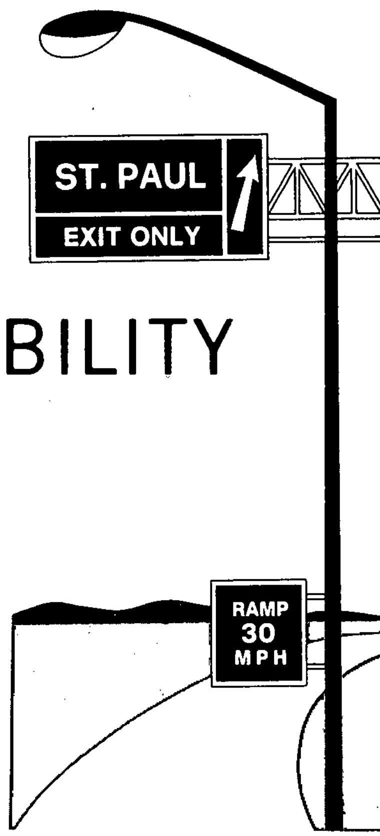
Highway Research Board
Special Report 134



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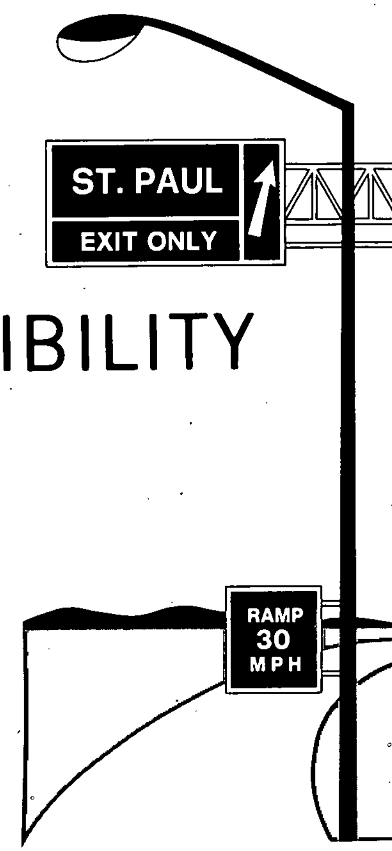

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FOREWORD

The papers and discussions in this Special Report will be of interest and use to a variety of specialists responsible for the design and operation of systems involving traffic control devices and roadway and vehicle lighting systems.

In the first paper, Henderson and Burg review current practices in visual tests for driver licensing and discuss recent and needed research in the area. Driver licensing authorities will find several practical suggestions in the conclusions drawn.

King examines the differences between illuminance (light falling on a surface) and luminance (light leaving a surface) as related to the design of lighting systems for optimum visibility under varying pavement reflectance conditions. Among other conclusions, he finds a significant need for further investigation of the light-reflecting properties of different types of pavements, both wet and dry.

Few people in touch with daily news can escape the attention given to the spectacular multiple-vehicle collisions that occur occasionally in fog. Schwab reports on the occurrence and effects of fog as related to accidents and describes abatement and warning procedures that have been or are being tested.

Visibility factors that affect the performance and effectiveness of highway signing are reviewed by Woltman. He concludes that, although much is known about elements of the sign systems in use, there is a need for system-wide analysis with emphasis on user-oriented needs for freeway-arterial interfaces, major street identification, urban signing, and pedestrians.

Meese describes the current practice in vehicular headlighting systems, pointing to major political and technical factors that tend to inhibit change. Improved headlighting technology is available, but application must always await evaluation of potentially harmful trade-offs such as opposing glare, complexity, cost, and maintainability.

In the last paper, Rowan reports on the state of the art of warrants for fixed roadway lighting. The cost of installing and maintaining such lighting systems makes it mandatory that administrators continue to be concerned with warranting conditions and benefit-cost relations. He concludes that there is a need to develop warrants that are more attuned to the needs of the public.

ACKNOWLEDGMENTS

The Highway Research Board extends its thanks to R. Clarke Bennett, under whose leadership the workshop was planned, and to C. L. Crouch, A. Ketvirtis, G. E. Meese, R. N. Schwab, R. P. Teele, and H. L. Woltman for their able assistance.

VISUAL TESTS FOR DRIVER LICENSING

Robert L. Henderson and Albert Burg

Officials have long sought a valid and reliable testing technique for use in driver licensing. The 3 general types of screening techniques in common use today (driving tests, "rules-of-the-road" written examinations, and one or more vision tests) have been selected because of their "face validity" and because of cost considerations; there is no substantial evidence that they do an adequate job of measuring driving ability or of predicting driving performance. The dramatic upsurge in interest and of activity in traffic safety brought about by creation of the National Highway Safety Bureau in 1966 has led to a critical evaluation of all aspects of driver licensing, an evaluation that is still under way.

The choice of vision tests for use in driver licensing should be based on factual information concerning the relations between various aspects of visual performance and driving performance. Research in this area has until recently failed to define basic relations between any of the various vision-screening devices and driving ability, regardless of the measure used. Goldstein (13) reviewed research on vision and driving up to 1961 and found no study that obtained more than a very slight correlation between accident records and measures such as visual acuity. Burg (3, p. 20) extended this review to 1964, at which time he stated that "...at the present time there is no widely recognized evidence that vision is related to driving." Two years later, another report (19, p. 76) contained the following statement: "At the present time, valid information is not available on relationships between various visual impairments and accidents."

Since the A. D. Little report (19) was published, however, findings from a major study of vision and driving conducted in California provide evidence that a small but significant relation exists between certain visual performance capabilities and driving record (9). The following sections will discuss these and other research findings and will explore their implications for driver licensing.

CURRENT VISION-SCREENING PRACTICES IN DRIVER LICENSING

The most recent data on driver licensing practices (20), when compared with the findings of earlier surveys (1, 12), reveal that there is an unmistakable movement toward greater uniformity among the states, both in administrative practices and in level of visual performance required for driver licensing. Undoubtedly, the emphasis placed on uniform driver-licensing practices among the states by the National Highway Safety Bureau [now the National Highway Traffic Safety Administration (NHTSA)] has played a large role in bringing about this trend toward uniformity of vision-screening procedures. The 1969 survey (20) revealed the following information about practices among the states at that time.

All 50 states and the District of Columbia required a visual acuity test of first-time applicants, but only 26 states and the District of Columbia regularly included a vision test in their reexamination of renewal applicants. Six additional states required reexamination, presumably including vision, after the applicant reached a certain age (varying from 65 to 75). Thus, in 18 states, no visual examination was scheduled after the initial license was issued. (It is possible that these figures may have changed somewhat in the 3 years since this survey was conducted.)

According to the 1969 survey, visual requirements for initial issue of a driver's license in the 50 states (plus the District of Columbia) may be summarized as follows:

1. Testing of depth perception is required in 25 states, is administered in special cases in the District of Columbia, and is optional with examiners in one state;
2. Fusion tests are given in one state (in place of depth perception);
3. Testing of color vision is required in 43 states and the District of Columbia and is administered in special cases in one state; and
4. Eye-foot reaction time is tested in 2 states, is optional with examiners in one state, and is tested in special cases in one state and the District of Columbia.

Data relating to acuity and visual field requirements are given in Tables 1 and 2.

In view of the long history of interest in night vision, the large number of research reports dealing with various aspects of night vision as it relates to driving, and the fact that more than one-half of all fatal accidents occur at night, it is particularly significant that at the present time no state includes a test of night vision in its testing program. It is also significant that, in spite of the dynamic nature of the driving task, no state currently utilizes any measure of the dynamic aspects of visual performance. The dynamic aspects of visual performance do not include only dynamic visual acuity or the coordination of the eye-movement musculature. They also include the perception of angular movement and movement in depth, in terms of both absolute threshold of detection and difference among thresholds. In addition, the dynamic aspects of visual performance include the ability to interpret the relevance of angular or in-depth movement to the observer by extrapolating to future positions those objects in the environment whose projected pathways constitute a hazard.

There are valid reasons why there are no tests for night vision or dynamic vision currently in use by any of the states. In order to justify its application in driver license screening, a vision test should be valid, i.e., predictive of driving performance; reliable, i.e., capable of producing repeated, uniform measurements; standardized, i.e., be widely used to permit development of normative values for scoring purposes; cost-effective, i.e., be of sufficient value in weeding out applicants who are potentially unsafe drivers (without mistakenly rejecting good drivers) to justify the cost of purchase, maintenance, and administration of the equipment; and commercially available.

Although a number of researchers (2, 6) have developed experimental devices for measuring visual performance under mesopic levels of illumination (as are encountered

Table 1. Static acuity requirements.

Both Eyes	Number of States	One Eye	Number of States
Without Glasses			
20/40	47	20/20	2
20/45	1	20/25	2
20/50	1	20/29	1
20/70	2	20/30	10
		20/33	1
		20/40	34
		20/50	1
With Glasses			
20/40	38	20/25	1
20/50	4	20/30	8
20/60	1	20/40	36
20/70	8	20/45	1
		20/50	1
		20/60	2
		20/70	2

Table 2. Visual field requirements.

Minimum Binocular Field (deg)	Number of States
90	1
100	2
110	1
120	3
130	1
140	4
150	1

Note: In 3 states range of minimum binocular field is not specified; in one state test is optional with examiners.

in night driving), none of these devices has yet been proved sufficiently valid to warrant its inclusion in the driver licensing procedure.

