in puzzling over the weather observer's writing. And, finally, the location of equipment is often based on the convenience of the technician installing it or the availability of an empty space in the console, rather than the requirements of the controller.

All equipment should have rheostatically controlled background lighting. This would be only a minor additional cost, but it would be valuable aid in many situations. A piece of equipment is frequently installed in a tower cab where there is no background lighting, and, as a result, the controller has to increase the light intensity in the operating area to make adjustments on the console, thereby increasing the general room lighting, which diminishes his night vision. Some tower cabs are equipped with bright white lighting. The controller, looking down on his work area, looks at a white pad and is then required to look 2½ or even 8 miles into the darkness to determine whether traffic is turning clear of a runway or whether an airport car is holding clear of the runway.

ATMOSPHERIC PHENOMENA

The tower controller must contend with many difficulties caused by atmospheric conditions. Searching for aircraft in a bright haze or fog can be extremely fatiguing. In clear weather, glare from the sun may be reflected from a window to an area that he much watch. Concave tower windows have been suggested as a remedy, but such windows might have other, undesirable effects. A light rain falling on the tower windows can also cause problems to the tower controller. Visibility will be four miles with light rain, but he will only be able to see ¾ of a mile through some windows because of rain on the windows on that side of the tower. Such a situation requires additional pilot reports of runway clearance and generally increases his workload.

The controller who works an evening shift in the tower or the tower controller who is reassigned from the tower cab to the radar room in the middle of the day may suffer from the effects of this exposure to sunlight upon his ability to adapt to darkness. The Air Force suggests that individuals exposed to intense sunlight for two to five hours show a definite decrease in their sensitivity at low brightness levels that persists for as long as five hours after exposure. Individuals who normally work in bright sunlight show a considerably retarded rate of dark adaptation and a loss of night vision. These effects are cumulative and persist for several days. For this reason, individuals who work in bright sunlight and who are called on for night duty must be provided with suitably dense filters or sunglasses if their vision at night is to be maintained.

Proper lighting is always a problem in a dark environment, for paper work is also necessary. For example, altitude or heading information must be written on strips, and this is done at the lowest possible illumination-level so that the controller's dark adaption will not be impaired. In radar rooms, the placement of overhead lights is critical because the angles at which the displays are mounted sometimes produce reflections and glare, a condition that may be difficult to correct.

We have taken a quick look at some of the visual problems as they relate to air traffic control, and I hope that their effect on the human performance in the control system can be improved, for, in this system, the controller is the system.

SOME DISPLAY CONCEPTS IN AIR TRAFFIC CONTROL

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In modifying a radar display specifically for air traffic control, the designer can improve the display in two ways: He can remove unwanted information from the screen and he can add useful information. I shall deal first with some problems encountered in removing information from the screen.

Echoes from terrain, bodies of water, and permanent structures, for example, are not needed by the air traffic controller and can be eliminated from the display. In a broad-band, raw radar system, echoes from a storm would completely blank out an area of the display and obscure targets of interest within this area. Considered in this way, a storm is unwanted information, and since it produces a signal that is fairly constant, strong, and slow-moving, it could be considerably attenuated or eliminated from the display without interfering with the display of target aircraft. On the other hand, the location of storms is of considerable interest to pilots since they wish to avoid flying through them or even near them whenever possible.* The problem, then, is to design a display that will tell the air traffic controller the location, extent, and motion of storms and yet not interfere with the display of other information.

The Federal Aviation Administration has developed a system that will outline storms in the radar coverage. At preselected intervals in azimuth, the radar looks at the intensity of the return signal from precipitation and displays the range at which any given level of signal strength begins or ceases. Thus it is possible to supply information that might be converted into a contour map of an area of precipitation showing the outlines of two or more degrees of precipitation density, one within the other. Since the gradient of these precipitation densities has been found to be related to the degree of turbulence, this contour map can provide important information.

* Radar systems in use today can display storms, but current operating procedures do not require that air traffic controllers provide weather advisories or vector instructions for avoiding them. Controllers are permitted, however, to issue advice and vectors on request or voluntarily if their workload permits.

The question is: How can we best display this information to the controller? Perhaps the ideal way would be to provide a series of connecting lines between adjacent outline points. These connecting lines would appear very much like a topographical outline map and would show the intensity of the precipitation and the steepness of the precipitation gradients. Such an outline map would be impractical, however, since it would place too great a burden on the system's computer. If even two or three radar units were to provide as few as a couple of hundred outline points to a central control computer, the task of storing and connecting these points might occupy at least half of the memory and computational capacity of the central computer.

Weather outlines also could be dislayed as discrete points depicting the degrees of precipitation density at each selected azimuth interval. Hachures connecting points of similar density have also been suggested. These hachures, or cross-hatchings, could be either radial or tangential to the radar antenna site, but the radial hachures appeared to be the more practical. The FAA conducted a series of tests to compare the recognizability and the utility of discrete symbols with radial hachures. The basic questions were: What azimuth intervals were most recognizable and most useful for radar weather advisories or vectoring, and which type of symbol should be used to display weather information, discrete points or radial hachures?

These tests indicated that radial hachures at about an 8° azimuth interval with symbols (X's) placed upon the radial hatched lines to indicate the inner, denser precipitation contours were slightly more depictive and more useful to operating controllers than were discrete symbols. The primary reason for this finding seemed to be the increased perceptual continuity that the hachures added to the display. The hachures were sufficiently useful and acceptable to be recommended for use in air traffic control radar displays, provided that they satisfy engineering and cost requirements.

What have we added to the displays in the traffic control system? Clutter is the word most frequently used to describe it. An example of a possible future source of clutter is the information that the next generation of semi-automated systems will add to the display. This information will include such things as identity, altitude, and speed of targets and will thus be potentially valuable, but it must be presented so that it will not interfere with other information on the display. The FAA is studying not only the adequacy of displayed information but the degree to which this information might render the displays unreadable and the extent to which the additional information might "cost" the operating controller more workload (in the way of personal manual input to the system) than the value of the resulting information might merit.

The FAA believes that as more aircraft and more ground stations—terminals as well as enroute control centers—become properly computerized, properly connected, and properly fed with necessary information (original and changed flight plans, beacon identity, and altitude transponders) *without* the necessity for operating traffic controllers to "feed the kitty," there will be a minimal increase in controller workload with a maximal increase in valuable information to the controller and a measurable increase to the safety and convenience of the industry and the travelling public.*

* Photographic examples were shown of the various modes of weather display, a typical automated terminal display system, computerized display and alternate controller input systems.

THE HELICOPTER IN HIGH DENSITY TRAFFIC

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The present mission of U.S. Army aviation has required an increase in the number of its aircraft and pilots. Although the number of aircraft has increased, the airspace available to them has remained limited. This situation has increased the threat of mid-air collisions for U.S. Army helicopters and, therefore, has increased the need for developing better methods for preventing mid-air collisions.

Correspondence from the Department of the Army, Army Concept Team in Vietnam (ACTIV) requested that the U.S. Army Aeromedical Research Laboratory initiate a project designed to reduce mid-air collisions. Specifically, ACTIV indicated that one of the primary accident-producing situations occurred during daytime landings in confined, dusty areas. Helicopter downwash from lead aircraft often creates a "dust signature" that partially or completely hides the airframe and main rotor-blades of this aircraft from the view of following aircraft landing in the same area. This loss in visibility appears to be the primary cause of aircraft collisions.

There are several methods for preventing mid-air collisions that might be used singly or in combination with others. These methods are: (a) complete air traffic control by means of Instrument Flight Rules and the types of radar system necessary for complete control of airspace, (b) complex, aircraft-mounted electronic equipment designed to provide automatic station-keeping, or a less complicated system to warn of the presence of other aircraft within a specified distance, and (c) visual warning. Training, enforcement of proper procedures, and other techniques can supplement these methods of control.

Consideration of these methods resulted in the selection of visual warning as the most practical and timely approach to the problem. Visual warning during daytime operations can be accomplished by exterior lighting mounted on the aircraft and by conspicuous paint schemes applied to the exterior of the aircraft. A review of the potential advantages and disadvantages of these methods indicated that both were promising. It was therefore decided to test both methods by means of in-flight research.

PAINT

Because of the physical configuration of the helicopter, it was apparent that the maximum benefit could be expected from the use of paint on the main rotor-blade rather than the body of the aircraft.

A series of three separate studies were performed. The first study employed four UH-1 helicopters that had their main rotor-blades painted with various colors and patterns designed to increase their conspicuity, and in-flight observations confirmed the feasibility of this technique. Certain questions concerning brightness and color contrast schemes remained unanswered following this test, and, as a consequence, a second test involving the TH-13T helicopter was scheduled. The main rotor-blades of five aircraft were painted with different patterns and paints. A sixth non-painted helicopter flew as a control. One paint scheme was found to be superior to all other schemes tested. It should be mentioned that rotary-wing-qualified pilots acted as subjects and that their observations were made while flying above the test aircraft in a simulated operational situation.

In order to answer queries concerning the effects of painting a three-bladed helicopter, specifically the TH-55, a third test was conducted at the U.S. Army Primary Helicopter Training Center. The results of this study confirmed the findings of the previous tests.

Our results show that the most conspicuous pattern was the following (from the tip inward): ⅙ of the blade surface painted white, ⅙ red-orange fluorescent ("Day-Glo"), ⅙ white, ⅓ black, and the remaining ⅙ "Day-Glo."

Virtually all rotary-wing aircraft assigned to the U.S. Army Aviation Center and U.S. Army Aviation School have been painted according to this scheme. Recently, the U.S. Army Aviation Systems Command published an official guidance for painting the top surface of helicopter main rotor-blades in accordance with U.S. Army Aeromedical Research Laboratory recommendations.

EXTERNAL LIGHTING

Rotor-tip lighting. A review of the literature and personal inquiry revealed that previous studies had been performed by other agencies to evaluate the feasibility and effect of main rotor-blade-tip lighting. Since these systems had all been designed for nighttime use and employed low output, steady-burning incandescent lamps, it was obvious that this type of lighting was of little or no benefit for daytime use. After discussing the problem with representatives of the aircraft lighting industry, it was decided that the best light source available for daytime lighting was the xenon gas-filled discharge tube. These lamps are energized from a centrally located power supply containing a bank of capacitors. The resulting luminous output is one of very high intensity for an extremely short duration.

With the aid of a prominent aircraft lighting company, a system was designed and fabricated for field testing on a UH-1D (Huey) helicopter. This system was composed of a five-contact slip-ring assembly with brushes, two pairs of rotor-tip lights, a power supply, and various miscellaneous components. The power supply was designed to provide energy simultaneously for both lamps with a power output of 16 W/sec at a repetition rate of 60 flashes per minute. The lamps were designed to withstand acceleration forces up to 650 g's. The remainder of the installation kit, which included the transmission-mounted stand-pipe assembly, was furnished by a helicopter manufacturer.

One pair of lamps was configured to shine upward in a cone roughly 30° to both sides of the vertical. The second pair was altered slightly so that the hub side of the light cone remained the same, but the peripheral side was opened to include the area within 5° above the horizontal. The purpose of the larger wedge of light was to evaluate the possibility of using these lamps as an aid to visual station-keeping during formation flight and as an anti-collision device.

During test flights of the aircraft, preliminary observations made from another helicopter indicated that the lights were visible even though the hovering test aircraft was completely hidden by dust. Observations made during normal flight at night showed that the system functioned quite well as a nighttime anti-collision light when viewed from the same level or above. At the time of this report, formal in-flight evalution of the tip-light has been delayed because of unfavorable weather conditions.

Anti-collision lighting. Concurrent with the tip-lighting project, a preliminary investigation has also been made to evaluate the use of the xenon discharge tube as a daytime anti-collision warning device.

During the time these projects were in progress, there were several daytime mid-air collisions at Fort Rucker. The aircraft most frequently involved was the TH-13T light helicopter, which is primarily employed as an instrument trainer. In this capacity, it is normally occupied by an instructor pilot and a hooded student pilot.

A prototype high-intensity-discharge lamp system was procured with the physical characteristics of this aircraft in mind. This system included a lamp assembly, wiring harness, switch assembly, and power supply. The power supply was designed such that the energy levels could be adjusted to 32, 64, 96 or 128 W/sec.

This omni-directional anti-collision light was mounted on a TH-13T, and in-flight observations were made. To date, no formalized test program has been undertaken, but it has been compared to a 100 W oscillating quartz-iodide incandescent lamp, the brightest incandescent lamp available off the shelf. The comparison clearly demonstrated the superiority of the xenon flashtube as a daytime anti-collision light.

CONCLUSIONS

Improving the visibility of these small helicopters is essential for maximum safety in the training environment for the following reasons.

1. Since the student pilot is usually hooded, only the instructor pilot is able to scan outside the aircraft. The time during which it is possible for him to scan is severely restricted since he must also closely monitor the instruments and the actions of his student.

2. The aircraft traffic density is extremely high because a large number of students are being trained within a limited airspace.

3. The maneuvers of aircraft flown by student pilots are somewhat erratic and unpredictable.

4. The structural characteristics of the helicopter, such as the tubular tail boom, the small rotor blade, and the large transparent bubble, contribute little to the overall silhouette or conspicuity. When this helicopter is viewed against some backgrounds, it disappears from view.

5. The relatively slow movement of the aircraft in relation to its background also reduces the probability that it will be seen when viewed from above.

The responses from instructor and student pilots who fly in the training area have shown a unanimous enthusiasm for the painted rotor-blades. However, the painted blade is most effective when viewed from above. There is no doubt that the addition of high intensity omni-directional lighting would add immeasurably to the overall conspicuity of U.S. Army aircraft.

Under certain combat conditions, it might not be desirable to have painted rotor-blades. Should this situation arise, the use of high intensity lighting would be of significant value since the lights could be extinguished during those periods when minimum visibility is desired. On the other hand, they would be available at all times to enhance visibility when the tactical situation permits. We intended to continue the air-to-air testing of the paint scheme and the tip and omni-directional lighting systems singly and in combination with others until the most conspicuous arrangement is found.

MEASUREMENT OF HEIGHT AND DISTANCE INFORMATION PROVIDED PILOTS BY THE EXTRA-COCKPIT VISUAL SCENE

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During the first eight years of commercial jet operations, that is, prior to 1967, approximately 16% of the major aircraft accidents occurred during night approaches over unlighted terrain or water toward well-lighted cities and airports. Meteorological conditions in all cases were such that the flight crew could have employed visual reference to light patterns on the ground. In 1967, the accident rate under similar conditions rose to 17.5% (Anon., 1969). Accidents involving highly instrumented aircraft continue to occur during seemingly safe night visual approaches.

This article discusses one subtle aspect of night visual approaches that can lead even experienced pilots into dangerously low approaches. The investigations reported here are based on commercial jet experience, but the problem is thought to extend to all types of operations and equipment —commercial, military, and private.

The objectives of my research were: (a) to determine the degree to which night visual approaches are unsafe, (b) to determine how specific topography, light patterns, descent paths, and other related conditions result in inadequate visual information, and (c) to determine the degree to which external visual cues provide information that may conflict with instrument readings. The results of this research will be used to identify requirements for hardware and operational procedures necessary to make night approaches safer.

OPERATIONAL AND METHODOLOGICAL PROBLEMS

My major emphasis is on the visual aspects of landing approaches, and research results have convinced me that at least some of the "pilot error" ascribed to approach accidents is based on incorrect assumptions concerning normal human visual abilities. For example, pilots generally seem unable to judge a safe approach altitude by vision alone if the terrain has an upward slope. They fly too low. On the other hand, they tend to follow too high an approach when only the airport is visible. Another finding is that they tend to use the pattern of city lights as a horizon reference even if it results in flying with one wing low.

Others have written of "illusions" and warned pilots of perceptions of height and distance that might lead them into dangerous operational conditions (Anon., 1966; Coquyt, 1953; Part, 1968). Whatever the mechanism—illusions, subthreshold stimuli, or adequate but invalid stimuli—the fact remains that nonstructually related accidents are occurring during night approaches under good weather conditions.

In our study of night visual approaches, I studied the problem in three ways. First, I searched accident reports for clues relating the accident to the visual environment. Second, I analyzed night approaches in terms of the visual information available to the pilot and what he would need to maintain or correct his flight path. Special emphasis was placed on those situations in which information from outside the aircraft may tend to conflict with that provided by instruments. Third, I measured the actual path flown by experienced pilots in a simulator and compared this with requested path and with pilots' estimates of altitude.

It will surprise no one that a survey of accident reports involving commercial jets showed up many more differences than similarities in the visual environments where these accidents occurred. However, I was impressed with the difficulties faced by the pilot whose approach path provided him with a poor set of visual cues—not the absolute minimum of dense fog but rather conditions that would lead him to trust an approach on Visual Flight Rules when visual information is marginal or possibly misleading. The most obvious of these is the situation in which artificial sources of light provide the only visual stimuli.

The complex pattern of a city at night can replace the normal daylight cues to a great extent, and the experienced pilot can successfully rely on them most of the time to get his bearings. There is an overabundance of such reference points in an approach over lighted terrain. However, an approach over water or unlighted terrain means that the visual reference points occur at a distance where altitude and sink rate are more difficult to judge.

My objective was to measure the amount of information presented pilots by the scene outside the cockpit. This quantitative information was not available to those writing of "illusions" in prior articles. I needed to know the influence of this scene on the pilot's estimates of his altitude that he flew while letting down.

Obtaining these measurements by flying night approaches to cities on various terrain was not compatible with the requirements for safety, economy, or adequate experimental control. The use of motion pictures to provide the night visual scene for use in simulators also proved unsatisfactory. The extremely small point sources of light on the ground from 20 miles away at altitudes of 20,000 feet were too small and too dim to photograph on high-speed 35mm film. Slower film of higher resolution was not compatible with aircraft approach speeds and exposure times for night photography.

Photographing models of cities for experimental purposes is limited by film grain and also by the insufficient resolution of color film. Furthermore, photographing to provide specific viewing angles and uniform resolution is most difficult.

APPROACH TO THE PROBLEM

An approach to the problem was selected to provide good quantitative data, compatibility with the operational procedures and conditions, and pertinent aircraft characteristics. The applicability of the final data was thus maximized as follows: (a) analytical investigation of cities, flight conditions, accident records, and airline procedures in relation to visual abilities, (b) operational flights to obtain realistic data, (c) design and construction of a simulator containing the essential elements of visual operational conditions, (d) experimental investigation of pilot performance and judgments in aircraft approaches toward cities, (e) quantitative assessment of each of the factors and their interactions, and (f) recommendations for improvements in hardware, procedures, and training through application of research data.

DEVELOPMENT OF A TESTABLE HYPOTHESIS

Looking at the problem from the standpoint of the visual environment, I asked: Was there something about those approaches in the accident reports that might have resulted in insufficient information or in false information to the pilot? In this examination, I considered the visual angle that provides information to the pilot. This is the angle subtended at the eye by the nearest and farthest lights of the city as the pilot follows his flight path. To a pilot flying on a level course at a constant altitude, this angle increases as he approaches the city. To a pilot descending vertically at a constant distance from the city, this angle decreases. There is a specific flight path in which the visual angle subtended by the city remains constant. If the airplane is maintained on this path, the pilot may be losing important closure information without being aware of it. This approach path follows the arc of a circle centered above the pattern of city lights, with its circumference contacting the terrain. Such a path provides no changing projection of the topographic plane formed by the pattern of city lights along the dimension that is, in visual terms, most relevant.

In addition to the changing projection of the topographic plane, visual information is available from the relative motion of the light pattern as seen from the cockpit. However, since this motion must exceed approximately one minute of visual angle per second before it is perceived, approaches over dark areas do not provide relative motion cues until the aircraft is relatively close to the city. Figure 1 shows that at 240 mph and 3,000 ft altitude, motion would first be perceived at 8.5 or 9 mi out. When slowing and descending, as one would in an approach, the motion threshold occurs later. At 1,000 ft and a speed of 120 mph, the threshold distance would be 3.5 mi.

Figure 2 illustrates the way in which visual angle of topographic plane projection and perceived motion relate to flight path and aircraft velocity for approaches to level and to graded terrain. The area of greatest interest is between 10 and 3.5 miles out, where dangerously low altitudes and fast sink-rates may result from the interaction between inadequate visual information and topographic variation.

SIMULATION FOR NIGHT VISUAL APPROACHES

A simulator for night visual approaches was constructed and the first studies carried out with movie films taken of fluorescent chalk models illuminated with blue light. The cameras were equipped with proper

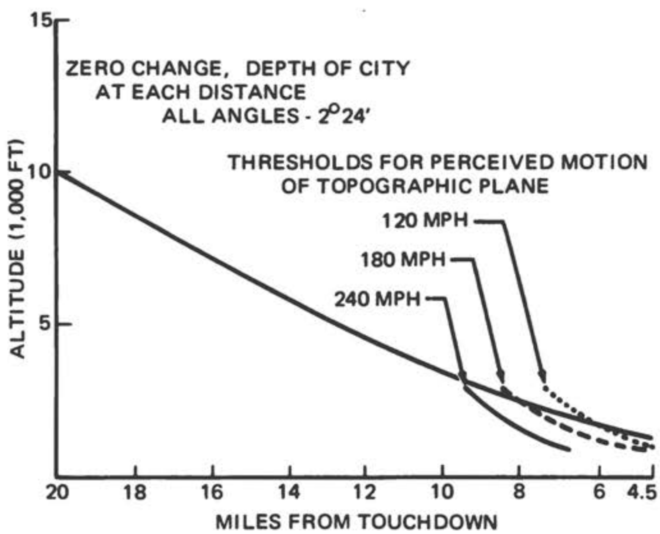

Figure 1—Zero change approach path and thresholds for perceived motion.

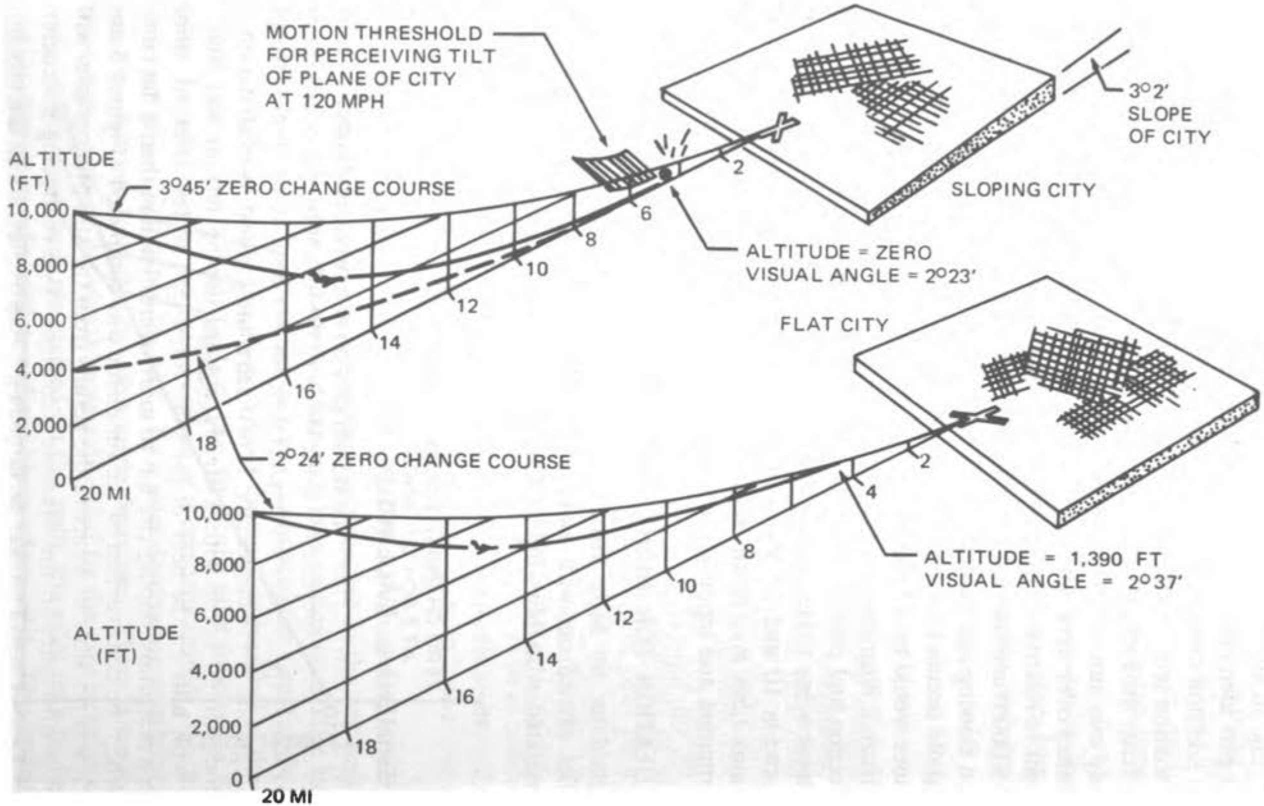

Figure 2—Influence of topography, distribution of lights, and motion thresholds on average approach paths.

filters and mounted on scaled approach tracks. With this simulation, the pilots provided altitude estimates but were not given control of their flight paths. In the current, more sophisticated simulation, the city model is situated atop an 8 x 10 ft table, which would appear as a large light panel if the city were removed. The city light pattern is made of thousands of tiny raised translucent bumps in an otherwise opaque film. The city thus remains visible at simulated ground level, with each bump a point source of light. Selective coloring has been used to simulate lights of sodium yellow, mercury vapor, and tungsten. The city model in the simulator is scaled 6 inches to the mile. There is a tendency on the part of the pilots flying the simulator to try to identify the city from their past experience.

The table containing the city moves vertically and is mounted on a wheeled carriage that moves toward the pilot on rails. The pilot's control of the stick and throttle in the cab is fed through the motors that drive the table along these two axes. Distance from 34 to 4.5 mi from the airport can be simulated. Maximum altitude is 16,000 ft; minimum altitude is minus 2,500 ft. The simulator is programmed to react like a 135,000 lb commercial airliner in an approach. Maximum forward speed in level flight is 380 mph IAS; maximum climb rate is 6,000 fpm; descent, 8,000 fpm. Stall speed is set at 110 mph IAS, and the aircraft loses altitude at the rate of 12,000 fpm under stall conditions.

To make the simulation realistic, the pilot's view was restricted to one eye because there would be no stereoscopic visual cues at the distances simulated as there are with the actual distances used in the simulator. The validity of the simulation is best indicated by the enthusiastic acceptance by experienced pilots of how realistic an impression it creates.

EXPERIMENTAL EVIDENCE

While the construction of the simulator's power, drive, and simplied computer was being completed, a static study of the influence of topography on night visual approaches was undertaken. In this static study, done with still photographs of the model city, I found that the greatest overestimation of altitude would occur with a steady upward-sloping terrain and that a city with hills on the near or far side would lead to less overestimation than a uniformly sloping city but to more overestimation than a flat city.

When the construction of the simulator was completed (Figures 3 and 4), it was possible to compare the results from the still photographs with pilot performance in the dynamic situation. Twelve Boeing instructors from Flight Crew Training each made 12 approaches, six to the city in a flat position and six to the same model at a 3° slope. They were informed of the slope or lack of it before each approach. Two other variables were

Figure 3—Simulator with pilot seat removed.

tested in the experiment: starting altitude (16,000 ft and 10,000 ft) and distribution of lights (airport only, airport with distant half of city, and airport with full city).

Pilots were instructed to choose their own approach path to the airport at the near edge of the display, except that they would attempt to be at 5,000 ft 10 mi out and at 1,240 ft 4.5 mi out, at which distance the problem ended. They were also asked to be flying 180 mph IAS at 10 mi out and 120 mph at 4.5 miles out. A recorder at the experimenter's station made a continuous record of the flight path generated by the pilot.