With regard to the dynamic aspects of vision in driving, again no appropriate tests are available. An experimental dynamic visual acuity test has been developed (4, 5) that is reliable, appears to have some validity, and has been administered to a sufficiently large number of drivers to provide normative data; however, this test is not commercially available, it is bulky, and its cost-effectiveness has not yet been established. The latter requirement will be difficult to meet, considering the relatively low predictive value of this test with regard to driving record (7, 8).

With regard to the dynamic aspects of vision, many of the parameters involved are not simple visual functions in the same sense as static acuity or visual field; they are more complex psychological phenomena that involve complex judgments and that may be sensitive to training and experience. Although consideration of these phenomena greatly complicates the development of an appropriate test, such consideration may be necessary.

NHTSA has not yet promulgated any formal standards with regard to vision testing for driver licensing application. NHTSA's most recent manual (15) in the area of driver licensing provides guidance to the states concerning preferred practices. It recommends the use of tests for static or dynamic visual acuity and visual field for initial licensing, with at least the acuity test repeated every 4 years thereafter at the time of license renewal.

No specific tests, procedures, or cutoff scores are indicated by NHTSA, which is not surprising in view of the current level of knowledge in this area. It is reasonable to assume that NHTSA will issue specific standards for vision testing procedures and scoring as soon as sufficient factual information is available to provide a basis for appropriate decisions.

Current thinking in the medical profession is perhaps best reflected in a recent publication (10), which puts forth provisional standards for driver licensing (Table 3). The report also discusses stereopsis, heterophoria, dynamic visual acuity, night vision, ocular pathology, and other areas of concern, but specific recommendations concerning testing procedures and scoring in these areas are not made.

RELEVANT RESEARCH FINDINGS

Relevant research concerning the relation between visual performance and driving performance has been summarized elsewhere (3, 13, 19) and will not be reviewed here. None of these reviewers found any incontrovertible evidence to confirm the widely held conviction that vision is related to accident involvement in driving. This means, of course, that this relation, which must inevitably exist, has been almost impossible to "tease out." Past attempts to uncover basic relations between vision and driving performance have proved unsuccessful for one or more of the following reasons:

1. Vision is only one of many factors that influence driving performance. This makes it difficult to demonstrate a close relation between a given vision characteristic and measures of driving performance such as number of accidents or convictions for traffic citations.

Table 3. Provisional standards for driver licensing.

	Class of License[a]		
Characteristic	1	2	3
Static visual acuity	Both eyes corrected to 20/25	One eye corrected to 20/40; the other corrected to 20/60	One eye corrected to 20/40
Field of vision	140 deg for each eye (90 deg temporal and 50 deg nasal)	140 deg for each eye (90 deg temporal and 50 deg nasal)	140 deg for both eyes together
Color vision	Able to discriminate among red, green, and amber with each eye separately	Able to discriminate among red, green, and amber with both eyes open	Not required

[a]Class 1 consists of bus drivers, for example; class 2 of truck drivers; and class 3 of passenger car drivers.

2. There may be considerable disparity between an individual's visual capability and the degree to which this capability is utilized in driving.

3. The extent to which individuals compensate for their defective vision is unknown, and compensation tends to obscure the true relation between visual performance and driving.

4. Most studies have dealt with a restricted range of visual acuities because they used subjects who had already been screened on the basis of their visual abilities. This restricted range limits the size of the correlation that can be expected between vision and driving.

5. The vision tests used may not have measured the same functions as those important to the driving task.

6. The reliability and validity of the tests or of the criterion measure(s) of driving used may be low.

7. There may have been methodological shortcomings in the study, such as a small or unrepresentative sample of drivers (or driving behavior) or a failure to control relevant variables such as exposure.

A search of the literature appearing since the A. D. Little review has been conducted as part of a study by Henderson et al. (14). This survey found a large number of studies directed at increasing our general knowledge of vision and visual performance, defining more accurately how the visual sense is used in driving, describing and defining the visual environment associated with driving, and isolating and measuring the relative effectiveness of various cues on specific driving behaviors or maneuvers. The body of literature in each of these areas is voluminous. Richards (18), for example, cited 196 documents that appeared between 1967 and 1969 related to vision at levels of nighttime road illumination. However, a complete review of this literature is clearly beyond the scope of the present paper.

Although such a review, or a series of reviews by subject area, would be of interest, it would not provide answers to the basic questions asked by driver licensing administrators; i.e., which vision capabilities should be tested? and which scores should be used as the cutoffs for granting a license?

To be of direct use in formulating policy concerning driver licensing practice, a study must be concerned with establishing the relation between visual performance and some direct criterion of driving safety, such as number of accidents. Only 2 such studies have appeared in recent years. Crancer and O'Neall (11) administered a number of visual tests to 2 groups of male drivers between the ages of 50 and 70. One group of 108 subjects had clean 2-year driving records; the other group of 177 subjects did not. They found the poor-record drivers as a group to be "visually more competent" than clean-record drivers in terms of static and dynamic visual acuity and glare vision. They conclude that the results of their tests warrant continuation of existing testing for static acuity and recommend future research to develop a test for glare vision and recovery and to study ways of integrating a visual examination with a driving simulator test to determine aspects of static and dynamic visual acuity more directly related to the driving task. Unfortunately, the results of the Crancer and O'Neall study are open to criticism because of the lack of scientific rigor with which the study was conducted. For example, the small sample size and lack of adequate control for the effects of age and miles driven tend to reduce the generality of the findings.

A large-scale study under way since 1961 at the University of California, Los Angeles, has reported experimental evidence showing that performance on several measures of visual capability may be of limited value in predicting driving record, i.e., accidents and convictions for traffic citations (7, 8, 9). Several visual capabilities were measured on nearly 18,000 California drivers of both sexes and all ages, and, of these, 4 measures were found to have significant, if limited, predictive value. These were static visual acuity, dynamic visual acuity, visual field, and night vision. Of these, dynamic visual acuity shows by far the strongest relation to both 3-year and 6-year driving records, with the other 3 trailing far behind. These results obtained when the effects of age, sex, and miles driven were controlled.

IMPLICATIONS OF RESEARCH FINDINGS FOR DRIVER LICENSING

The results of the research conducted to date have a number of implications for driver licensing and suggest several courses of action.

First of all, it is clear that there are a number of unanswered questions, such as the following:

1. What relation exists between specific visual performance measures and specific types of accidents and violations?
2. How would vision-driving relations change if qualitative (as well as quantitative) exposure to risk (type of driving) is taken into account?
3. Is it possible to specify cutoff scores for the various tests that might be useful to driver licensing administrators?

Work is currently under way at U.C.L.A. in an attempt to find answers to these questions, which is the first course of action implied by the results.

Secondly, the results are encouraging enough to warrant effort toward developing an acceptable vision-testing device for driver licensing purposes. Such a device should be compact, reliable, not too expensive, easy to administer and score, and should permit measurement of several aspects of vision. These measures should include, at a minimum, one or more dynamic tests of visual performance, a static test of visual resolution, and useful horizontal visual field, and the instrument should permit these measurements to be made under a range of illumination levels. This course of action is currently under way in the form of a research and development program supported by the U.S. Department of Transportation.

In addition, study results indicate that static acuity vision testing, in universal use in the driver licensing procedure at the present time, is of some value, and its use should be continued until such time as the vision-testing device currently under development is completed and validated. The same statement may be made with regard to visual field testing, currently used for screening driver license applicants in a third of the states.

Finally, it should be pointed out that an enormous amount of information has been collected that can be used to describe driver characteristics, both personal and driving. These data can be useful in themselves in formulating operational decisions. For example, all of the research data clearly show the decline on the average in visual performance capabilities with advancing age. This finding suggests that licensing examinations (i.e., vision testing) should be given more frequently (especially to older drivers), which would result in shorter term licenses. This practice is already in effect in several states. Further research is necessary before we can recommend at what age or at what level of vision more frequent testing should begin.

In spite of these research findings, there still are insufficient data of a type necessary to provide real guidance to the administrator responsible for establishing screening standards. The necessary data concern total visual performance requirements for safe driving. Because the causes of automobile accidents are so diverse and complex, it may be fruitless to expect that a high degree of correlation will ever be found between individual visual functions and accidents—perhaps a different approach is required. Without elaborating in detail, it would appear that an alternative to past attempts to relate performance on individual visual functions to accidents would involve (a) identification, definition, analysis, classification, and cataloging of the complex man-machine-environment interactions that comprise the driving task and (b) identification, definition, and analysis of the visual requirements associated with the individual elements of driving behavior. This is what Michaels (17) has termed the systems approach to the study of highway safety. What may be required is not the study of accidents or violations, but an intensive analysis of the driving task to determine what the human is required to do in driving an automobile and to determine the demands made on him by the design of the vehicle, the roadway, and other aspects of the system. Of critical importance, also, is the interaction among various elements of the system. It is not sufficient to say that a person must have the capability to resolve the taillights and running lights of a truck at a given distance and to judge that distance accurately. He must also be able to perceive that he is overtaking the truck and to accurately estimate the rate of closure. Estimating rate of closure probably requires very complex judgment—it certainly is not a simple visual function—yet it is based on a complex of visual cues that do represent visual functions. However, because of complex interactions and other factors as yet not understood, satisfactory performance with respect to all of the individual functions does not guarantee that an accurate estimate of closure rate will be made, and, conversely, accurate closure rate estimation does not necessarily require satisfactory performance on all individual functions. Even though ability or lack of ability to perceive rate of closure may not correlate highly with frequency of accidents, it can be shown analytically that, at modern highway speeds and with current roadway geometrics, a minimum capability to judge rate of closure is required to avoid accidents and a still greater capability is required to avoid creating situations that, when combined with some slight additional perturbation in the roadway system, would result in an accident. This is but one example of the type of effort that may be required. Through careful analysis, modeling, and empirical research, the basic performance requirements of the human visual system in the driving situation can perhaps be determined without relying on accident statistics as the sole criterion. A start in this direction is discussed in the following section.

CURRENT RESEARCH

NHTSA is currently funding a research project to develop an Integrated Vision Testing Device for use in screening driver license applicants. As a part of this development effort, for the first time, a systematic analysis has been made of the basic visual requirements of the driving task. This analytical effort involved examination of the driving tasks identified by the Human Resources Research Organization (16) in order to identify and define for each task, subtask, and individual driving behavior, the basic visual requirements, without regard to either feasibility of testing or "face validity." Independently of the analytical effort, the contractor experimentally investigated the interrelations among visual functions important to driving for which tests are readily available. Unlike most research studies of this type, which have used essentially normally sighted individuals, this study used a heterogeneous population whose corrected visual acuity ranged from 20/20 to 20/200. Major findings obtained in the first phase of this study are reported by Henderson et al. (14). Among the conclusions reached by the authors are the following:

1. Based on the results of a comprehensive literature survey and a detailed and systematic analysis of the visual requirements of the driving task, the visual functions judged to be most important to driving and which should be included in the Integrated Vision Testing Device are as follows: perception of movement in depth; perception of angular movement; visual field (useful peripheral vision); saccadic, pursuit, and steady fixations; static acuity; and dynamic visual acuity.
2. Night driving creates environmental conditions that are generally detrimental to visual performance, particularly of older drivers. Any realistic visual screening program must evaluate the effects of glare and low illumination level on all visual functions important to driving. Thus, provisions for testing under glare and low illumination should be included in the Integrated Vision Testing Device.
3. Only limited information is currently available concerning basic human capabilities on many of the visual functions judged most important to driving, such as movement in depth and angular movement. Information is urgently needed concerning the range of normal human variability in capability and the degree to which perceptual training can be used to improve performance.

The second phase of the study, now under way, involves construction of a prototype screening device and the conduct of a rigorous field evaluation to determine whether performance on the device relates sufficiently well to driving record to justify its use for screening driver license applicants.

Three of the prototype devices have been built and are currently undergoing field evaluation. The device provides the following performance measures:

1. Static acuity, i.e., the ability to resolve a stationary target;

2. Ability to perceive movement in depth, measured both centrally and peripherally;
3. Ability to perceive angular movement, measured both centrally and peripherally;
4. Useful peripheral vision, measuring the ability to detect, acquire (by head and/or eye movement), and identify acuity targets appearing briefly at random locations within a 180- by 20-deg field; and
5. Dynamic visual acuity, i.e., the ability to track and resolve a moving acuity target.

The device provides the capability for performance measurements under both normal and low levels of illumination as well as under conditions of either spot or veiling glare. In the field evaluation, the devices are being used to gather performance scores on a large random sample of licensed California drivers as well as on smaller samples of novice drivers, drivers with poor records, and commercial (bus and truck) drivers. The performance scores obtained will be correlated with driving record information (accidents and traffic violations) made available by the California Department of Motor Vehicles.

CONCLUSIONS AND RECOMMENDATIONS

There does not exist at the present time a sufficient body of scientific data to provide appropriate authorities with the guidance they require to establish vision test requirements and cutoff scores for screening driver license applicants. There are, however, sufficient data available to warrant continued use by all of the states of a test for static acuity and, for those states now utilizing it, a visual field test. Additional research and/or further analysis of existing data is required in a number of areas to produce the type of factual information needed for development of effective vision-screening procedures. Some of these areas are as follows:

1. Detailed evaluation of significant vision-driving relations is required to specify cutoff scores for those vision tests that appear potentially valuable.
2. A longitudinal study (of at least 5 years duration) is necessary to study further the deterioration with age of performance on vision tests in use or those being considered for driver license screening. Such a study is necessary to determine the desirability of differential frequency of reexamination for various age groups.
3. A systematic and detailed analysis of the visual requirements for driving should be conducted. In addition to identifying individual visual functions important to driving, consideration should be given to the complex psychological judgments involved in driving that require the dynamic interpretation, as well as the sensing, of visual information. This analytical effort, if extended to include the total driver-vehicle-roadway complex, may also yield criteria for evaluating visual performance requirements that may be used to supplement the traditional criterion of the driving record. (A start in this direction has been made in the aforementioned study currently being supported by DOT.)
4. A compact, reliable, and not-too-expensive multipurpose visual tester should be developed that can be used as a standardized test device to measure static acuity, one or more measures of dynamic visual performance, and some aspects of night vision. Once developed, this device should be subjected to a rigorous evaluation and validation program. (As indicated earlier, this activity is currently under way.)
5. All states should be urged to make a permanent record of all visual performance data collected on all applicants. These data should be maintained in a form readily accessible to those concerned with establishing the relation between visual performance and driving record and with making decisions regarding useful tests and cutoff scores.
6. A complete and detailed driver record file should be established at the federal level, containing data on accidents and convictions for traffic violations reported to any governmental or private organization or agency. Such records should be kept as long as is economically feasible because the reliability of such information increases as its period of accumulation increases. This recommendation is made under the assumption that driving record will remain the prime indicator of driving performance for some time to come and, thus, should be made as valid as possible.

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DISCUSSION

Oscar W. Richards

Henderson and Burg summarized the variety of driver licensing tests and the lack of agreement among them with regard to passing standards. They emphasized that there are no tests or requirements for night vision, nor is any consideration given to the dynamic aspects of visual performance. The study shows some relation between static visual acuity and greater correlation between dynamic visual acuity and driving record. A vision test for driver license screening should be valid, reliable, standardized, cost-effective, and commercially available. Currently used tests fail these requirements. The authors propose research toward understanding the role of vision in driving.

I agree with Henderson and Burg and again call attention to the need for standardized tests. Color vision testing is unnecessary beyond recognition of signals revealed during the road test, and I doubt that stereopsis is of enough importance in driving to justify testing time. I do believe that cerebral response patterns, gradually built up with experience, determine driving skill and could be another approach to driver certification. On the question of retesting, I suggest 30, 50, and 70 years of age when changes occur in the visual system of human beings.

ILLUMINANCE VERSUS LUMINANCE

L. Ellis King

Illumination is the measure of the amount of light flux falling on a surface. Illumination is independent of the direction from which the light comes; the number of light sources, or their positions; the type of light source; and the type of surface on which it falls. A surface may be illuminated to a level of 1 footcandle by one concentrated source placed normal to the surface or by several less intense sources placed obliquely to the surface. The illumination is the same whether the surface is a polished steel plate or a piece of black felt cloth. In roadway lighting, illumination is a useful quantity in the calculation of problems of lighting but has little value in describing the observed situation.

Luminance is a measure of the amount and concentration of light flux leaving a surface and is the light by which an object is seen. It is the luminance that controls the magnitude of the sensation that the brain receives of an object. The luminance of a surface depends on all of the quantities of which illumination is independent, such as the direction from which the light reaches the surface, the direction from which it is viewed, and the reflective properties of the surface itself. The amount of light falling on a small area of a surface is measured as the illumination on that area. This incident light is generally reflected in all directions by the surface, and its directional distribution is determined by the properties of the surface and the manner in which the light strikes the surface. The apparent luminance of the area on the surface is determined by the amount of light reflected toward the observer's eye.

Current roadway lighting design practice in the United States is sponsored by the Illuminating Engineering Society and approved by the American Standards Association (1). Current standards state that one of the principal objectives of roadway illumination is "to enhance the brightness of the pavement and uniformity of brightness along and across the full width of the roadway..." (1). However, the recommended design practice gives no further specific consideration to the concept of pavement luminance. Instead, the standard consists essentially of an average horizontal footcandle specification, measured on the pavement surface between 2 adjacent luminaires. This implies that the roadway brightness patterns are adequate if the average horizontal illumination is at the recommended level. But rather than rely entirely on the light incident on the surface to reveal the roadway scene, we should consider the amount of light reflected from the surface in the direction of the observer because the information needed by the motorist to evaluate the visual scene is provided by the luminance patterns on the roadway (2). In this regard, the roadway ahead of the motorist should present an average luminance adequate to maintain eye adaptation, a minimum luminance to ensure adequate visibility of any object on or near the roadway, and a uniformity sufficient to maintain continuity within the visual scene, to ensure comfort, and to render frequent and rapid eye movements by the driver unnecessary. Many illuminating engineers have long been aware of the inadequacy of an illumination specification and have frequently suggested roadway luminance as a substitute parameter for design purposes, but the latter has seldom been used in this country.

All surfaces, including roadway surfaces, may be classified into 3 major groups according to the way in which they reflect light. The ideal specular surface is one that reflects all the luminous flux received by a point at an angle of reflection exactly equal to the angle of incidence. The reflected ray, the normal to the surface at the point of incidence, and the incident ray all lie in the same plane. An observer looking at a perfect specular surface along the direction of the reflected light will see an undistorted image of the object, and the image will be the same size as the object. The luminance of the image will be proportional to the luminance of the object. Some practical surfaces, such as mirrors, highly polished metal surfaces, and the surface of liquids, closely approximate the ideal specularly reflecting surface.