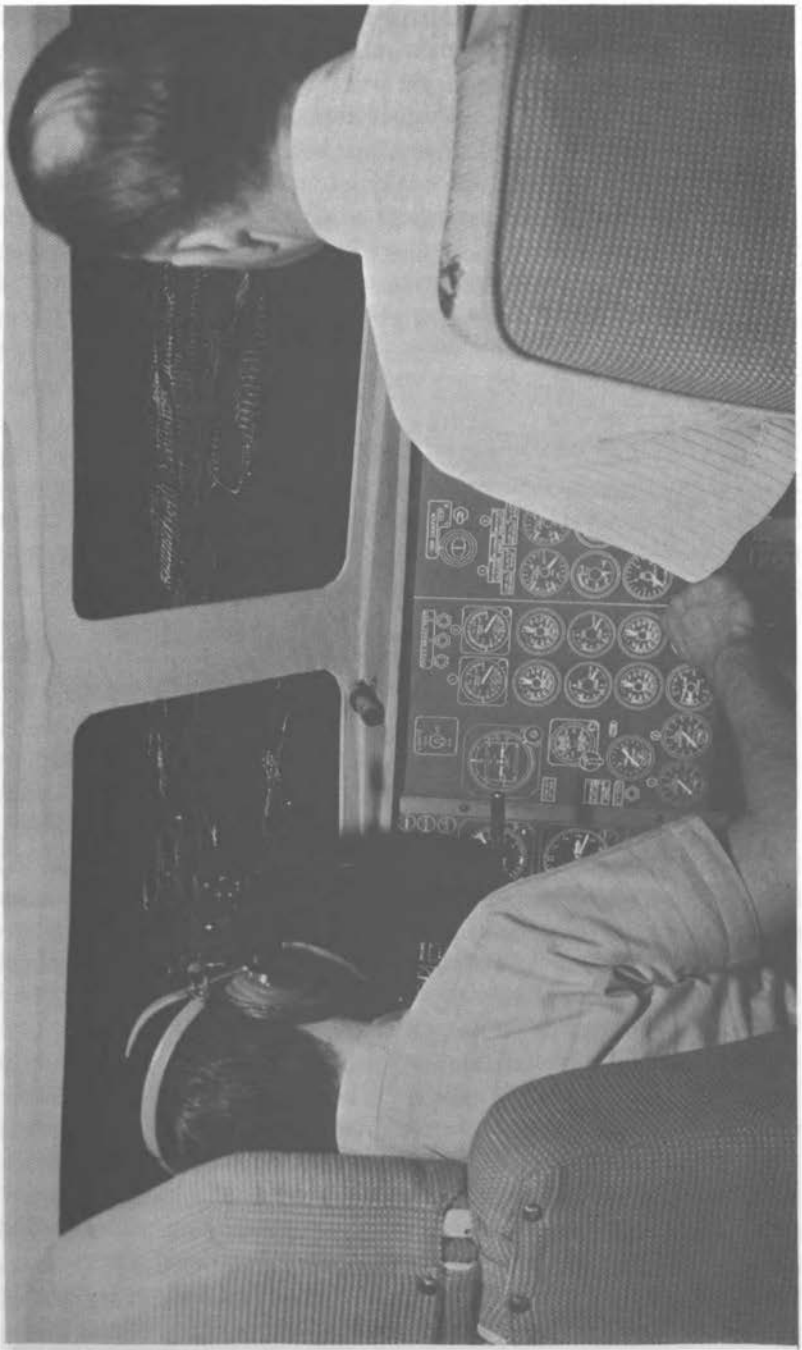

Figure 4—Test crew flying the Boeing simulator into "Nighterton."

During each approach, the pilot received eight requests for altitude estimates, starting at the 18 mi point. He was forced to guess because there was no altimeter in the cockpit.

To increase the workload on the pilot during his approach, he was required to report the presence of other aircraft in the area. Two simulated aircraft orbited over the city, one clockwise and the other counterclockwise. A special switching arrangement made one or the other aircraft visible for 10 seconds at a time, for a total of eight such exposures during each approach. The pilot was alerted to the presence of other aircraft when he heard communications between the ground and the airplane he was to locate. On detecting the other airplane, he was to report its position and altitude relative to his own and its heading.

EXPERIMENTAL FINDINGS

Homogeneous Terrain. The performance variable of major interest was generated altitude (the approach actually simulated by the pilot). Table 1 shows the relative importance of the effects of the main experimental variables on generated altitude.

TABLE 1. Sources of Variance in Altitude of Approach Paths.

Source	Percent of Variance
Pilots	24.9
Distances	19.8
Slope of city	16
Light distribution	4.3
Beginning altitude	—

One of the main variables, beginning altitude, had no significant effect on generated altitude. The remainder of the observed variation in performance (the 35% that does not appear in the table) occurred as a result of two or more variables acting together. All such interactions included differences in distances or pilots.

The largest source of variation in generated altitude (25%) is due to differences among individual pilots. While individual differences are typically large in human factors studies, that finding is particularly interesting in this study because it is assumed that approach paths would be rather standardized for commercial jet aircraft. The performance of Boeing pilot instructors in the simulator suggests that there are broad limits in the range of altitudes chosen on the basis of visual reference.

The second largest source of variation in generated altitude is distance from touchdown (20%). This measure is actually a difference score, the difference between a straight path (between requested altitudes) and the path flown. The pilot started his run at an experimenter-controlled altitude (15,840 or 10,000 ft) and was requested to be at 5,000 ft 10.0 mi out and 1,240 ft 4.5 mi out. Unexpectedly, this factor of distance from touchdown causes less variation in generated altitude than differences among pilots.

City slope, the main experimental variable, accounts for 16% of generated altitude variation and is the third most potent variable tested in this study. The effect of this variable was consistently that of causing the pilots to take a lower approach path, i.e., they flew lower when the city was sloping than when it was flat.

The remaining variable, distribution of lights on the terrain, had a small but significant effect on approach path (4.3%). It is the direction of this effect that is most interesting. One would expect that increasing the amount of visual information by adding lights would provide better reference information. However, the data suggest that more visual information may actually be detrimental if it tends to be misleading. Thus, the addition of lights in this study caused a greater deviation in approach path toward dangerous altitudes than was true when only the airport was visible.

It was anticipated that the detection of other aircraft would be easier when only the airport lights were on, and this expectation is supported by the data. Approximately four times as many aircraft went undetected when all or part of the city lights were on as when only the airport was lighted.

Returning to the major experimental variable of city slope and the performance variable of generated altitude, let us look at the two curves in Figure 5 for the effect of city topography on approaches to an airport when all the city lights are on. Although the pilots were informed prior to beginning each approach as to whether the city was flat or sloping, their flight paths were obviously quite lower when the city was sloping. The visual angle subtended at the pilot's eye by the city was very nearly the same at 4.5 mi for both cases—2° 49′ for the flat city, 2° 46′ for the sloping city. Beginning at the 8-mi point, the approach path to the sloping city was dangerously close to zero altitude.

What path did they think they were taking? Look at the shaded bars projecting upward from the points on the lower curve in Figure 5. The tops of the bars represent estimates of altitude at these points. It appears that these experienced pilots thought they were at approximately the same altitudes as they were in the approach of the flat city.

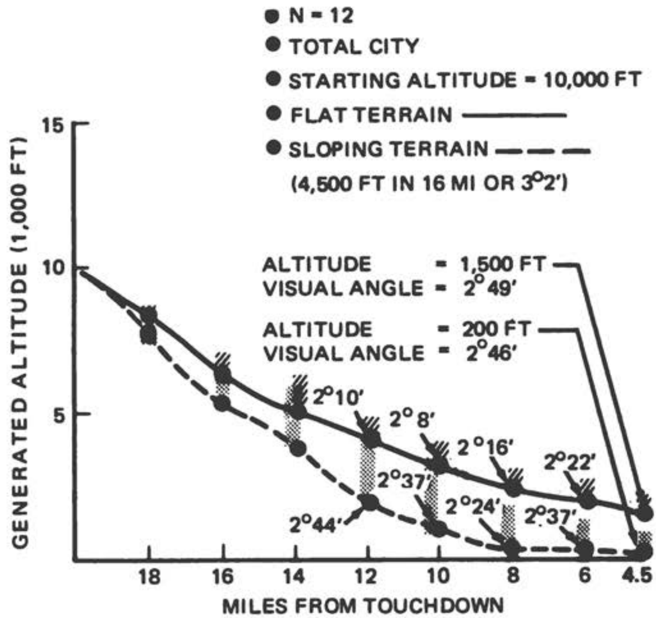

Figure 5—Influence of city topography on descent.

Heterogeneous Terrain. In the experiments discussed above, the runways, taxiways, and support areas had the same terrain as the city. Controlling airport terrain to conform with city topography allowed as to measure its effect as a separate independent variable. Although runway slopes exist that exceed 3°, they are much more commonly graded to be approximately level and, therefore, do not conform to the surrounding topography. The next logical step was to determine whether the influence of a sloping city was independent of the airport terrain.

In addition, there was the question of whether additional instrumentation providing pilots with rates of climb and descent (without absolute altitude information) would provide sufficient information for safe letdowns. It was an experimenter's "gamble" that these two variables could be studied in the same experiment using the prior experiment as a baseline.

The follow-on experimental design also included starting distance as a variable. Starting altitude had not proved to be a significant variable, but, despite the close relationship of distance and altitude in any let-down, one could not assume a common influence.

Therefore, the 2 x 2 factorial design used as independent variables (a) city terrain—a flat and a 3-degree slope and (b) starting distance—20 mi and 34 mi. The beginning altitude parameter was always 10,000 ft, and instrumentation included air speed (and this also was true ground speed) and rate of climb and descent. Prior experimentation had been done with a military seat, side-arm (rate) control, and throttle on left. This experiment's cab configuration was wheel and column, trim tab, and throttle on right pedestal.

First, I shall discuss the results with the 20 mi starting distance.

The average descent paths from 10,000 ft and 20 mi toward the flat and sloping (3°) city are not significantly different from each other. The final altitude for the flat city averages 1,800 ft, representing a visual angle of 3° 23′. For the sloping city, the final altitude was 1,470 ft, and this represents a visual angle of 5° 14′. The airspeeds at 10 mi were similar and about 10 mph less than requested. At 4.5 mi, the average airspeed was about 20 mph faster than the requested 120 mph. The standard deviations for speed were twice as large when the approaches were made toward the sloping city.

The estimated altitudes were higher than the generated altitude for both topographic conditions, which is consistent with our previous data. Differing from previous results was the absolute magnitudes of these estimates for the sloping city, as the estimates approximate the actual altitudes (See Figure 6).

In prior experimentation, the average generated altitudes indicated that pilots used the visual angle as a source of altitude information. Thus when the visual angle was "invalid," pilots proceeded to lower altitudes to match the experimentially familiar visual angle typical of flat terrain. In these earlier experiments, though, runways were on the same plane as the city whether it was flat or sloped.

The new data were gathered with a flat runway, and the slope of the city varied independently. The results obtained with the 20 mi starting distance indicated that the pilot allowed the visual angle to exceed that for a flat city when his approach was to a sloping city. Thus we might conclude that runway topography may be the source of altitude information and operates independent of the city topography.

A second conclusion would also apply, that the inclusion of rate of climb or descent information (combined with air speed) is sufficient for pilots not to follow the visual angle to too low an altitude.

Pilots, therefore, could have set up a specific approach-speed and descent-speed combination and could have depended less on the visual scene. This is particularly true since they are very practiced with the 20 mi/10,000 ft altitude combination.

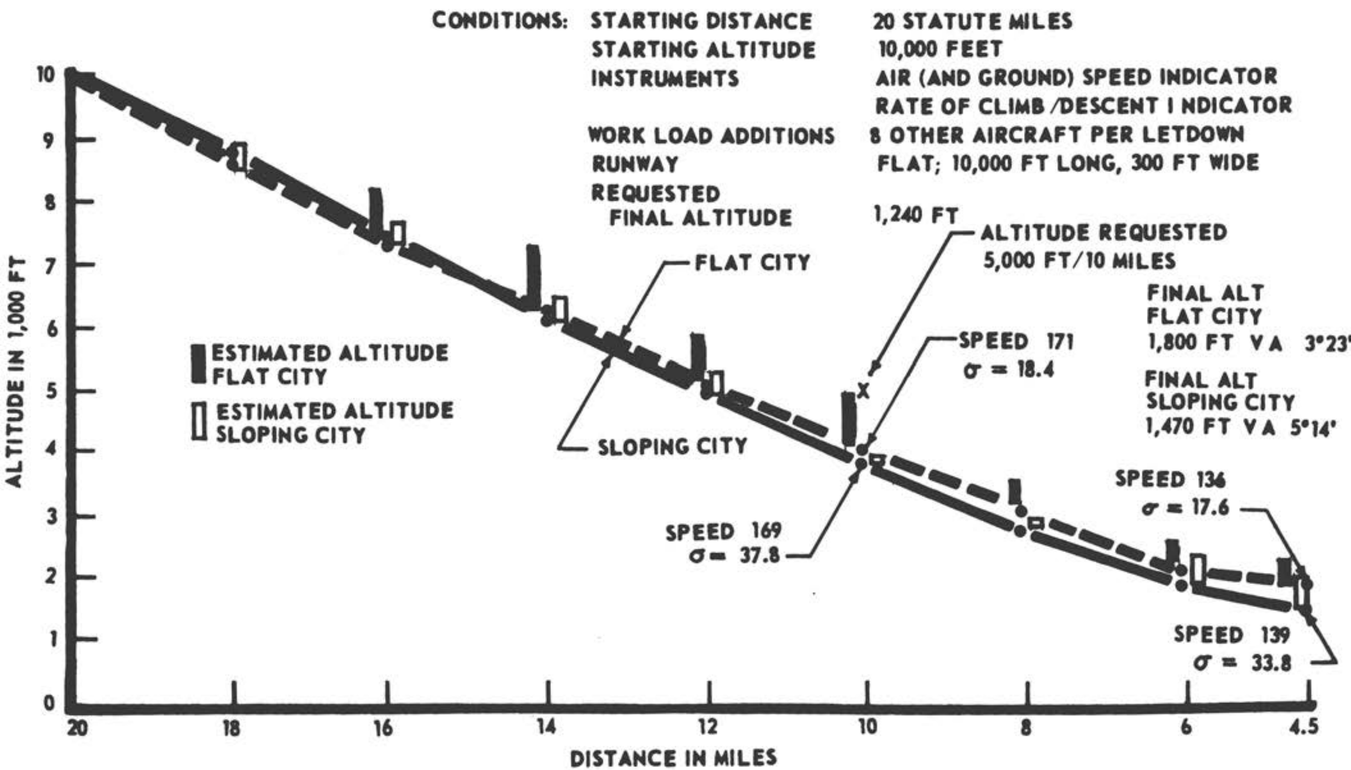

Figure 6—Average letdown performance to flat and sloping (3°) cities. Generated altitude.