The perfectly diffuse surface is at the opposite pole from the ideal specular surface. The diffuse (or mat) surface reflects light as a cosine function of the angle from the normal, regardless of the angle of incidence. Because the luminance of the surface is equal to the intensity divided by the projected area and the projected area is also a cosine function of the angle from the normal, the perfectly diffuse surface appears equally bright to an observer from any viewing angle. The luminance of this surface is nearly independent of the luminance of the source of light but proportional to the illumination of the surface. Photometric test plates exhibit the characteristics of almost uniform diffusion for most practical purposes.

Many surfaces, such as a mirror or highly polished steel plate, closely approximate the ideal specular surface, and many surfaces, such as white mat-finished paper or walls finished with flat white paint, would appear to closely approximate the perfectly diffuse surface at first glance. However, closer inspection reveals that these surfaces behave as diffuse surfaces only if the angle of incidence is close to 0 deg as measured from the normal to the surface. Large angles of view will also cause these surfaces to exhibit properties unlike those of a diffuse surface.

Most surfaces encountered in everyday life fall between the ideal specular and ideal diffuse surfaces and exhibit properties of mixed reflection. These surfaces form no geometric image but act somewhat as a diffuse surface, showing some preference as to direction of reflection. The apparent brightness of such a surface changes with changes in angle of incidence and with changes in observer viewing angle. The larger these angles become, the more noticeable are their effects.

Figure 1 shows the types of reflection discussed here.

Roadway surfaces, where observer viewing angles and angles of incident light (as measured from the normal) range from 86 to 89 deg and from 0 to 87 deg respectively, exhibit characteristics of mixed reflection. A single luminaire suspended over a roadway produces a single luminous patch on the surface of the roadway. To the observer traveling on the roadway, this luminous patch has the form of a T with the tail extending toward the observer. The luminous patch is almost completely on the observer's side of the luminaire because the reflecting properties of the pavement surface are such that only a small amount of the light striking the surface in a direction away from the observer is reflected back toward the observer. The tail of the T always extends toward the observer regardless of his position on the roadway. The size, shape, and luminance of the T depends to a great extent on the surface characteristics of the pavement. For a mat surface, the head of the T predominates, and only a short tail is evident; a surface polished smooth by traffic, however, exhibits a long tail and a small head. On a wet roadway the head may completely disappear and the tail become very elongated. These 3 cases are shown in Figure 2.

The statement, "the apparent brightness of the pavement depends upon the intensity and angle of incident and reflected light and the pavement-reflecting characteristics (specular and diffuse) at typical angles of view" (1), perhaps gives a clue to the reasons that illuminating engineers continue to adhere to an illumination specification for roadway lighting, even though it is generally acknowledged that a luminance specification would be preferable. Whereas levels of illumination have been relatively easy to determine, either by measurement or calculation, the derivation of roadway luminance from photometric data has involved tedious measurement of pavement reflectance as well as a formidable number of calculations. Developments in recent years, however, have greatly simplified this task—a straightforward method for computing roadway luminance having been previously reported (2). The calculations, moreover, by their repetitive nature, readily lend themselves to computer programming. Nevertheless, the lack of reliable information concerning the directional reflecting characteristics of pavements is a retarding factor in this process. Several attempts in the past to measure directional reflectance factors for representative roadway surfaces have met with only limited success (3 - 8). Both field and laboratory studies have produced only a meager amount of published data. These data generally have been collected by using either visual photometry or photographic techniques. Although both of these methods offer certain advantages, the direct reading instruments available today make laboratory studies both practical and desirable.

In summary, it can be said that illuminating engineers have long known the importance of pavement luminance in roadway light designs. It is also widely known that pavement luminance depends on the relative positions of the observer and the light source as well as the directional reflectance characteristics of the pavement surface. However, in the past there has been little information available on the directional reflectance properties of various highway surfaces that would permit the calculation of pavement luminance from an illumination specification.

PREVIOUS INVESTIGATIONS

The scientific study of roadway lighting began with P. S. Millar (9) in 1910. However, little consideration was given to pavement luminance until 1928 (10). Since this date there have been a number of studies, both in the United States and abroad, that have in some aspect considered the role of pavement luminance in roadway lighting. However, none of these studies has produced a comprehensive table of directional reflectance factors for relating pavement illumination to pavement luminance.

The foreign studies have generally attempted to relate the candlepower output of a single luminaire to the pavement luminance produced by this single luminaire. These studies have, in most instances, involved full-scale tests of actual roadway surfaces. The resulting data have been meager in quantity and difficult to use.

A notable exception is the work of A. W. Christie (11). The experimental arrangement simulated an observer and a luminaire on a reduced scale. Both visual and photographic methods were used to measure the pavement luminance produced by a light source of known intensity for several incident angles of illumination and one viewing angle. The results for 3 typical British pavement surfaces, together with a method for using the results, are given by Christie. The data are presented in such a manner as to be most useful when combined with Christie's suggested method for calculating roadway luminance. The usefulness of the data is further limited in that only one simulated viewing distance was investigated.

In this country, Reid and Channon investigated pavement samples, cut from traffic-worn asphalt and concrete roadways, for several incident angles of illumination and a simulated viewing distance of 200 ft (12). Luminance measurements were made with a Luckiesh-Taylor Brightness Meter by observers accustomed to its use. Two sets of data, representative of the 2 types of pavement surfaces previously mentioned, were reported. The data are presented in the form of isocurves that show the horizontal footcandles and candlepowers required from a single luminaire to produce a uniform luminance of 1 ft-L on the roadway as viewed by the motorist. These curves are cumbersome to use and are representative of only one simulated viewing distance.

Kraehenbuehl (5) investigated pavement surface characteristics. An automatic recording reflectometer was built to make reproducible photometric measurements on a pavement sample for all angles of incident light and all angles of reflected light. The data for one concrete pavement sample were reported. No absolute values were given, all reflectance factors being in the form of a "relative" reading of the recording instrument.

More recently King and Finch (6) have reported both laboratory and field procedures for obtaining pavement reflectance data. A pavement reflectometer was developed for measuring the directional reflectance properties of pavement surfaces in the field. The reflectometer, basically a form of goniometer, consists of an incandescent lamp mounted on a curved rotating boom and a rigidly mounted telephotometer with provisions for angular position adjustments. The lamp was positioned to illuminate a given spot on the pavement from several vertical angles. The telephotometer, which can be positioned to correspond to various driver viewing angles, was focused on the illuminated spot as the motor-driven boom rotated the lamp through a 360-deg horizontal angle about the spot. The telephotometer output is fed to a strip-chart recorder. The telephotometer consists of a modified surveyor's transit and photomultiplier tube. During field measurements, the entire reflectometer assembly was enclosed in a light-proof covering to avoid interference from external light sources such as vehicle headlights.

The authors concluded that, even with a high degree of automation, field collection of data is a slow and cumbersome process, and the nature of the problem is such that a laboratory setup would be desirable for large-scale investigations.

A second paper by King and Finch (7) describes the instrumentation and procedures associated with a laboratory method for determining the directional reflectance characteristics of pavement surfaces. The reflectometer, basically a form of goniometer similar to the one previously mentioned, is capable of simulating various light sources (vertical and horizontal angles) as well as several driver viewing distances. The telephotometer contained an oval-shaped aperture, which ensured that only the surface of the pavement sample was being viewed during testing. Data were automatically recorded on paper-punch tape for computer processing. Measurements made on 12-in. pavement core samples proved to be accurate and repeatable. The directional reflectance factors for a traffic-worn asphalt surface are shown in Figure 3.

The preceding research studies focused their attention on developing methods for both measuring and calculating pavement luminance. The necessary equipment is specialized and the calculations complex; hence, the results of the studies have seen little application outside the research laboratory. Many of the problems associated with measuring and calculating luminance values would be eliminated if a road surface classification system were available. Classification of pavement surfaces would allow the engineer to predict the results of any proposed roadway lighting system before actually installing the system.

King and Finch (8) report one approach to classifying roadway surfaces according to the directional reflectance properties of the surface. The reflectometer was used to record the reflectance characteristics of 2 asphaltic concrete pavement core samples. The characteristics of the 2 samples are described and compared both mathematically and graphically. Three procedures for fitting polynomial equations to the data were also reported. The authors conclude that the curves or the equations, or both, could be used to classify the pavement surfaces according to their directional reflectance properties.

DISCUSSION OF RESULTS

It is evident from the preceding analysis and other related investigations that there is a need for further study of the directional reflectance characteristics of typical roadway surfaces. At the present time there are not enough data available to allow the illuminating engineer to relate the quantity of light incident on a pavement surface to the pavement luminance as seen by the motorist.

In order to be used for design or evaluation of roadway lighting systems, data on roadway luminances must be combined with visual criteria. The optimal roadway lighting system may or may not be the one with the most uniform pavement luminance. Object contrast is also important. Object contrast is influenced by the same factors that influence roadway luminance and also by object reflectance and vertical illumination. Research is currently being conducted to determine visual criteria, for use in assessing roadway lighting installations, which will be expressed in terms of object contrast and roadway luminance.

At the present time only a small fraction of the total road system has some form of fixed roadway lighting. In most rural areas and in many urban areas, the driver must rely on his headlights to provide illumination on the roadway. It has been estimated

Figure 1. Intensity distribution curves.

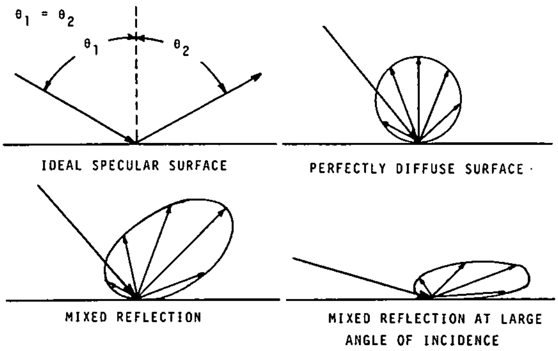


Figure 2. Luminous paths.

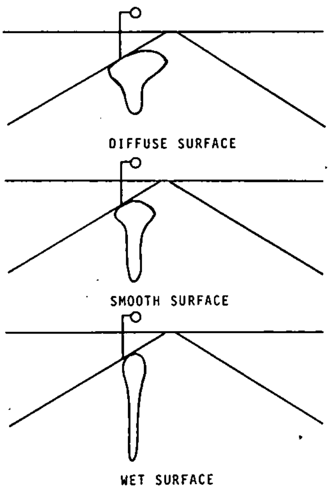
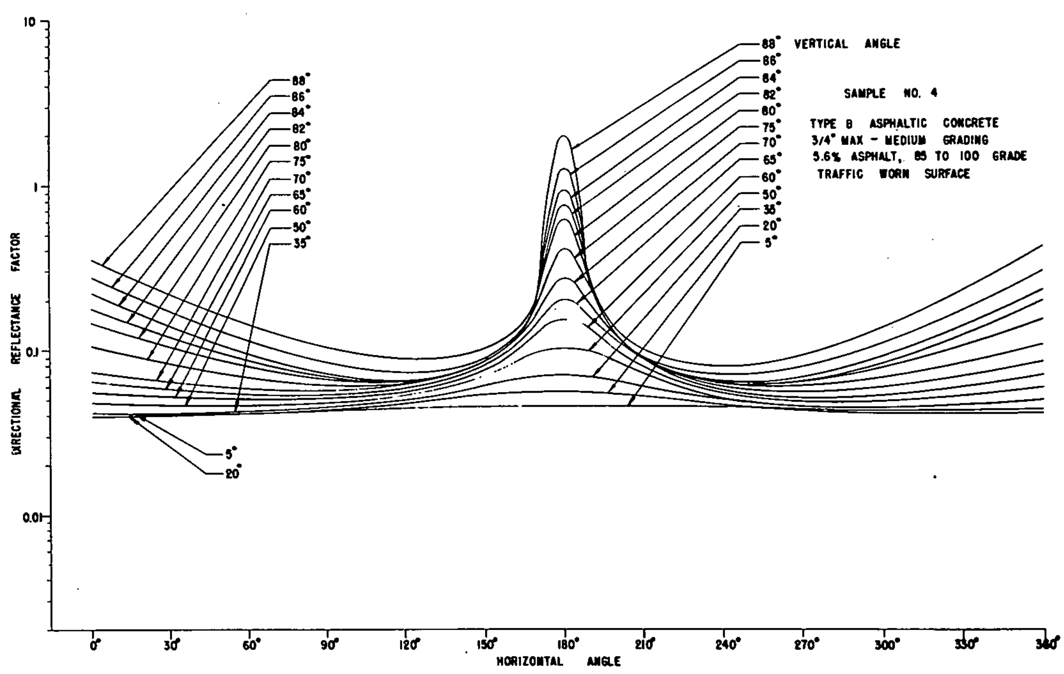


Figure 3. Directional reflectance factors for 50-ft viewing distance.



that the magnitude of travel on rural highways will increase by approximately 50 percent within the next 20 years. Therefore vehicular-mounted headlights must continue to be relied on for a large portion of night driving. Although it is beyond the scope of this paper to provide a detailed discussion of vehicle headlighting, it should be mentioned that there is an interaction between vehicle-mounted lighting and fixed lighting. This interaction is not well understood and is currently the subject of a relatively large research project.

FUTURE RESEARCH

The research projects described in this report indicate a growing interest in the role of pavement luminance in highway lighting design. Safe operation of a motor vehicle on a highway requires that the driver be able to preceive any hazard on or near the roadway. Perception of a hazard is directly related to the luminances and contrasts within the driver's field of view. Of these, the roadway luminance is probably the most important. The luminance of the roadway depends on the relative positions of the light source and the driver and the directional reflectance characteristics of the pavement surface.

Future research should be devoted to investigating the light-reflecting properties of various types of pavements, both asphalt and concrete. Directional reflectance characteristics should be recorded for wet as well as dry conditions. These data could then be used to develop a classification system for pavement surfaces. Such a system would allow the illuminating engineer to calculate the pavement luminance that would be produced by any proposed roadway lighting system before actually installing the system. Computer programs should be developed for calculating pavement luminance using known calculation techniques. These programs should be written in a universal computer language that could be easily adapted to a wide variety of computers. This would make it feasible to compare a large number of geometric configurations and light sources for any proposed roadway lighting installation. Research of this nature is currently being carried out at West Virginia University under the sponsorship of the Illuminating Engineering Research Institute.

In order to evaluate proposed installations, we should devote more research to developing design criteria based on pavement luminance. This research should recognize the nonuniform texture of actual pavement surfaces, traffic wear, and changing weather conditions. Pavement luminance patterns, as viewed by the moving driver, are constantly changing, and it may be practically impossible to achieve complete uniformity of pavement luminance. Other factors, such as object contrast and the interaction of vehicle lighting and fixed lighting, should also be considered. Various roadway surfaces should be investigated to determine which type is most compatible with both fixed lighting and vehicular lighting.

Many highway accidents, particularly during inclement weather, involve a skidding vehicle. Research should be undertaken to establish any existing relation among surface texture, light reflectance properties, and skid resistance properties of various pavement surfaces.

It has been frequently suggested that the reflectance properties of roadway surfaces, particularly asphalt surfaces, could be improved by the addition of light-colored materials to the surface course. This claim should be more thoroughly investigated.

Research effort should also be directed toward relating the directional reflectance characteristics of a pavement surface to some easily measurable physical properties of the surface. The development of such a relation or classification system would eventually allow the illuminating engineer to design a lighting system and then specify a pavement surface to complement the system. Or conversely, knowing the type of surface, he could design the most appropriate type of lighting system.

ACKNOWLEDGMENT

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DISCUSSION

J. Stuart Franklin

King's paper represents another step forward in understanding the area of luminance within the night driving environment. The paper gives a very short history of the efforts of researchers during the past 50 years in the area of pavement luminance versus pavement illumination. In each case, equipment and techniques were developed, and a few pavement samples were measured. In recent decades computer programs have been written and demonstrated. At the present time we have laboratory equipment available at University of West Virginia to measure pavement reflectance characteristics and at Ohio State University the ability to measure visibility.

Some recent work in Europe demonstrates effects of wet, damp, and dry pavements with different light distributions (13, 14, 15). The Blackwells (16) have shown the effect of light distributions on visibility of objects. Block (17) has broken down the pavement surface into its fundamental components. Work done by Fisher in Australia (18, 19) includes the interaction of vehicle lighting and fixed overhead lighting systems on pavement characteristics and visibility.

The tools, techniques, and theory have been demonstrated time and again, and still the practicing engineer uses illumination in his designs.

King's paper should mark the time for a change in approach. I would like to propose the following courses of action so that the practicing engineer can start handling luminance in his day-to-day work:

1. Funds should be made available to get dry, damp, and wet pavement reflectance data on 200 to 300 samples of actual pavements from all over the North American continent;
2. If, in the above program, statistically significant sample sizes have been taken,

then analyses of the data should indicate the confidence limits applying to its use within each pavement classification;

3. Computer programs should be made available nationally on recognized time-sharing computer networks;

4. Several typical practical examples should be worked out and published in the technical literature; and

5. Practicing street and highway lighting engineers should then be encouraged to use this approach in their day-to-day lighting applications.

In the course of such a program, techniques will be refined, problem areas defined, and operating procedures documented. Perhaps then, the standard practices for street and highway lighting could be revised to include luminance as well as illumination.

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A. Ketvirtis

In his paper, King discusses one of the key aspects in roadway lighting design procedures. Although the recommended design methods in North America are based on horizontal levels of illumination, practicing engineers cannot ignore the actual road luminance. A lighting system designer always thinks of what the road will look like when the illumination system is energized. Unfortunately, the method based on horizontal levels of illumination does not provide him with such information. As Dr. King described in his paper, the only way to predict illumination performance is when the design is based on the principle of luminance instead of horizontal illumination.

The question raised, however, is how such a method can be implemented in practice. Various national committees have done a considerable amount of investigation in recent years. At the last quadrennial CIE conference in Barcelona, brief reports were published summarizing the results of these investigations. Perhaps one of the most significant reports was presented by Sabey of the British Road Research Laboratory. According to this report (20) reliable information on pavement surfaces cannot be easily obtained due to the fact that reflectance characteristics are influenced by climatic conditions, materials used for road construction, and traffic wear. According to this report, reflectance of the road surface can vary as much as 3:1. Waldram verbally reported that the reflectance variation can be even greater than the ratios suggested by Sabey. The conclusions drawn by the Sabey report are that, because of difficulties in obtaining reliable information on road surface characteristics, a design based on road luminance is not practical at this time.