Both of the above conclusions would be questioned if pilots followed the visual angle hypothesis with the 34 mi starting distance. The reasoning is that the descent from 34 mi is less familiar to the pilot. The elapsed time is longer and time estimations are more variable with the longer interval. Therefore, a fixed approach-speed and descent-speed combination becomes a less reliable technique with the unfamiliar distance-time relationship, and the pilot must again depend on the visual scene for altitude-distance information. This explanation is supported by the data since the visual-angle hypothesis is applicable when the starting distance was 34 mi.

Figure 1 illustrates the similarity of the final visual angles and the lack of similarity in generated altitudes. The estimated altitudes are almost identical inside of the 12 mi distance; the pilots generally underestimate their altitude when approaching the flat city and overestimate their altitude when approaching the sloping city.

I would conclude that the city light pattern does have an influence on the pilot's let-down performance independent of the plane of the runway.

These data were converted into difference scores by subtracting them from an ideal let-down profile. These difference scores were subjected to an analysis of variance. The F ratios in Table 2 indicate that all the main effects except starting distance are significant. Starting distance and topography of city interact significantly, and these statistics support the above interpretation as does the unusually large F ratio for the intersection of starting distance and pilots.

In prior experimentation, the flight deck workload of the operational situation has been approximated by introducing the task of visually detecting and reporting the presence of other traffic. This task has provided data that agreed with some operational data, i.e., the difficulty of detecting other aircraft at night increases with the presence of city lights. The

TABLE 2. Analysis of Variance of Deviation from an Ideal Approach Path.

Source	F	P
Terrain	16.9	$<.01$
Starting distance	2.57	NS
Distance (out)	13.33	$<.01$
Pilots	21.01	$<.01$
Terrain × starting distances	14.57	$<.01$
Terrain × distance (out)	1.56	NS
Starting distance × distance (out)	2.09	NS
Terrain × pilots	10.95	$<.01$
Starting distance × pilots	84.85	$<.01$

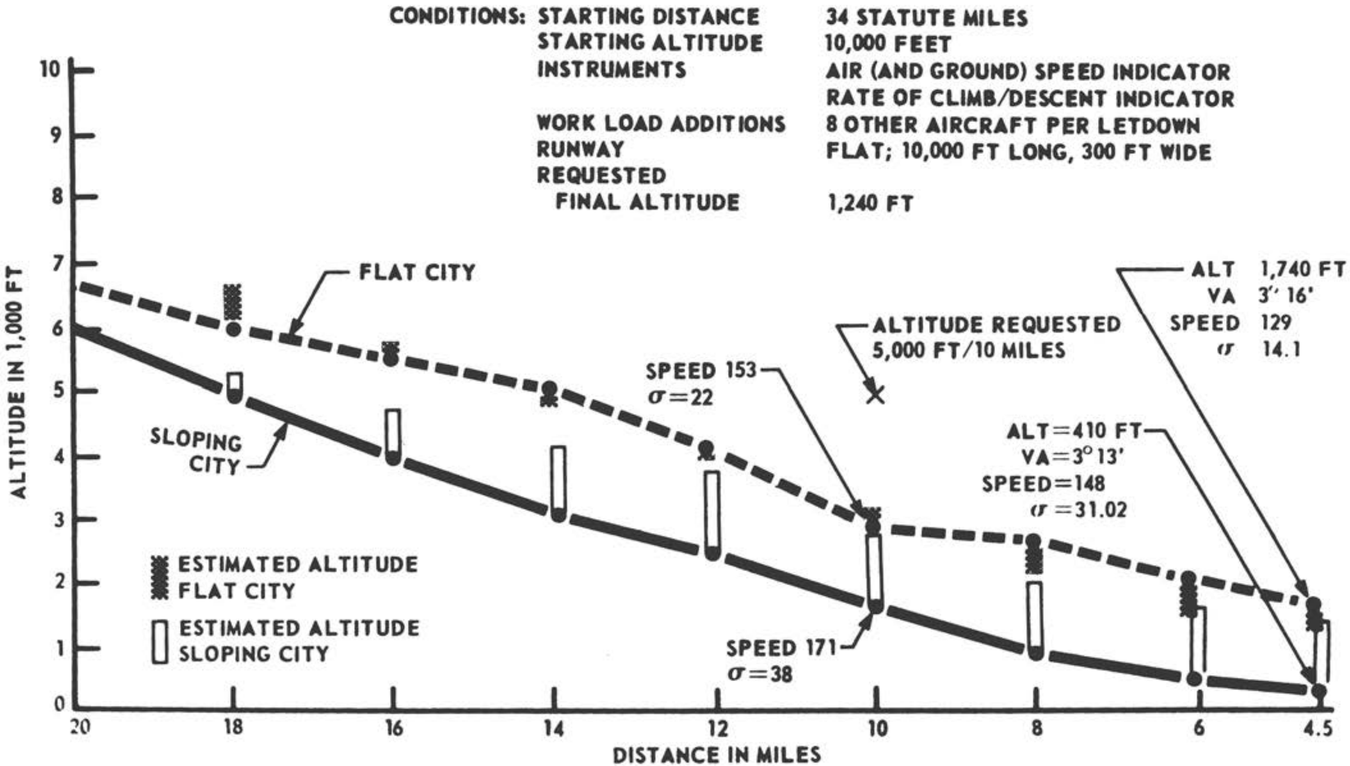

Figure 7—Average letdown performance to flat and sloping cities. Generated altitude.

operational data obtained by others indicated that flashing lights, high-intensity areas, and lights of similar color were, in that order, detrimental to detection of aircraft. These confusion stimuli exist in our simulation and our prior data indicate that the presence of city lights decreases the detection of other aircraft by a ratio of about 4:1.

In this study, the reporting of other aircraft task had three parts: (a) the location in azimuth of the other aircraft's position relative to the simulator's flight path, (b) the detection and reporting of the other aircraft's relative heading, and (c) the detection and reporting of its altitude relative to that of the simulator's altitude. Location was reported in clock position; heading as "toward" or "away," to the right or left; and altitude as "above," "same," or "below." The criteria was ±15% for the first two areas of judgment and ±1000 ft as the equal category for altitude. To put the difficulty of this task in perspective, one needs to know that no aircraft was presented for longer than ten seconds.

Table 3 indicates that the proportion of correct responses is similar for all of the sub-tasks, city topography, and starting distances. The average percentage is 35.6%, which indicates the difficulty of this task.

From the standpoint of air transportation safety, the most decisive data come from a review of all responses made in judging the other aircraft's altitudes. Previous discussions have dealt only with the frequency of correct responses in reporting other aircraft. Additional data are obtained by the quantitative examination of altitude separations and the associated judgment categories. These data indicate that city lights on sloping terrain have an influence on a pilot's judgment additional to those previously discussed. Other aircraft's altitudes are underestimated when viewed in the presence of lights on a slope. These underestimations will be of greater magnitude when the aircraft approaches the sloping city along a

TABLE 3. Percent Correct Reports of Other Aircraft During Approach.

Type of City	Category of Report		
	Location	Heading	Altitude
Flat			
20 mi	29	36	45
34 mi*	37	42	45
Sloping			
20 mi	32	34	32
34 mi*	36	35	24

* In this comparison, only the aircraft presented between the 20 mi and 4.5 mi points are considered, regardless of the starting distances.

descent path of a lower mean altitude. The range of statistically significant mean underestimations varies from 1100 ft to 3800 ft depending upon the combination of topographic and flight conditions. The implications for safety are obvious.

RECOMMENDATIONS

The modification of valid visual-angle information occurs as a function of natural, economic, and chance conditions; that is, topography, distribution of population, irregularity of lights within city limits, and attenuation of brightness and clearness of lights by atmosphere. Man has also made the design of certain cities or airfields more dangerous than others. He was designing, in these instances, for man's other comforts or safety when he created the more dangerous airports for night visual approaches. He locates airports away from cities, requiring approaches over water or over deserted farm lands, to avoid noise and potential injury for the terrestrial population. He builds airports by filling in shorelines and by using remote land. In solving some safety problems, he may unexpectedly raise others. Operations research people will undoubtedly see the need for their type of work in this problem.

The following features of cities, airport, and approach are considered to aggravate this problem: (a) an approach over dark land or dark water where lights to the side and below the aircraft do not exist, (b) a long straight-in approach to the airport located on the near side of the city, (c) an airport runway length-width relationship that is unfamiliar to the pilot, (d) the airport situated at a slightly lower elevation and on a different slope from the surrounding terrain, (e) the navigational facility located some distance from the airport, (f) substandard lighting of the runway with no other landing aids available, (g) a sprawling city with an irregular matrix of lights spread over various hillsides in back of the airport, and (h) industrial smoke or other obscurations, which decrease the brightness of lights and make them appear farther away.

The data being developed at Boeing support the visual-angle hypothesis as one systematic explanation of night visual approach accidents. Investigations of possible solutions to this problem and their interaction with other phases of operations will take time. However, there are immediately available means for potential reduction of night visual approach accidents. These include more frequent references to a barometric or radar altimeter, cross checks with other crew members, and, most important of all, knowledge and awareness of the special problems associated with these approaches.

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VISUAL ILLUSIONS IN AIRCRAFT ACCIDENTS

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Bell and Chunn (1964) have shown that spatial disorientation and visual restrictions were the psychophysiological factors responsible for approximately 22.3% of the aircraft accidents that occurred between 1957 and 1961. In a review of aircraft accidents in the U.S. Air Force, restricted vision and spatial disorientation were shown to be involved in 28% of all major accidents (U.S. Air Force, 1962). Nuttall and Sanford (1959) found that spatial disorientation was the cause of 4% of all flying accidents and 14% of all fatal accidents in a major overseas command. Zeller *et al.* (1955) identified "faulty distance-rate-of-closure on the part of the pilot" as the primary cause of undershooting or overshooting in nonemergency accidents.

The U.S. Air Force is not alone in accidents caused by illusory phenomena. Ruffell-Smith (1956) credited disorientation as the most common probable cause of fatal accidents in the Royal Air Force. More recently, the Military Airlift Command found that the number of landing-short accidents caused by illusory phenomena resulting from visual, emotional, or vestibular factors continue to constitute a major portion of all U.S. Air Force accidents.

It is the purpose of this article to analyze some of the visual factors that contribute to disorientation and faulty distance judgment so that this information can be used to analyze and prevent aircraft accidents.

VISUAL ILLUSIONS ASSOCIATED WITH ACCELERATION

Mach (1875) reported that vestibular stimulation could result in a visual illusion, and many subsequent investigators have added to our knowledge of the oculo-vestibular reflexes. The advent of high performance aircraft and manned spacecraft has served to emphasize the role of the vestibulo-ocular reflexes and their importance in the spatial orientation of man.

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A simplified functional description of the non-auditory or vestibular division of the inner ear will be briefly presented (Figure 1). On the floor of the ampulla of each of the three semicircular canals lies the crista ampullaris. The crista ampullaris is covered with hair cells. The hair cells are embedded in a gelatinous substance, the cupula, and project toward the ampullar roof. A component of each angular acceleration acts in the plane of one or more of the semicircular canals. The rotational inertia of the endolymph within the ampulla and semicircular canal deflects the cupula and its hair cells. This deflection is transduced into neural impulses that are transmitted along the ampullary division of the vistibular nerve to the vestibular nuclei. From the vestibular nuclei, the neural impulses are distributed to the central nervous system.

On particular parts of the floor and walls of the utricle and saccule are

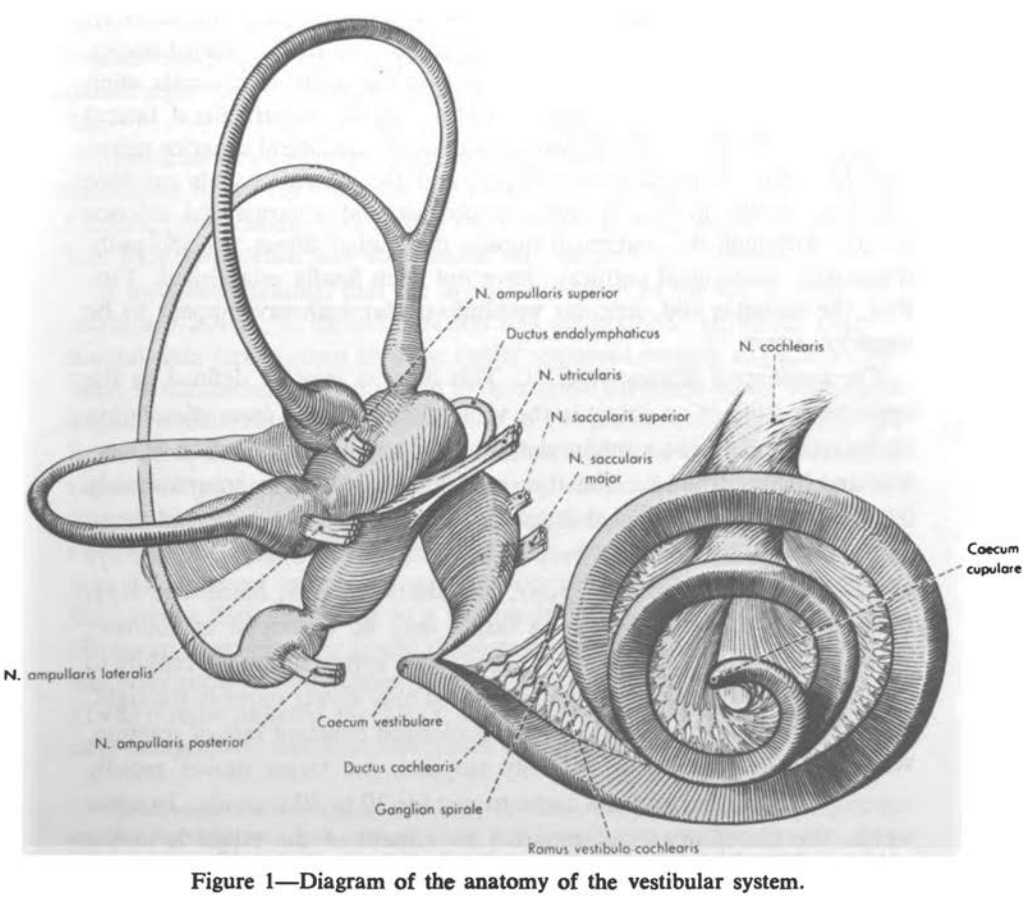

Figure 1—Diagram of the anatomy of the vestibular system.

located sensory epithelia, the maculae. Macular hair cells project into gelatinous matrix of the otolithic membrane covering the macula. Calcium carbonate granules embedded within the matrix create a difference in density between the membrane and the endolymph. When linear acceleration occurs, the otolithic membrane slides over its macula. This sliding bends or shears the hair cells and is transduced by the hair cells into neural activity. The neural impulses contain information concerning both the magnitude and direction of the linear acceleration. The impulses pass out over the utricular or saccular branches of the vestibular nerve to the vestibular nuclei for transmission to the central nervous system.

Thus, the semicircular canals are stimulated by angular acceleration while the otoliths, the sacculi, and the utricle are stimulated by linear acceleration. The neural activity from both the semicircular canals and otoliths serves to bring about postural and orientation reflexes. Vestibulo-ocular reflexes are initiated by way of the medial longitudinal fasciculus and the nonspecific reticular formation through the III, IV, and VI nuclei. Szentagothai (1950, 1964) has found that the horizontal canals elicit responses in the ipsilateral medial rectus and the contralateral lateral rectus; the superior canals show responses in the ipsilateral superior rectus and the contralateral inferior oblique, and the inferior canals produce responses in the ipsilateral superior oblique and contralateral inferior rectus. Although this statement implies that rather direct, specific pathways exist, anatomical pathways have not been finally established. Further, the saccular and utricular vestibulo-ocular pathways appear to be more uncertain.

The oculogyral illusion (OGY). This illusion may be defined as the apparent motion of an object in the visual field resulting from stimulation of the receptors of the semicircular canal by angular acceleration (Graybiel and Hupp, 1946). The threshold for the OGY is approximately 0.2° to 0.3° of angular acceleration per second; however, reported threshold values in the literature vary from $2.0°/sec^2$ to $0.035°/sec^2$ (Buys and Rijilant, 1939; Graybiel, Kerr, and Bartley, 1948; Mann and Ray, 1956). The apparent motion of target may be described as follows: When a subject is rotated to the left, the target appears to move rapidly to the left, gradually becomes motionless, then may slowly move to the right. The target appears motionless with a prolonged constant rate of rotation. When the left rotation is suddenly stopped, the target moves rapidly toward the right and may not come to rest for 30 to 40 seconds. In other words, the direction of the apparent movement of the target is in the direction of the angular acceleration.

The magnitude of the OGY varies with the rate of angular acceleration, position of the head, illumination of the target and background, complexity of the background, acoustic noise, and the experience of the individual. In ordinary daylight the apparent motion of a target is seen only after a relatively high rate of angular acceleration. Strong illusions can be initiated with smaller angular accelerations in darkness.

The most important implication of the OGY to the pilot is that a relatively small angular acceleration of the type encountered during flight maneuvers may produce a marked illusion. This is particularly true for night operations since the semicircular canals possess a threshhold of approximately $0.3°/sec^2$ at low levels of illumination.

The "graveyard spin" furnishes an example of the danger of this illusion when it occurs during flight maneuvers. If the pilot makes an abrupt maneuver to the left, large angular accelerations usually result. After recovery from the abrupt left maneuver, the pilot experiences the sensation of turning to the right. If the pilot attempts to correct the apparent right turn, the aircraft will again be placed into a left turn (Figure 2).

Thus a series of aircraft maneuvers could result in an illusory situation hazardous to the operation of the aircraft. Since OGY is a compelling illusion, pilots should be aware of the circumstances in which it occurs so that they will realize that they should rely on their instruments.

It has been assumed that the apparent motion in the OGY would be continued as long as the acceleration was maintained. However, experimental data have shown that the initial apparent motion stops, may reverse in direction and then return to its original direction under continued angular acceleration. The explanation of the phenomenon is believed to lie in either the characteristics of the endolymph fluid or an adaptation of the neural pathways between the sensory elements in the semicircular canals and the apparent motion perception. Since the endolymph possesses the inertial characteristics of fluids, it would be logical to assume that during some period of constant acceleration the movement of the fluid would cease, resulting in a change in the stimulus to the receptor. However, nystagmus* is found throughout the period of acceleration and has been shown to be related to vestibular stimulation. Whiteside *et al.* (1963) reinvestigated the OGY for human subjects with real targets, after-images, and simultaneous presentations of the two. They concluded

* Oculovestibular nystagmus is a type of reflex eye movement resulting from angular acceleration. The eyes move in one direction to maintain fixation, then swing back quickly in the opposite direction. The initial slow deviation is called the slow phase, and the quick return is called the fast phase of nystagmus.

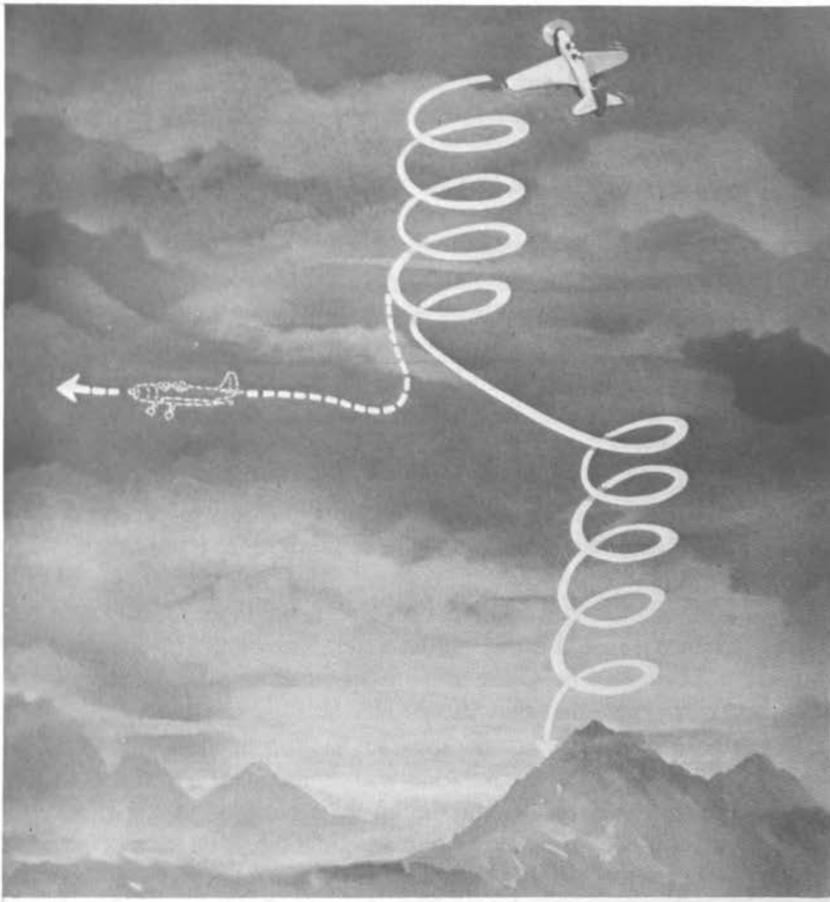

Figure 2—The graveyard spin. In recovering from a prolonged spin, the pilot perceives the start of a spin in the opposite direction. (The dotted line indicates perceived motion; the solid line shows actual motion.) Correcting for this impression, he goes into another spin in the original direction.

that "the apparent movement is associated with efferent activity in the agonist to the slow phase efferent activity present as a result of labyrinthine stimulus." Further, Gruesser and Guesser-Cornehls (1960) have shown activation and inhibition interactions between single neurons of the visual cortex when the vestibular nuclei were electrically stimulated. Therefore, the vestibular interaction with the visual system apparently occurs in both the efferent and afferent visual systems. This could result in an inhibition of the illusory motion and, yet, in continued stimulation of the nystagmus.

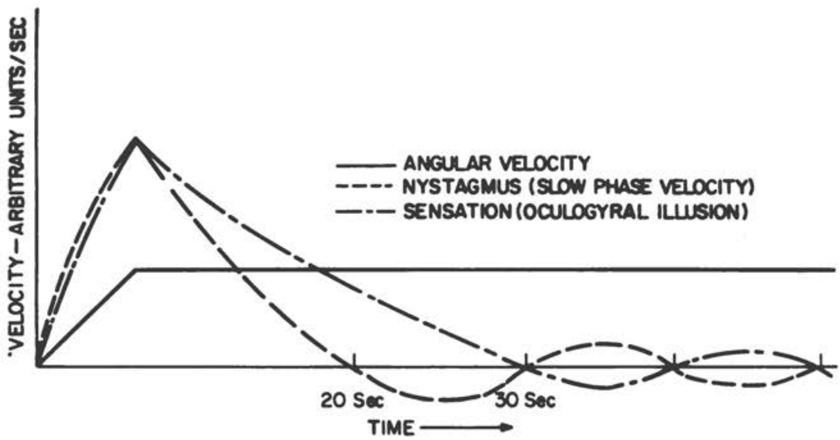

Figure 3—Schematic relationship between angular velocity of the stimulus, slow phase velocity of the nystagmus, and sensation (after van Egmond, *et al.* 1952).

The OGY is a sensitive indicator of vestibular stimulation (Hallpike and Hood, 1953). Geldard (1953) has suggested that visual effects from angular acceleration are correlated with nystagmus responses. However, it is much more likely that the OGY is more closely related to the rotary sensation (Byford, 1963). Cramer (1964) has found that the dynamic characteristics of the OGY are different from nystagmus responses when determined from the relationship between phase distortion and frequency of harmonically varying accelerations. The responses of sensation and nystagmus to another kind of acceleration are shown in Figure 3. It is necessary to show nystagmus and sensation separately because, to some extent, they utilize different parts of the nervous system.

Repeated angular acceleration in aircraft or on other mechanical devices reduces sensitivity to angular acceleration in that it raises the threshold, causing the response to supraliminal accelerations to become attenuated. Pilots demonstrate this attenuated response to angular acceleration in the sensation cupulogram* and the nystagmus cupulogram (Beauchamp *et al.,* 1961; Beauchamp *et al.,* 1962; Aschan, 1954). Habituation to the OGY has been reported by several authors (Graybiel *et al.,* 1961; Guedry and Ceran, 1959; Guedry *et al.,* 1958). Guedry and

* The cupulogram is usually obtained by supplying an angular acceleration of a given magnitude to the subject for a certain period of time, then stopping the angular acceleration and measuring the length of time the sensation of movement persists. Plotting the angular acceleration as the ordinate and the sensation or nystagmus in seconds as the abscissa produces the curve identified as the cupulogram.

Ceran (1959) show habituation effects after only four experimental sessions (Figure 4). Graybiel *et al.* (1960) demonstrated habituation in subjects after 64 hours of almost continuous rotation. Most of the decline in the OGY occurred during the first 16 hours. It is interesting to note that, on terminating the 64-hours experiment, illusory difficulties opposite to those encountered during rotation persisted for several hours. This research suggests that the vestibular canal system is subject to training.

The oculogravic illusion (OGI). This illusion may be defined as the perception of tilt or translational displacement resulting from stimulation by linear acceleration (Graybiel, 1952). The magnitude of the apparent displacement is related directly to the resultant of the linear acceleration and the force of gravity. When a horizontal linear force is acting simultaneously with the gravitational force, the resultant force makes an angle, ϕ, with the direction of the gravitational force.

Research has shown that the apparent displacement angle, ϕ', corresponds quantitatively to the angle, ϕ, that the resultant force makes with the force of gravity. Thus, the apparent displacement of the subject corresponds to angle ϕ and is determined by the magnitude and direction of the resultant force. Therefore, the OGI appears to bring visual cues into conformity with linear accelerative cues for the orientation of a subject with the resultant force.

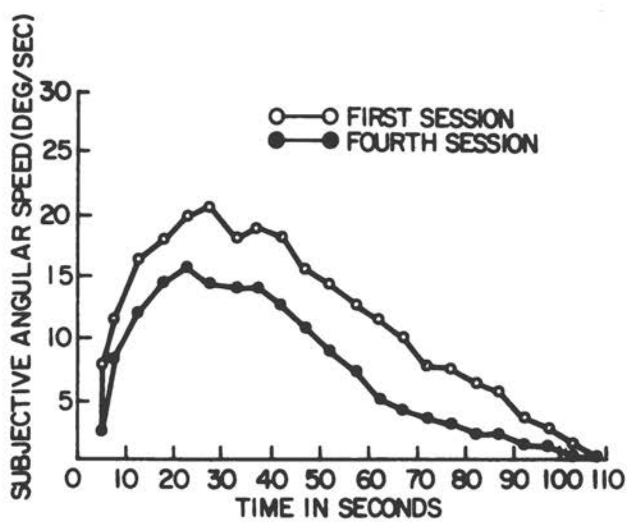

Figure 4—Subjective angular speed with respect to time during a 1.0°/sec² stimulus comparing the first and fourth sessions. Ten subjects, four experimental sessions at 1.5, 1.0, 1.5 and 2.0°/sec² angular acceleration (after Guedry and Ceran, 1959).