Some European countries, however, established stricter control on the aggregates used for road surface construction and obtained remarkable results. For instance, the city of Malmö in Sweden has used artificial aggregates extensively to create specific road reflectance characteristics. However, these artificial aggregates add considerably to the construction cost and perhaps would be difficult to apply on this continent, where the mileage of highways is so much greater.

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MINIMIZING THE HAZARD OF RESTRICTED VISIBILITY IN FOG

Richard N. Schwab

The purpose of this paper is to briefly describe the nature of fog and its formation, effects of fog on driving and accidents, current fog abatement techniques, and possible guidance systems to aid drivers in minimizing the hazards encountered in fog.

THE NATURE OF FOG AND ITS FORMATION

Fog is a visible concentration of small water droplets that average between 10 and 20 microns in diameter (depending on fog type) and are in contact with the ground or close to it such that visibility is seriously affected. By meteorological definition, fog reduces the visual range to less than 3,300 ft (1 kilometer); however, even a dense fog by meteorological standards (visual range less than 1,300 ft) may not have any significant effect on driving performance.

Various mechanisms involving energy, heat, and moisture all contribute to fog formation (1). Specific mechanisms are associated with specific kinds of fogs. For example, a fog will occur if sufficient condensation nuclei are present in the atmosphere and the temperature and specific humidity conditions are above the values of the curve shown in Figure 1. This condition may arise from the cooling of air without altering the moisture content, by raising the relative humidity by evaporation of rain droplets, or by the mixture of 2 parcels of air having different temperatures and relative humidities. It is obvious that the formation of most fogs represents a complex and delicate balance of favorable meteorological conditions together with sufficient hygroscopic nuclei in the atmosphere to encourage condensation. This explains the relative rarity and unpredictability of fog and why it tends to be particularly troublesome in areas where industrial activities produce an abundance of nuclei in the effluents.

Figure 2 shows the average annual number of days having some period of dense fog (2), i.e., less than 1,300 ft visibility. Fog in this density range may or may not be significant for highway operations; however, the figure is included here simply to show the geographical distribution of fog. As can be seen, fog is rarely a problem in the Southwest and only an occasional problem in the Great Plains. On the other hand, fog occurs frequently along the west coast, in the Appalachian Mountains, and in much of New England. At times it is locally dense enough to affect traffic behavior. The local character of fog is itself a major part of the problem because driving into and out of small fog banks can be more dangerous than a more general reduction in visibility.

Many fogs are of short duration in local areas. For example, Figure 3 shows conditions at Newark Airport where approximately one-half of all dense fogs (¼ mile or less) endure for less than 1 hour (3). The median duration of denser fogs is about 1½ hours. This is contrary to the popular belief that most fogs last many hours, which is probably related more to the driver's lack of knowledge as to when fogs are of sufficient density to limit visibility than to the geometric design of the roadway on which he is traveling. This factor probably leads to an overstatement of the fog accident problem in the mind of the general public.

Figure 1. Atmospheric saturation curve (2).

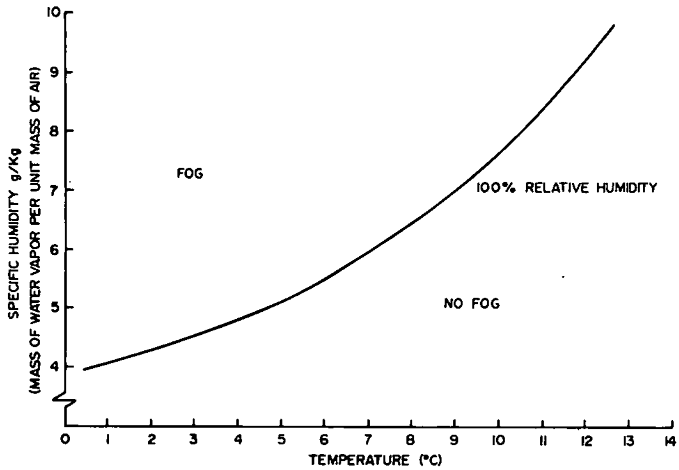


Figure 2. Average annual number of days having dense fog (2).

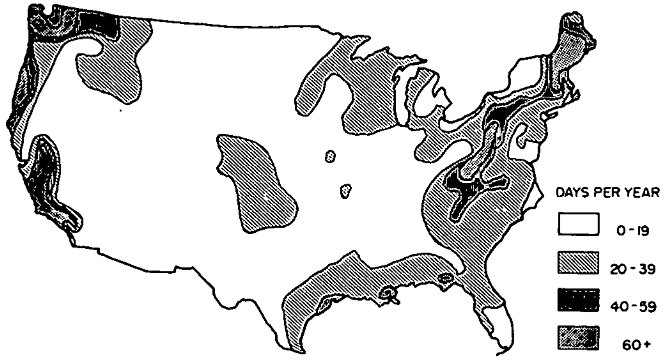
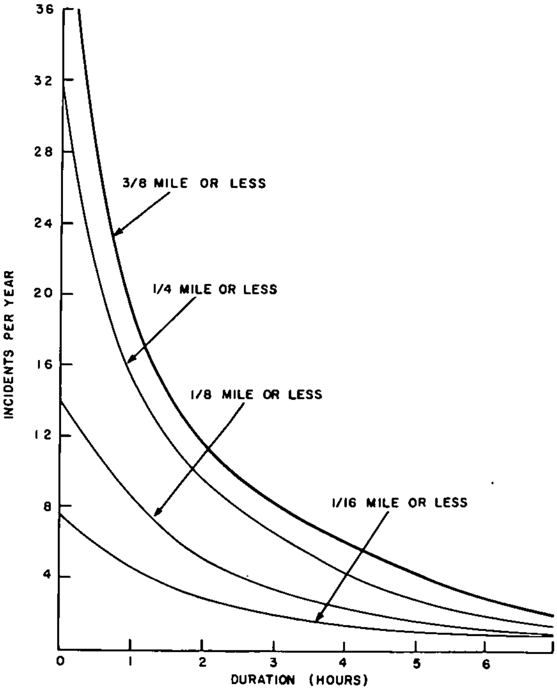


Figure 3. Incidents of reduced visibility at Newark Airport, 1956-1965 (3).



EFFECTS OF FOG ON DRIVING AND ACCIDENTS

An Australian study indicated that, for conventional roads, fog reduces the accident rate by 6 to 10 percent with the largest reduction in the more severe categories of accidents (4). Although comprehensive accident rate data are not available for fog accidents in this country, it does appear that fewer fatal accidents occur during fog than during clear weather conditions (5). This effect has been attributed to the driver's awareness of fog as a hazard, but the slight speed reduction observed on conventional highways in fog may also be a contributing factor, particularly with respect to reducing the severity of accidents.

For freeways, fog has proved to have the opposite effect. A California Transportation Agency study shows that the fatality rate for fog accidents on freeways was almost twice that of nonfog accidents (6). A study of California freeway accidents showed that the probability of a multiple-vehicle accident was greater in fog than in clear weather, particularly when 5 or more vehicles were involved (7). Fog did not have much effect on the mean number of vehicles per accident because there were also more single-vehicle accidents in fog. In fog, 98 percent of all accidents involved 4 vehicles or less. However, as indicated in Table 1, nearly two-thirds of all accidents involving 9 or more vehicles occurred in fog. These accidents accounted for less than 0.01 percent of all accidents and about 0.25 percent of fog accidents. The multiple-vehicle accident, because of its spectacular nature, is widely reported in the news media, giving the impression that accidents are widespread under fog conditions.

Measurements have shown that traffic behavior does not change significantly when visual range is reduced by fog, except for a slight reduction in average vehicle speed under some conditions (2, 8). Because of the reduction in visibility, however, there is an increased probability of overdriving. For free-flowing traffic operating on high-speed facilities with good geometric design, there appeared to be no consistent change in speed variability, lateral position, or collision course time (vehicle headway and speed differential with lead vehicle) that can be directly related to visibility restrictions caused by fog.

FOG ABATEMENT

Dry-ice seeding and other techniques have successfully dispersed cold fog, i.e., fog with liquid water droplets colder than 32 F (2). However, such fogs comprise only a small fraction of all fogs in the continental United States. For highways, dry-ice seeding might be useful at a few intersections with high traffic volumes in a limited area of the Northwest.

Most fogs in the United States occur at temperatures above 32 F and in the denser forms usually involve industrial pollution. Presence of pollution particles in the air will not in itself cause fog. However, when atmospheric conditions are right for the formation of fog, hygroscopic particles present in most industrial effluents will increase the density of the fog. Therefore, reductions in industrial pollution should decrease the occurrence of very dense fogs that are a safety problem for motorists. The clean air standards set forth by the Environmental Protection Agency are leading in that direction.

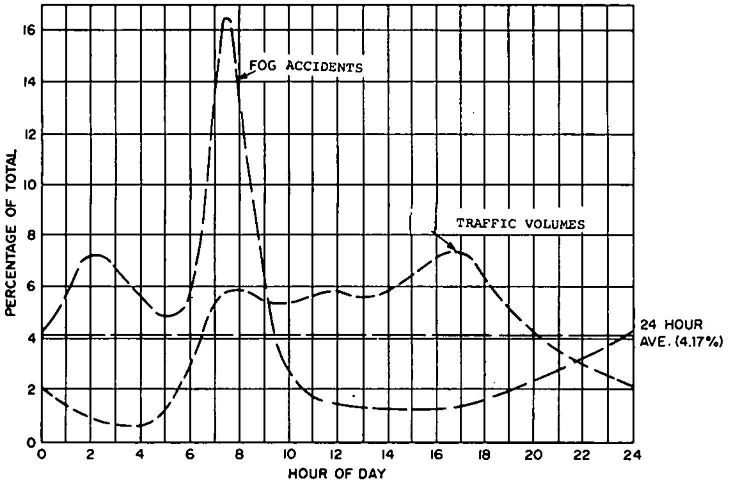
Efforts to achieve a reliable warm fog dispersal capability that might be economically feasible for highway use are far from encouraging. Four general fog dispersal techniques have been attempted: thermal (evaporation of droplets), chemical (evaporation and/or altering drop size), electrical (coalescence of charges droplets), and mechanical. A recent review of this research was contained in another report (2). Fog dispersal techniques require large installations, standby procedures, and maintenance expenses, and are often ineffective in dissipating the fog when it occurs. These techniques may be feasible at busy intersections or in other limited cases.