The illusion may be described briefly as follows: If a subject faces toward the line of the resultant force, he perceives an apparent change in body position as though he were being tilted backwards. An object on the horizon will appear to shift above the the horizon. Conversely, facing away from the resultant force results in the sensation of being tilted forward and an object will appear below the horizon. If a subject is at right angles to the resultant force, a horizontal line will appear to rotate clockwise if the direction of the resultant force is from left and counterclockwise if the direction of the resultant force is from the right.

Graybiel and Patterson (1955) established the threshold for a perceived change in the direction of horizontal or vertical at 1.5°. They report that this is equal to an increase of 0.000344 g; however, calculations reveal that this corresponds to 0.02 g at right angles to the gravity vector. Further work is needed to establish the quantitative value of the OGI threshold more precisely.

The OGI is not just a laboratory phenomenon. Clark and Graybiel (1952) Schock (1958), and Roman *et al.* (1962) have described upward displacements of fixed visual targets during aircraft maneuvers that increase g-force. In this respect, the influence of framework of visual reference and the initiation and cessation of the illusion are important considerations. As long as the pilot has an external visual reference, the illusion will be reduced to a minimum. Therefore, during daylight operations the OGI would be minimal, but during night and weather operations it would be maximal. Further, the onset of the illusion is 30 to 60 seconds after the stimulus, remains constant during constant stimuli, and ceases immediately upon cessation of the stimulus. Thus, if disorientation results from the false "illusory" information, reorientation should occur immediately upon cessation of the flight maneuver. However, if the pilot were already on a gravitational reference for spatial orientation (he is unfortunately prone to be on gravitational reference during night or weather operations), the onset of the illusion could be immediate. Thus, disorientation might result unless the pilot were well trained for instrument flying.

One potentially dangerous illusion related to vertical linear accelerations from turbulent weather deserves mention. Suppose the aircraft were taking off in inclement weather. Since the pilot usually flies IFR (Instrument Flight Rules) and cruise altitude is usually above the weather, he begins the process of leveling off as he reaches cruise altitude. If turbulence is severe during this leveling off, it is possible that a linear acceleration may exceed threshold and cause the pilot to feel as though the aircraft were still climbing. If he corrects for this illusory sensation, the aircraft will be placed into a dive, the result of which will be a crash if the structural limitations of the aircraft are exceeded. Complete reliance on instruments would allow the pilot to adequately interpret the situation and remain correctly oriented during such conditions.

The elevator illusion (Niven *et al.* 1963) and the oculoagravic illusion (Gerathewohl and Stallings, 1958) are special types of oculogravic illusion. The elevator illusion is induced by means of vertical linear acceleration. When the vertical acceleration is greater than 1 g, a real target is displaced upward while the visual afterimage is displaced downward. These relationships are reversed for vertical accelerations less than 1 g. Niven *et al.* (1963) attribute the elevator illusion to the otolith organs because labyrinthine-defective subjects fail to exhibit it.

Gerathewohl and Stalling (1958) found that an increase in acceleration produced downward movement of an afterimage while weightlessness produced an apparently upward movement of the visual afterimage. This latter phase of the illusion was termed oculogravic because it was associated with the subgravity condition of weightlessness. Schock (1958) and Roman *et al.* (1962) studied the phenomenon with the parabolic maneuvers of aircraft flown to produce weightlessness. The apparent displacement of a real target and an afterimage during a parabolic maneuver is shown in Figure 5. It can be readily seen that the apparent displacements of the target follow those expected from the acceleration profiles involved. These subgravity illusory effects could be expected to assume some importance in aircraft maneuvers when zero gravity follows

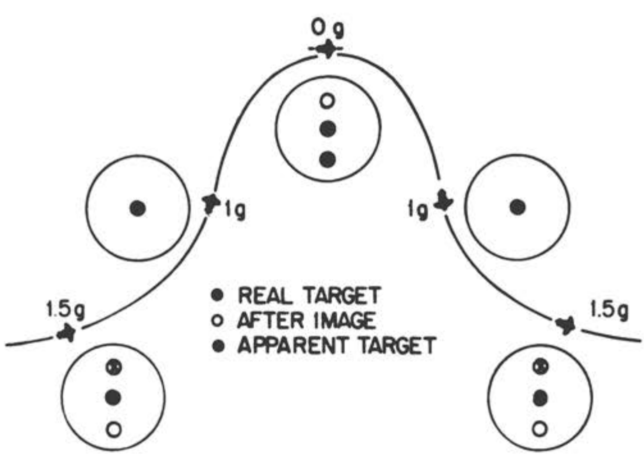

Figure 5—The apparent displacement of a real target and a visual afterimage during an aircraft parabolic maneuver (after Gerathewohl and Stallings, 1958).

quickly increased gravity. Since recovery from these effects would be almost immediate, however, disorientation would not prove hazardous unless repeated stimulation were encountered.

JUDGMENT OF APPARENT DISTANCE

During the landing phase of the flight profile, the pilot is busier than during normal flight, but, at the same time, he is more attentive to the procedures required for landing. Many of these procedures require visual observation prior to the pilot's making decisions regarding the safety of the landing. It is recognized that there is a wide difference of opinion regarding the visual cues necessary to land an aircraft and many of the visual variables remain unevaluated (Wulfeck *et al.,* 1958). A review of some of these visual factors may prove valuable in understanding the role that vision plays during this phase of flight.

One of the most important judgments a pilot must make during landing is the judgment of height of the aircraft. Of course, this height judgment is a complex function and involves the integration of continually changing visual impressions with past experience. It is greatly affected by both the speed of the aircraft and the angle of the glide slope. The distance, speed, and glide-slope judgments essentially combine into the problem of height judgment. There are several visual or physical factors involved in the judgment of distance. Throughout the discussion of visual factors utilized in landing an aircraft, it is assumed that the judgment of apparent distance corresponds exactly to the physical distance. While this is not always true, errors between apparent distance and physical distance are usually quite small and can be disregarded except in special cases. The important fact is that pilots use these apparent distance cues to formulate the perception of height and then set up their glide path and speed to touch down at a predetermined point on the runway.

Retinal disparity, or stereopsis, and accommodation and convergence are often cited as cues to apparent distance. Ittleson (1960) points out that the experimental evidence shows apparent distance as a determiner of accommodation and convergence rather than the reverse. In other words, changes in accommodation and convergence did not necessarily result in a change in the estimation of distance, but changes in the estimation of distance result in a change in accommodation and convergence.

The importance of stereopsis to flying or landing an aircraft would depend on the limiting distance for stereoscopic perception. For a person with a stereopsis threshold of 12 seconds of arc (0.000046 radian) and an interpupillary distance of 64 mm, the limiting distance for stereopsis would be approximately 1,300 m. Stratton (1898) reported the limiting distance at 580 m, which is equivalent to a threshold of 24 seconds of arc. At distances greater than 200 m, stereopsis is not reliable and is not possible at distances greater than 1,300 m. Thus, none of these factors is reliable for the pilot's distance judgments when landing aircraft.

The experimental determination of the limiting distance is difficult because secondary factors in depth perception become stronger and complicate interpretation of the data. Secondary factors are monocular in origin but usually contribute to both monocular and binocular vision. Monocular factors such as aerial perspective, apparent foreshortening, vertical position in the field, illumination, geometric perspective, loss of discrimination, gradient changes, and motion parallax are most often mentioned as contributing to depth perception.

Without doubt, perspective constitutes a strong cue in the judgment of distance. Such a judgment would be dependent on past experience and knowledge of the width and length and shape of runways. Ittleson (1960) states that "shape-distance relationships are closely allied with that of size." Further, the shape of any object cannot be divorced from its gradient or slant, and Gibson (1950) has stressed that the apparent shape and slant of surfaces are interrelated with apparent depth. Thus, perspective combines size, shape, slant, and other cues to provide one of the most important factors in judgment of depth. Because his judgment of depth is the product of a complex interaction of such determinants as his knowledge of the airfield, his past experience, and his present visual environment, a pilot would be expected to make poorer approaches and landings on unfamiliar airfields. This would be particularly true if the slant-shape-distance-size relationships were drastically different from those at airfields with which he has had previous experience.

Motion parallax is the apparent movement of objects in the visual field across the retina. Grindley (1942) presented discussions and calculations to show that a pilot could estimate touchdown distance during landing by the apparent movement of objects in the visual field.

The apparent movement of objects on the ground depends on the height, speed, and direction of flight. If the aircraft is descending at a constant speed and constant glide path, the touchdown point will be stationary in the pilot's visual field. All other objects in the visual field will be expanding from this point at different velocities. This expansion pattern will be constant as the airplane descends; however, the apparent velocity at any given point in the visual field will depend on the aircraft's distance from touchdown. If the pilot changes speed, glide slope, or aircraft attitude, the expansion rate of the visual fields will be different, but he still should be able to estimate his touchdown distance if he is sufficiently experienced.

An important fact regarding motion parallax is that when a moving observer looks at a stationary object the object will not move if the apparent distance and the real distance coincide. If the apparent distance differs from the true distance, however, the observer will experience movement for an actually stationary object. Thus, objects will have apparent movements different from actual movements if apparent distance and real distance differ.

Grindley (1942) maintains that the judgment of distance based on motion parallax or apparent retinal movement is no more complex than the previously discussed cues. Apparent movement does have the advantage of being independent of the size or discriminability of detail.

Approach and runway illusions. The reduced visual cues received by the pilot during landings at night and in inclement weather complicate the problem of distance judgments. Several studies have emphasized difficulties and shortcomings common to many approach lighting systems (Calvert, 1951; U.S. Navy, 1953).

There is always the danger of confusing approach and runway lights. When a double row of approach lights joins with the boundary lights of the runway, pilots have reported confusion in determining where approach lights terminate and runway lights begin. The beginning of the runway must be clearly shown, and this can be accomplished by installing radically different runway and approach lights or special lights separating the approach from the runway.

Approach lighting systems should be designed so that they do not give illusory or false information. When flying into a gradually thickening fog on approach, the pilot feels that he is climbing; in compensating, he descends too low. Under certain conditions, approach lights can make the aircraft seem higher when it is in a bank than when its wings are level.

The intensity of the approach and runway lighting system is important. For example, pilots have the impression that they are in a bank when they are actually flying level if one row of runway lights is brighter than the other. Robson (1956) has called attention to a rather unique illusion. If a single row of lights is used along the left side of the approach path, a pilot misinterprets the perspective and "corrects" his glide path to the right. Thus, the touchdown point would be too far to the right of the runway as the aircraft crosses the runway threshold.

The approach and runway lighting problem has received extensive research in recent years to minimize these illusions (Albers, 1965; Griffith, 1960 and 1961; Strong, 1959). As improvements are tested and evaluated, changes are incorporated into present systems. It is important to note that a standardized approach lighting system has not been adopted; therefore, one of the major hazards in approach and glide-slope systems is that different airfields utilize different systems and, consequently, complicate the pilot's task of making height and distance judgments on approach and landing. Instrument approach systems combined with a standardized improved approach lighting and glide-path system should eliminate or drastically reduce the false or illusory information received by the pilot.

When actual or physical height, x, corresponds to apparent height, y, the resulting glide slope provides a safe landing. Illusory cues may be provided by a runway that is narrower or wider than the runway to which the pilot is accustomed. Additionally, the runway slope and terrain around the runway approach can induce visual illusions. I shall attempt to illustrate these factors. In most of these illustrations, x will represent the normal glide path height; y will indicate the apparent height due to illusory cues, and x' will represent the compensatory glide path which the pilot uses so that the glide path will appear normal to him.

Illusions can result when a runway is narrower than that usually experienced by the pilot (Figure 7). The actual height of the aircraft for a normal runway width is $h + h'$. For a narrow runway, the pilot feels as though he were at $h + h'$ when he is actually flying at a height of h'; therefore, the apparent height does not correspond to real height but is somewhat less. Thus, the glide path results in a low approach and a tendency to undershoot or land short of the runway. An approach of this type could result in a serious aircraft accident.

While landing on a wider than normal runway, the pilot feels as though he were flying at h when is actually at a height equal to $h + h'$ (Figure 8). Again, the actual height does not correspond with the apparent height. The apparent height is somewhat greater than the real height. The glide path would result in a high approach and the tendency to overshoot or land down the runway. This would not be a serious illusion if the runway were long enough for safe braking.

Most runways are level, but those few that have some degree of slope provide misleading visual cues to the pilot. For the upslope runway (Figure 9), the pilot feels as though he is at y height above the terrain; therefore, in an attempt to fly a normal glide path, his compensatory glide path at x' results in landing short of the runway. A similar situation occurs when there is a downslope in the approach terrain; i.e., the compensatory glide path results in landing short of the runway (Figure 10).

The downslope runway provides illusory cues that make the pilot believe that he is lower, y, than his actual height, x. To compensate for this belief, he flies a compensatory glide path, x′, that will result in his landing long or overshooting the runway (Figure 11). Upslope terrain in the approach zone creates a similar illusory effect (Figure 12).

If a pilot is in doubt concerning the runway and approach terrain slopes, he should "drag" the landing strip to become aware of any illusory effects that may be present. It should be emphasized that a pilot usually encounters multiple illusory cues instead of the simplified single cues mentioned above. Combinations of these cues may serve to lessen or increase the total illusory effect. A severe illusion might result from a narrow, upslope runway and downslope approach terrain. Conversely, an upslope runway could be cancelled as an illusory problem by upslope terrain or a wide runway, or both. Inclement weather and poor ambient luminance would probably increase the effect of these illusions.

It may be valuable for pilots to be aware of other deviations from his usual surroundings that may result in poor height and distance judgments or give false cues for landing. For example, an approach over water reduces visual cues to a minimum and pilots not accustomed to such approaches tend to fly too low. Objects on the approach path may serve as false cues to height. If a pilot were accustomed to approach over large evergreen or spruce trees and were required to land in the Aleutian Chain, he might misjudge his height and distance from the runway because the spruce trees in the Aleutians are small and scrubby.

One of the best means of eliminating or reducing aircraft accidents resulting from these types of illusory cues is through careful briefing of the crew prior to flight. Pilots must not be allowed to forget that their distance and height judgments can err considerably in an unfamiliar environment. Such errors can be prevented by makine a simulated landing before attempting an actual landing. Good aircrew briefing and discipline are necessary to achieve safe approach and landing procedures over all types of terrain and landing-field configurations.

This discussion of the visual factors that ordinarily aid the pilot in estimating height has not been exhaustive; only the most important were included. Of the factors discussed, perspective and motion parallax afford excellent cues to depth but can be modified easily by changes in aircraft speed or glide slope. It should be emphasized that the overall distance perception is the result of complex integration of these visual cues with past experience and that any change in the visual cues may result in a different depth judgment. Any time there is a change to an unfamiliar situation, substantial errors in judging distance may occur.

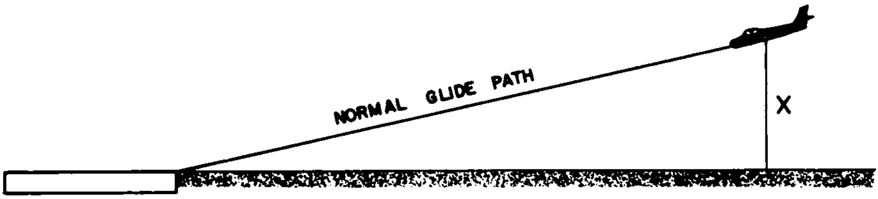

Figure 6—Normal approach glide path.

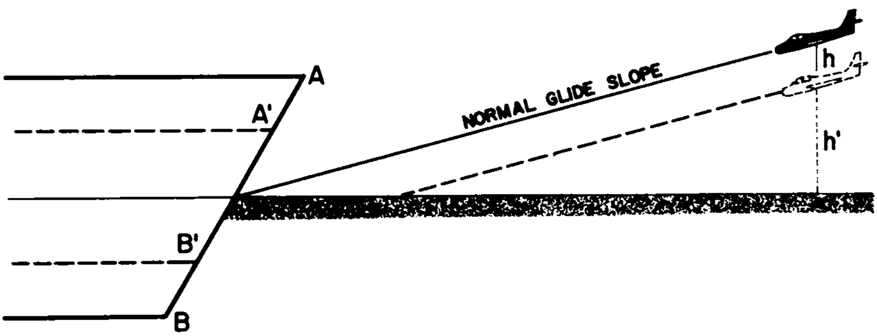

Figure 7—The effect of a narrower versus a normal width runway on landing an aircraft. AB is the width of a normal runway; A′B′ is the width of a narrow runway; h′ is the height for a narrow runway; h + h′ is the height for a normal runway. At the same point in the approach the pilot feels as though h′ is equal to h + h′. A normal glide path at height h′ results in the tendency to undershoot or land short of the runway.

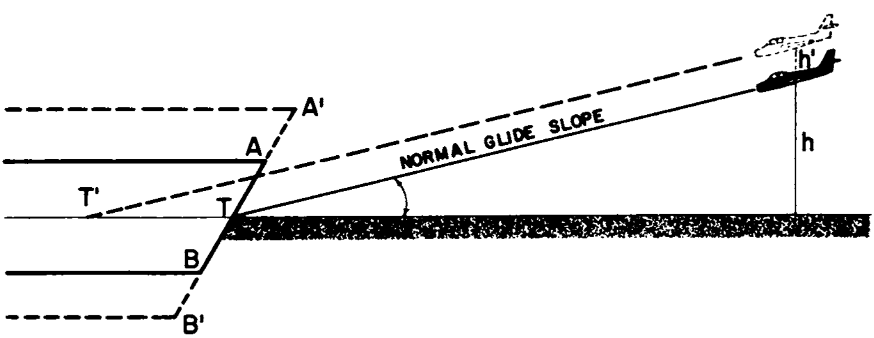

Figure 8—The effect of a wide runway versus a normal width runway on aircraft landing. AB is the width of a normal runway; A′B′ is the width of a wide runway; h is the height for a normal runway; h′ + h is the height of aircraft for a wider runway. At the same point in the approach, h + h′ is thought by the pilot to be equal to h. Thus, the aircraft's normal glide slope results in an overshoot or landing too far down the runway.

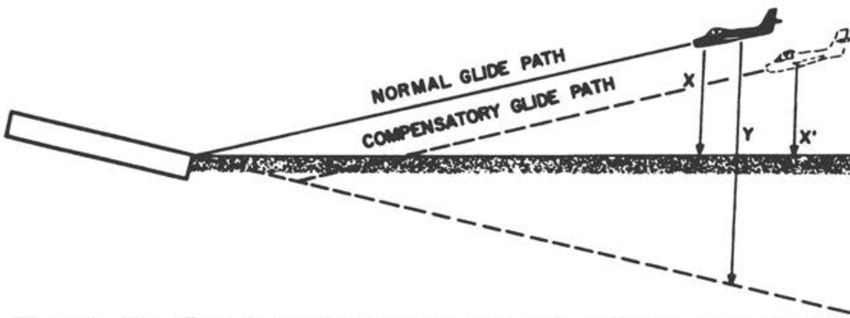

Figure 9—The effect of runway upslope on glide path. When the runway has an upsolpe, the normal glide path will seem too steep. Flying in glide path that appears more normal could result in a landing short of the runway.

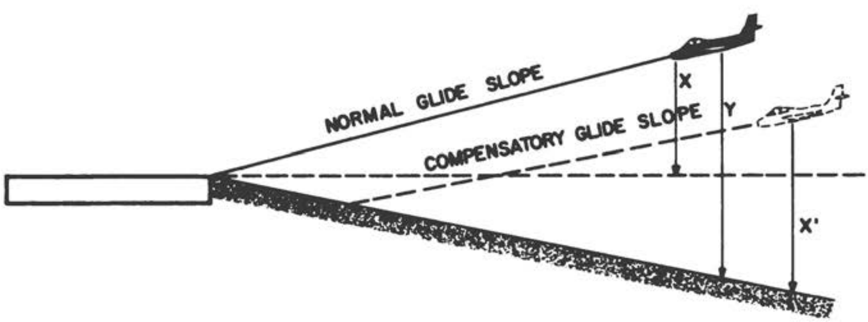

Figure 10—The effect of terrain downslope in the runway approach on aircraft glide path. With a terrain downslope, the pilot will believe the aircraft to be on low, flat approach, and there is a tendency to land short of the runway.

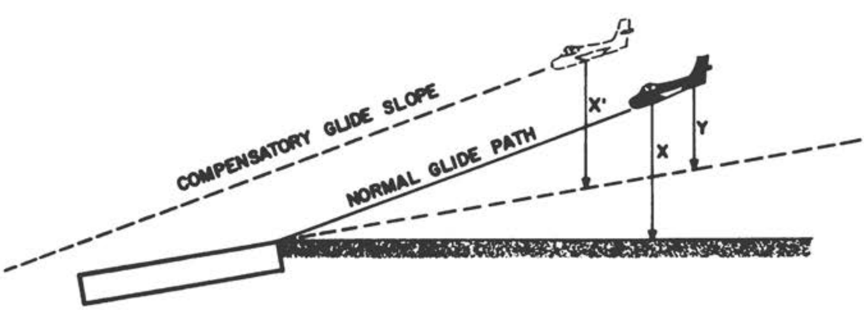

Figure 11—The effect of runway downslope on the aircraft glide path. When the runway has a downslope, the normal glide path will appear flat, and there is a tendency to overshoot.

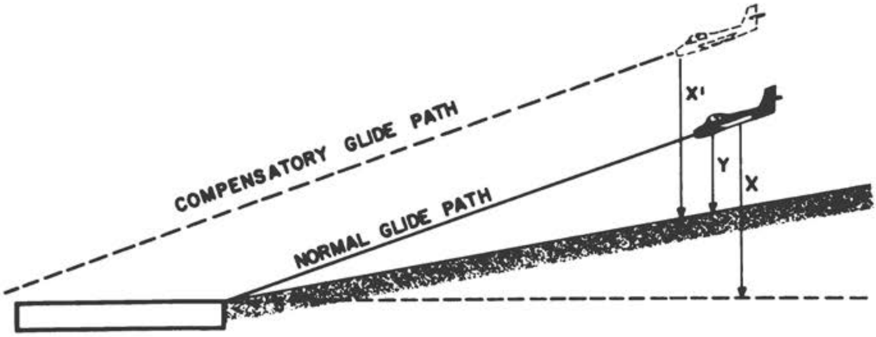

Figure 12—The effect of terrain upslope on the aircraft glide slope. When there is an upslope in the runway approach zone, the aircraft appear to be above normal glide path. To compensate, the pilot would fly a glide slope that results in a long landing.

Furthermore, the greatest degradation in visual cues occurs in darkness and inclement weather. Thus, these conditions require special training and the constant use of instruments to insure safe approaches and landings.

Standardized runway and approach lighting systems would certainly aid the pilot in his height and distance judgments by providing nearly identical visual cues for each landing. Thorough briefing before flying into a strange or unfamiliar airfield is necessary. Even when an adequate briefing has been given, a pilot should "drag" the landing strip at least once before landing to familiarize himself and the rest of the aircrew with the approach and runway. A portable self-powered approach lighting system would be desirable at remote airfields to aid the pilot in maintaining the proper glide path.

A pilot must trust his instruments and cross check those that give him information on aircraft attitude. All instruments seldom fail at the same time, and pilots should be trained to rely on their instruments even though the instruments contradict seat-of-the-pants orientation cues. Therefore, instrument performance should be an integral part of each annual checkride.

It is recommended that investigation teams for aircraft accidents compile data relative to runway conditions, i.e., width, length, lighting, and surrounding terrain. These data would probably reveal the factors responsible for certain types of accidents and remedies could be devised to correct the misleading cues in any particular situation.

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SUMMARY

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Our speakers have done an excellent job of summarizing a number of problems involving visual factors in transportation systems that merit our serious concern. I would like to summarize what for me have been the high spots of the various presentations preparatory to our general discussion.

William Neidig, of the Eastern Conference of Teamsters, has made a number of significant points. One of them, which has appeared in other forms in the presentations of other speakers, concerns the failure to consult with users in the design and development of transportation systems. Neidig has made a very good case for the value of obtaining the advice of the truck driver on matters of the design of the truck cab, mirror systems, and other aspects of the vehicle. He suggested that valuable information that might be obtained from drivers has not always been sought and, judging from the designs currently in use, not always been followed if it has been sought. Also, it would certainly be possible to design better road signs. Much work is being done on these signs, and some of it has been presented to us by another of our speakers. It is clear that additional work is needed, however, and it is also clear that there has been too little effort to standardize the size and location of signs, particularly in the case of signs giving place information.

A point made by Neidig that I have not heard emphasized in vision research is the matter of the loss of information in peripheral vision with increased speed. Relative motion of images on the peripheral retina increases greatly with increased speed, and hence the information that may be derived from peripheral vision can be expected to be reduced accordingly. Neidig has given us the figures of 50% loss of visual field at a speed of 30 mph as compared with standing still and 75% loss at a speed of 60 mph. He emphasized the need for movement of the head and continuous scanning of the visual world.

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The higher elevation by as much as four to six feet of the truck driver of today as compared with the truck driver of twenty years ago has probably provided some advantages. In addition, the wider windshield is helpful. Night driving continues to be a problem, and Neidig has indicated that more than 50% of all accidents occur after sundown. He made a point of the importance of dimming headlights to prevent visual impairment of the drivers of cars ahead because of glare reflected from rear-vision mirrors and other surfaces.

I have sometimes thought that the ability to observe the headlights of approaching vehicles after dark provided some advantages after dark as contrasted with daylight hours. I must confess that it has never occurred to me to turn out my own lights in order to maximize this advantage, however. I am referring to Neidig's suggestion that he sometimes picked up time around curves by turning off his headlights and driving on the wrong side of the road with the assurance that no one else was coming if he could not see the headlights of an approaching vehicle. I, for one, plan to leave my headlights on.

He mentioned the importance of clean windshields, inside as well as outside, and the problem of deposition of the various tars and resins from cigarettes after smoking for 8 or 10 hours while driving. He didn't say anything about the fact that smoking also elevates the visual threshold, but that should probably be a consideration in driving at night.

With respect to the use of drugs, he has told us that benzedrine is used by truck drivers, but not those driving under regulated conditions. The independent driver, or "gypsy driver," a man who drives for an independent owner, may use an excitant in order to be able to cover more distance in less time and, hence, increase his income. The point was emphasized that we need somehow to extend the coverage of regulations to those truckers who are not now regulated by the interstate commerce commission or other regulatory agencies.

Neidig has given us a better appreciation of the problems of the truck driver, particularly those that relate to vision. We may hope for improvement and standardization of such aids as mirrors, window sizes and locations, lighting, regulatory laws in the various states, and the visual standards that must be met by drivers.

Warren Heath, of the California Highway Patrol, gave us some interesting information from the standpoint of a member of an enforcement agency. The problem of visibility through the windshield was one that he also discussed. Newer windshields are wider, but, with the increased width, increased curvature has been introduced at the sides, and this is accompanied by increased distortion. The use of convex mirrors greatly increases the field of view to the rear, although such mirrors also introduce distortions. Segmented mirrors, which also expand vision rearward, introduce step distortions of the visual world. Advantages afforded in the detection of other vehicles and objects to the rear may offset the distortions introduced. Judgments of distance may still be accomplished by the use of a mirror or mirrors that do not introduce distortion or by turning to look directly. Nonetheless, distortion in the windshield as well as distortion in mirrors may be a problem. The "fastback," although stylish, increases the angular extent of the blind area for the driver, and this is certainly bad.

Heath dealt at length with the problem of internal reflections from the dashboard and problems arising from the reduced visibility of recessed lights from the side. On the other hand, the more recessed a tail light and the less chrome around it, the better is its visibility from the rear in daylight. The optimum design for a light, for a mirror, or for any other visual aid may exist in a given model in a given year, but good designs may be eliminated from the next year's model in favor of some design which is more esthetically pleasing to the designer.