The relatively short persistence of most fogs limits the utility of portable dispersal equipment and installations that require long start-up times. Another limiting factor with portable dispersal equipment is the requirement for repeated application to the same roadway section. For example, with a 5-knot wind at 45 deg to the centerline and a device that initially clears a 100-ft wide path, fog would begin closing in again

Table 1. Accidents in fog on California highways, 1965-1968 (2).

Number of Vehicles per Accident	Total Number of Accidents	Accidents in Fog		
		Number	Percentage of All Accidents	Percentage of Involved Vehicles
1	149,798	3,631	2.4	20.3
2	262,346	4,911	1.9	54.9
3	38,344	786	2.0	13.2
4	7,623	223	2.9	5.0
5	1,708	81	4.7	2.3
6	471	43	9.1	1.4
7	160	23	14.4	0.9
8	47	15	31.9	0.6
9 or more	39	25	64.1	1.4

Figure 4. Hourly distribution of traffic volumes and fog accidents (11).



within approximately 10 sec. Therefore, if a 60-sec repeated-application cycle is required to keep the roadway above some minimum visibility level during periods of dense fog, a 2-mile section of freeway between interchanges might need as many as 8 vehicle-mounted dispersal devices (assuming 5 miles of travel per vehicle during each dispersal cycle at an average speed of 40 mph).

Natural vegetation (i.e., judicious landscaping with some forms of tree stands) has been applied in some specific locations to prevent shallow fogs from drifting over the road (2).

GUIDANCE SYSTEMS

A variety of methods designed to assist drivers during fog have been proposed, and some have been experimentally tried. These include both active and passive guidance systems. Because of the clear economic infeasibility of justifying active guidance systems, such as "automated highways," as possible solutions to the fog problem alone, they will not be discussed here. These types of systems might be justifiable for general purposes and, if so, would provide a solution to the fog problem by eliminating the driver from the control loop.

Under certain nighttime conditions, some highly directional types of fixed-lighting systems have proved to be effective in providing additional guidance information in fog (9). However, as is shown in Figure 4, the fog accident problem is particularly severe after dawn between the hours of 6 a.m. and 9 a.m., with the peak occurring about 7:30 a.m. (1). Approximately 50 percent of the fog accidents occur in daylight. Fixed-lighting systems can be designed (10) to be effective for the 50 percent of the fog accidents that occur at night. However, the additional expense of such equipment would probably not be recovered from the resulting reduction in accidents. Conventional types of street lighting may be useful in light and moderate fogs but are not of much help in a dense fog.

Present reflectorized pavement marking techniques result in only a slight increase in visibility during daytime fog and have virtually no effect on traffic behavior. The use of inset "pancake" marker lights has been suggested to provide guidance. They are relatively expensive and do not provide any information on stopped vehicles. Perhaps such a display technique, combined with the information on lane occupancy obtained from instrumentation similar to the passing-aid system, would work.

Results of research on vehicle rear lighting systems indicate that current vehicle rear lights are ineffective in fog, especially during daytime. Increased candlepower would be desirable, and the National Highway Traffic Safety Administration appears to be moving in that direction. The major problem concerns the control and possible misuse of a 2 or more level taillighting system.

The most successful of the proposed plans involves the use of variable message signs that warn drivers of fog conditions ahead and advise them as to desirable operating speed. Although these signs have little influence on mean operating speeds, they do reduce speed variance when the sign is set at approximately the mean speed of traffic (8). If the signs are set much below the prevailing speed, a bimodal speed distribution results, increasing the likelihood of rear-end collisions. Part of the reason for these results may be the lack of reliability of information provided by such signs in the past. Particularly, where manual changing of speed limits or folding advisory signing was required, the messages were often exposed long after the reduced visibility condition ended. Therefore, many drivers may have assumed that such lighting is meaningless.

A major installation of remotely controlled warning signs is being evaluated in Oregon at the Murder Creek Interchange on Interstate 5 (11). There are 3 large overhead signs in each direction with the final sign at the point of maximum accident occurrence. The variable speed message is controlled on the recommendation of a state police officer stationed in the signed area and is based on the distance he can see and traffic flow in the area. Research is currently investigating traffic and fog detection equipment for use in automating control of the signs.

Preliminary reports indicate that the Oregon installation is having a beneficial effect in terms of accidents and traffic flow. Traffic flow parameters, such as mean speed,

speed variance, and headway, may be more useful in determining required information to be displayed to drivers than in developing devices for detection of fog density. Use of optical and electronic devices for detection of fog appears to be too expensive for widespread use and too sensitive to small changes in local conditions within a few yards of the measurement station. Research (12) currently under way is attempting to relate the output of such a device to a meaningful fog index for drivers.

The Federal Highway Administration is currently planning research aimed at developing a speed advisory system that will inform drivers of the current status of other vehicles' speeds on the road ahead but beyond the limit of the drivers' available sight distances. Such a system might involve a simple fog-no-fog detector for system activation and a speed sensor with a simple roadside sign indicating an advisory speed. The speed would be set at approximately the mean speed of traffic ¼ to 1 mile ahead. The logic devices for controlling the system should probably be interconnected so that no sign calls for a speed that is more than 10 to 20 mph higher than the following sign, except under exceptionally critical conditions.

The installation of such a system should reduce speeds of traffic gradually and should aid in reducing multivehicle secondary accidents. Because the system will be designed to alert drivers to any slowing of traffic ahead regardless of cause, it is expected that the system will be useful for many situations in addition to those produced by fog.

In summary, there is no technology currently available that will solve the fog problem in a cost-effective manner. Current research in the area of warning-advisory signing for fog appears to hold significant potential. The only real safe advice at present is, If the situation gets bad enough, close the road.

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DISCUSSION

W. H. Heiss

Because there is no basic disagreement with the discussion paper, these remarks will be in the nature of a supplement to the paper.

It may be initially noted that fog works to reduce visibility by reducing the contrast ratio between the object to be seen and the background. This occurs because the fog reduces the amount of light (principally by fog scattering) reaching the observer's eyes from the objects and from the veiling produced by the scattering of light illuminating the intervening fog. Because of the veiling effect of illuminated fog, the practical visibility can, for a given fog density, be worse in daylight than at night. This is evident from the results of both the previous NCHRP study (2) and the current NCHRP highway fog study (Project 5-6A).

In studying and making measurements in natural fog, one fact soon becomes evident: Fogs have a wide degree of variability from area to area, and in many cases such variability exists within the fog itself. This variability can make the locating of fog measuring instrumentation critical because in many localities fog density can vary every ½ mile and in some cases can differ substantially over distances of less than 100 ft. Because of the variability among types of fogs, statistical data such as those shown in Figure 3 must be used with care. For example, incidences of fog of less than ⅛ mile in area and greater than 1 hour in duration are shown to be comparatively rare, averaging less than 10 per year. Also, the incidence rate drops rapidly for increasing durations. Although this is typical of many fogs and areas, in some areas the duration of the fog, when it occurs, may be greater on the average. Similarly, the hourly distribution of fog accidents (Fig. 4) shows the composite for all of the fog accidents of the study area; however, it does not necessarily follow that the fog accident experience of a particular location will exhibit the same hourly distribution. Also, it may well be that the hourly distribution of single-vehicle accidents differs from the distribution of the multivehicle accidents.

The NCHRP study (2) has included a study of visibility as perceived by a driver as a function of measurable fog parameters. Results of the analytical portion of the study have indicated that the prediction of driver visibility based on fog (and ambient light) measurements is feasible, and on-road tests to gather data for the validation and calibration of the analytic models developed are currently under way. Basic to any such instrument visibility determination is an instrument capable of measuring fog density. In the past 2 years there has been a considerable increase in interest by instrument manufacturers in the highway fog measurement problem, and there are several instruments now being sold for such usage although none is being produced in large quantities. The fog measuring instrument that has been used most frequently is the transmissometer; one or more of these has been installed at virtually every major airport in the world. Of the available fog measuring instruments, the transmissometer is probably the most accurate. It is not considered particularly useful for highway fog measurements, however, because of higher initial purchase and installation cost and the comparatively frequent periodic maintenance required to maintain its accuracy.

Most of the other available fog instrumentation measures some scattering property of the fog, e.g., back scatter, forward scatter, or an approximation of total scatter. All of the commercially available fog instruments are limited in that they sample only a comparatively small volume in the immediate vicinity of the instrument. Such measurements can be misleading in patchy and bank fogs. There are, however, some experimental devices being tested that are potentially capable of detecting fog at distances of 1 mile. Until such time that probing devices become available, a somewhat larger number of existing devices, carefully sited, will have to be used for instrumented systems.