More regulations in the design of vehicles, particularly with respect to mirrors, windows, and lights, would probably be desirable. Chrysler automobiles, in general, provide the best all around visibility. Ford's tail lights are perhaps the most visible in daylight, but they are uncomfortably bright to the driver to the rear at night. They provide an excellent signal to stop but may also impair night vision. Differences that arise within the industry serve to emphasize good and bad features. The question of concern is whether more restrictive, obligatory standards could be developed that would maximize good features.

Heath pointed out the need for improvement in research methods since the results of poorly conceived research may be of little value or even harmful. The only solution to the problem, however, would appear to be increasing the number of adequately trained people who are engaged in research on driving safety. This would require a significant increase in either government or industry support for such research, and the current rate of highway fatalities would appear to justify such an increase.

Heath concluded with a discussion of the enforceability of specifications. There are SAE standards for lighting and other vehicle characteristics, but these are not enforceable unless they are adopted by regulatory agencies, and they are difficult to enforce in any case by reason of their vagueness.

Theodore Forbes, of Michigan State University, spoke to us about the visibility of highway signs and reported on some of the principles that have been developed over the years with respect to stroke width, visual angle, contrast, color of the background, and the relative merits of light characters on a dark background and dark characters on a light background. He informed us that we can see a letter at a distance of about 55 feet per inch of letter height in daytime, 33 feet per inch at night. These values are for a person with 20/20 vision. Someone with 20/40 vision, the usual cut-off for a regular driver's license, must be approximately half as far from a given letter in order to see it clearly.

Experimental work that Forbes has done using nonsense syllables and random sequences of letters yields quite different results than work done with familiar words. Familiar words can be detected at a much greater distance.

As a consultant, Forbes was able to influence the design of signs used on freeways in the state of California. What were to have been 6-inch letters were finally made 18 inches high after the significance of the factor of height had been made clear. Without expert advice, cost factors might have been given more weight with a resulting reduction in visibility.

Increasing the lateral spacing and size of letters on signs as well as increasing the vertical size increases legibility. This may be important when there is ample horizontal space but restrictions on vertical space. We are indebted to Forbes for his extensive treatment of such factors as brightness, size, and contrast and the empirical formulations for the relation of these variables in the determination of legibility.

Dan M. Finch, of the University of California at Berkeley, dealt with the matter of highway lighting. The more recently adopted sodium vapor lamps provide approximately 150 lumens per watt, an order of magnitude more illumination than that available from incandescent lamps of the same power. This increased efficiency has permitted higher mounting of lamps and their greater spacing along the highway. Finch pointed out the great diversity of local lighting regulations. Apparently highways in California can be illuminated only if there are lights on the surrounding roadways that might confuse the motorist on the freeway. A careful evaluation of highway lighting requirements and the introduction of uniform standards would appear to be of some importance.

Rudolf G. Mortimer, of the University of Michigan, was concerned with the lighting of vehicles both so that the occupant can see and so that others can see his vehicle. The illumination of the roadway ahead provided by an automobile headlamp is now restricted by a 15,000 candlepower limitation. According to Mortimer, this limit is much too low. If the shape and direction of the headlamp beam were better controlled, as high as 40,000 candlepower might be possible without hazard to approaching drivers, and this would provide much improved visibility. In many areas of Europe, it is customary to drive on illuminated streets at night with only parking lights. If streets were adequately illuminated, this might be an excellent system, but in many instances illumination is far from adequate and the practice dangerous.

Mortimer had some very interesting comments on the value of automobile exterior lights as signaling systems for other motorists. A single set of rear light fixtures may be used to indicate the presence of an automobile; when they are illuminated at night, they may be used to signal application of brakes by illumination of additional bulbs for increased intensity, and they may be used to signal turning by flashing illumination of the fixture on one side or the other. These lamps also provide distance information because there are two lights with a reasonably constant lateral separation. The visual angle subtended by the separation is thus a cue to the distance of the vehicle. In the case of trucks, rear lights extended in an array along the two sides or supplemented by an adidtional light at the top of the truck provide some information as to the nature of the vehicle. With the aid of rather detailed experimental results, Mortimer presented a convincing case for the value of using independent lights, i.e., separate fixtures for stopping and turning. Such a separation of function has been demonstrated to speed the reaction time of a following driver in response to such signals. When three sets of fixtures are used, one for indication of the presence of the vehicle, another for signaling stops, and a third for signaling turns, it also becomes a relatively simple matter to introduce color coding. The largest advantage for this kind of change was found when a different color was used for the stoplights. Different colors for each of the three functions proved to provide no advantage over just using a different color for the stoplight signal.

Mortimer made one very important distinction that bears emphasis. That was the distinction between the amount of time spent in operating a motor vehicle and the number of miles traveled in operating a motor vehicle. Automobiles are driven under a wide range of conditions, and, unless such factors as the nature of the traffic, type of road, and amount of congestion are taken into account, comparisons based solely on time at the wheel may be irrelevant. There has perhaps been too much concern with the problem of glare and insufficient attention paid to ways in which visibility may be increased and benefits be derived therefrom with a minimum of increase in glare. Mortimer suggested that we have sufficient information on visibility, nature of illumination available, and the ways it can be controlled to develop a computer model that might serve to design an optimum system of automobile external illumination for night driving.

The part of our program dealing with visual factors in air transportation was introduced by Harry Orlady, of the Air Line Pilots Association, who spoke on visual problems of the air line pilot. The pilot must function in two visual environments, the internal cockpit environment and the external environment. Optimal design of the cockpit environment is somewhat complicated by the fact that there is a bimodal distribution of pilot ages. The older group of pilots, many of whom received their early aviation training in the second World War, average about 48 or 50 years of age. The younger group of pilots have an average age in the late 20's or early 30's. Developing presbyopia in the older group influences the optimum distance at which internal instrument faces and other indicators should be located with respect to the pilot. Location of indicators overhead above the windshield and fairly close to the pilot's eyes has prompted some individuals to wear their bifocals upside down. Special lenses could of course be provided with higher magnification sections both above and below the middle. Location of an indicator or dial at a distance of 13 inches from pilots in the younger group is probably no great problem. Such a distance would be uncomfortably close for many of those in the older group without glasses, however. Orlady commented upon problems in chart lighting, difficulties in reading charts and instruments related to the size of characters, and difficulties arising from poor selection of ink color for chart printing relative to the wavelength distribution of available illumination. These are not new problems and the Committee on Vision has been concerned with them since early in World War II. It seems probable that many of those with responsibility for design of visual displays and their illumination in commercial aircraft may be unware of the extensive work that has been done on these problems, much of which has been published in reports of the Committee on Vision. As is so often the case, the efficiency of our communication systems is less than maximal. It seems unfortunate that it is sometimes necessary for pilots to reduce the luminance level of caution lights by covering them with semi-translucent masking tape. Certainly the user, if disturbed by a high luminance caution signal, is justified in introducing some correction. Adequate design would eliminate the need for such corrections.

Our next speaker was Peter A. Nelson, of the Air Traffic Control Association, who spoke to us on visual problems of the air traffic controller. As he outlined some of these problems, I could not help making comparisons with the role of the harbor and river pilots, who navigate large ships into our nation's ports. These men maneuver ships at speeds that range predominantly from 10 to 16 knots with the requirement that they present commands to the helmsman at intervals that are rarely less than 20 or 30 seconds and frequently much longer. The air traffic controller can be responsible for as many as ten or fifteen aircraft at a time. The speeds are high and the margin for error is incredibly small. Air traffic controllers often work a ten hour day and at present usually work a six day week. They are entitled to four weeks of annual vacation but rarely have time to take it. The hours of work of the harbor pilot are determined by his own independent organization, and he may work two weeks and have the third week off. His day may be a long one, considerably in excess of eight hours, but the strain does not appear to be as great as that imposed upon the air traffic controller. The air traffic controller's responsibility is so great and the job such a critical one that the occupation is under the control of the Federal Government and air traffic controllers are employed through the Federal Aviation Administration. The independent river pilots, subject to far fewer regulations, have an average income of twice that of the air traffic controller. This is so even when one considers the overtime pay received by air traffic controllers for their extra hours in a given working day and their six day week. Air traffic controllers are probably of an average age of approximately thirty-five years, and very few continue beyond the age of forty. The circumstances, particularly when one makes a comparison with another similar profession as I have done, suggest that the air traffic controller is grossly underpaid and that critical attention, which is not now being given, should be given to the problem of air traffic control.

Air traffic is increasing at a very substantial rate. All of us who travel by air are concerned about the delays that confront us in arriving or departing at large airports. The air line pilots certainly must share the concern of those who are merely passengers. I suggest that all of us with a concern for this problem also have a responsibility to speak out in favor of substantial increases in the support of our nation's efforts to solve the visual problems of the air traffic controller.

The visual demands on these men are considerable. They must observe activity outside of their station as well as seek information from status boards, radar plots, and other indicators inside. Large-screen remote presentations have been developed, but these have been found to be extremely fatiguing. Part of the cause of fatigue may be the result of variation in sharpness of focus of the projection system. The use of grid lines on the screen itself might serve to relieve this if it is the basis of the problem. Air controllers have raised a number of criticisms about the equipment that they use. Control and adjustability of the size of the letter displays and brightness of various indicators should be available, it has been suggested, but such controls may not be available. Illumination of the tower location of the air controller has also been criticized.

Outside visibility may be complicated by fog, glare on windows, and rain splashing against windows. Adaptation problems arise when men are shifted from the tower location to radar space. The use of blowers for cooling electronic equipment produces a considerable amount of dry, hot air in the working space, and the air conditioners installed to compensate for the blowers and electronic equipment create additional problems. The difficulty of the job is attested by the high incidence of diseases of stress in air controllers. It is probable that their working hours should be shorter, their environmental situation improved, and their pay increased. Their responsibilities are great and becoming greater. Improvements could certainly be made in the environment of the air controller as well as in the equipment with which he works. Increasing automation will help to reduce error due to human mistakes. Increased costs to improve the situation are trivial when weighed against the value of equipment and lives for which these men are responsible.

Donald W. Connolly, of the Federal Aviation Administration, reported on display concepts in air traffic control. We were given information on various ways of filtering out noise and the effects of weather from radar screens. It was also pointed out that air turbulence may not be as great within clouds as it is between clouds during electrical storms. Such information may be very important to an air traffic controller. With the automation of radar displays, it is possible to present a variety of information with number and letter coding. Various colors of phosphor have been employed, but the value of such coding has been related to a greater extent to differences in rate of decay with the different phosphors rather than differences in color *per se*. Tagging of targets on a scope increases the amount of information on the scope, and when the information is irrelevant to the duties of the user, the results may be negative. It is therefore important that a controller be able to limit the amount of additional coding information on the scope he is employing. This is now possible with some computer systems. Connolly's presentation made it clear that there is much work going on toward the improvement of displays. This is valuable as long as the displays continue to improve, but it also implies that the users, often air traffic controllers, must continually learn to use new equipment.

Col. Robert Bailey, of the U.S. Army Aeromedical Research Laboratory, discussed high-density helicopter traffic. There are as many as 1,000 launches a day at Fort Rucker, and both Navy and Air Force personnel as well as Army personnel are undergoing helicopter training there. A variety of techniques has been investigated for increasing the visibility of helicopters and their rotating blades. One apparently successful technique has been the use of bright yellow paint on the blades in a conspicuous pattern. Such a pattern has greatly increased visibility and thus reduced the probability of collision. Col. Bailey pointed out to us difficulties that exist even in an organization as regulated as the Army. With recommendations as to optimum methods of painting blades, there is nonetheless no guarantee that all commands using helicopters will follow the recommendations. Lights have also been employed on the blade tips for increasing visibility. These have an advantage over paint in that they can be turned on or off at will. During covert operations it would be desirable, for example, to reduce the visibility of an aircraft rather than to improve it. The possibility that light patterns either reflected from paint or emitted from lamps on the rotating blades, might cause photic driving and attendant difficulties has been investigated. Apparently this does not constitute a significant problem.

Conrad L. Kraft, of The Boeing Company, presented a very detailed evaluation of the problem of estimating height and distance from the inside of a landing aircraft. By examining the situation in several cases in which Boeing 727 aircraft were lost on landing, he was able to demonstrate a relationship between the nature of the terrain and inappropriate actions of the pilot during landing. There is a tendency for the pilot to hold the visual angle subtended by the outside world constant when approaching an airport near a city, whether the city is on horizontal terrain or sloping terrain. Such action is appropriate for horizontal terrain but may be quite inappropriate when the terrain slopes by even a few degrees. The introduction of error appears to be most significant at distances greater than 3 miles with the worst distance range being between 6 and 8 miles. Kraft has investigated this situation extensively and has simulated the situation, and the results of his work must be regarded as of very great significance.

Lt. Col. Donald Pitts, of the U.S. Air Force School of Aviation Medicine, reviewed the relation of visual and vestibular sensory systems. Such illusions have undoubtedly been responsible for a large number of fatal accidents. It is estimated that 23% of fatal accidents are a result of visual problems, and as much as 4% are a result of vestibular problems. Errors in judgment of the rate of closing are a very significant element in these accidents. Col. Pitts challenged the widely accepted opinion that stereoscopic depth perception is an extremely important factor for the aircraft pilot. It would undoubtedly be desirable to investigate the role of stereoscopic vision further. The problem is confounded by the fact that a wider field of view is available with vision in both eyes. The element of stereoscopic depth discrimination may be less important than the increased field of view. It is probable that cues derived from continuous motion parallax effects are at least equally important and perhaps far more important than stereoscopic depth discrimination. Skill in interpreting and responding to information derived from an ever-changing pattern would seem logically to be more important than good static visual acuity or good static depth discrimination ability. Col. Pitts provided confirmation of the conclusions that Kraft presented from his simulator studies. In general, pilots do tend to come in too low. They respond to visual cues afforded by the runway in a relatively stereotyped fashion although runways differ greatly in their physical characteristics. To this stereotypical response may be attributed much of the difficulty in landing safely and consistently under widely different conditions.