Fog frequently tends to be stratified, being typically heaviest close to the ground at night and increasing in density with height during the day. The instrument should therefore be mounted such that the sampled volume is close to the height of a typical driver's sight line during restricted visibility.

In the area of fog countermeasures it is agreed that fog abatement techniques are not promising for widespread use, but they may have some application in selected areas where the fogs are typically associated with dead, still air. The California Division of Highways conducted a small study on an abatement technique last winter. The results, however, were inconclusive due in part to a lower-than-normal incidence of fog during the test period. The Division is considering the possibility of further testing.

Because of the variability in the nature of the different types of fogs that may be encountered at different locations, the efficacy of potential fog countermeasures is best considered in light of typical fog characteristics, driver behavior patterns, and accident experience at the particular location under consideration.

Although it is true that fully satisfactory cost-effective fog countermeasures are not currently available for generalized use, there are techniques that may be of use in specific trouble spots. The use of variable message warning and regulatory signs may be of considerable help, as evidenced by the encouraging preliminary results of the installation in Oregon on Interstate 5. Automatic control of warning signs may well be effective at specific spot locations where fog frequently occurs and drivers encounter the fog unexpectedly. The use of flashing or strobe lights or other improved delineators to mark the location of the roadway and to help prevent disorientation of the driver may be helpful, although care must be exercised in this latter case to avoid encouraging excessive overdriving, which could lead to increased multivehicle "chain-reaction" accidents. California has had sufficient success with Operation Fogbound (which includes an extensive educational campaign, public radio broadcasting announcements, and the use of pacer patrol cars) that it is planning to expand the program for the coming winter fog season.

Although the cost involved in implementing some of the more complex fog warning and guidance systems may deter their installation, the combination of such a system with a freeway or turnpike surveillance and control system may prove to be cost-effective.

Dwayne Hofstetter

With regard to Schwab's paper, we do not know yet whether the mean speed is the appropriate speed to use in signing. This is something that will be determined from the research being done in Oregon. Oregon's warning sign system was completed on November 15, 1968. The installation includes 6 remote-control variable message signs that are operated from the state police office.

Since the installation of the signs, research equipment, including detectors and a computer for vehicle speed and headway measures, has been installed. The system has been used by the Oregon State Police for a variety of reduced visibility driving conditions and for various emergency road conditions. The signs have been activated during periods of dense local fog, a hail storm, a severe snowstorm, periods of heavy smoke caused by field burning in the area, icy periods, a period of construction on the highway, and periods after vehicle accidents. The signs have also been activated during periods of generalized area fog when the entire Willamette Valley from Portland to Eugene was experiencing fog conditions.

The research project associated with the warning signs has not yet been completed, and the amount of information accumulated is not statistically significant; consequently, no quantitative conclusions may be made concerning the effectiveness of the signs in altering vehicle operating characteristics. However, early indications are that the vehicular stream does in fact very closely observe the indicated speeds shown on the variable message sign.

Accident experience since November 15, 1968, has been extremely favorable. No "chain-reaction" collisions or other serious types of motor vehicle accidents have occurred during the periods of limited visibility when the signs have been in use. The only accident that might at least partially be attributed to fog was one that occurred on December 18, 1970. Fog signs were on at the time, and visibility had dropped to 300 to 600 ft; however, the accident was primarily caused by skidding on ice (as stated in the accident reports).

The Oregon State Police, through mutual agreement with the highway division, are regulating the use of the signs on a very strict basis. They are used only when warranted by weather conditions or other abnormal conditions. As a result, state police reports indicate that driver observance of the signs is very good. During periods of generalized Willamette Valley fog, police reports indicate that the speeds shown on the signs in this section are still being observed by vehicle operators miles beyond the signed section. Verbal reports from the local patrol officers indicate a surprising amount of driver observance of the signs and also an increase in reliance on the part of the state police to use the signing system as an important supporting system for its reduced visibility patrol activities. During this past year, the signs have been used to control traffic more often during the aftermath of vehicular accidents than for reduced visibility in fog. The state police indicate that at least one less patrolman is generally needed in the sign section when the signs are in operation and that, for wreck situations, which formerly required 3 patrolmen, only one is needed when the signs are in use.

Based on the results of our studies so far, we are quite optimistic about the benefits that can be obtained from the use of variable message signs for reduced visibility conditions.

AUTHOR'S CLOSURE

I would like to express my appreciation to Heiss and Hofstetter for the time they spent in reviewing my paper.

I would like to stress again Heiss's point that, because of the variable nature of different types of fogs and the locations at which they occur, there is a great need to study the specific problem before exploring countermeasures. Currently, there is no technology available that will solve the highway fog problem in general. There is specific technology that may be helpful under limited sets of conditions. For example, certain types of fixed illumination might be useful. However, this is only true if the bulk of the fog accident problems occur at night in the specific situation for which the illumination system is installed. Stopping of vehicles and convoying them through the fog area with specially equipped lead vehicles will work if the fog is patchy and all vehicles can safely be stopped before they enter the affected area.

It is my belief that the warning-advisory signing approach is the most likely to produce effective results that can lead to a more general solution. Therefore, I would recommend that future research effort be concentrated on further development of advisory systems and especially in providing answers to the many driver behavior questions that influence the design and effectiveness of such systems. To achieve the desired improvements in traffic flow and safety, we must direct the next phase of research to these problems.

REVIEW OF VISIBILITY FACTORS IN ROADWAY SIGNING

H. L. Woltman

The transmission of information to drivers on the highway has been a challenge since the early days of the automobile. Visual transmission by means of signs was an obvious development. The many highway problems (among them visibility, legibility, message content, and national uniformity) that have developed since World War I have required systematic work and resolution.

It is generally acknowledged that sign performance is dependent on attention value and legibility. Forbes (8) has reported that these are functions of target value and priority value, pure legibility and glance legibility respectively. Each factor is related directly to contrast—the sign with surround, providing attention value; letters with background, providing legibility.

Literally, contrast is the difference in brightness and color between an object and its background. It is a subjective experience that is given to extreme variation, particularly at night. Excessive stimuli from glare sources (such as opposing headlights and luminaires, colored taillights, and electric advertising) contrast with the generally inadequate luminance for effective nighttime perception elsewhere in the highway scene. A study by Forbes (8) described pure legibility as the reading distance derived from an unlimited observation time for reading the sign and glance legibility as the distance under limited reading time.

Target value is generally employed to describe those characteristics that make a sign stand out against its natural background or surround, and priority value refers to other factors, such as location or mounting position, that affect the order in which signs might be read. It has been shown that contrast factors affect target value and that location, number of signs, reading habits, search procedure, and "mental set" affect priority value.

LEGIBILITY FACTORS

Many studies of sign legibility have served to identify such factors as letter-to-background contrast, letter height, height-width ratio, stroke width, spacing between letters, and vertical spacing between lines as being important to daylight legibility (10).

Mills (25) tested various color combinations in studying sign legibility. His first recommendation was black on yellow, and his second was black on white or white on black, thus indicating the importance of letter contrast. In 1932 Lauer (21) recommended a light yellow and also a letter height-to-width ratio greater than 33 percent, a stroke width of 20 percent of average letter width, and a spacing of 50 percent of average letter width.

Two later studies (20, 31) indicated an optimum stroke width for block letters in the range of 15 to 25 percent of letter height. Other studies (11, 2) have shown that legibility increases with letter width up to a square letter.

A number of studies have investigated the irradiation effect of black-on-white versus white-on-black letters. Although they differ in detail, all of these studies indicate that the light letter is more effective when letter design and spacing are optimized. Case et al. (6) found black letters better at close spacing and white letters better when spacing was wide [equal to letter height of Series E (wide) letters]. In a laboratory experiment, Allen and Straub (2), using 3 alphabets of different width [Bureau of Public Roads Series A (narrow), C, and F (wide)], found bright internally illuminated letters better at intermediate brightness.

Allen et al. (1) found bright letters on a low-luminance background more legible than the reverse against low and medium ambient illumination, but not against a high ambient background. Based on the information from the Case et al. study (6), the National Committee on Signs, Signals, and Markings and the Bureau of Public Roads developed first a standard block-letter alphabet, then a rounded-letter alphabet, and finally a lowercase alphabet design.

LEGIBILITY DISTANCES FOR HIGHWAY SIGN DESIGN—HUMAN FACTORS ENGINEERING

It has been known for many years that 1 min of arc represents so-called normal vision for young subjects, but this is not of much assistance to the highway sign designer. Traffic engineers and those designing highway signs have needed to know the maximum distance at which most drivers can read a sign of certain letter size and design. Accordingly, a method for determining legibility distances for a standard block-letter alphabet was developed by Forbes (8) and applied by Forbes and Holmes (11).

From these full-scale outdoor observations a linear relation was noted between letter height and legibility, yielding a distance of about 50 ft/in. of letter height in daylight for black-on-white Series D (medium-wide) letters. The narrower Series B letters gave about 33 ft/in.

Six- to 24-in. letters and 6-letter place names with one misspelling were used for test signs. Floodlighted signs at night gave legibility distance from 10 to 20 percent shorter. Subjects were required to record all letters accurately, including misspellings.

LOWERCASE LETTERS AND FAMILIARITY EFFECTS

A comparison of legibility distances of lowercase and capital letters using both familiar words and scrambled letters (12) showed distances similar to those found in the 1939 study (8) for the scrambled letters. Legibility distances for lowercase alphabets in terms of loop height were comparable to those with capital letters. Longer legibility distances resulted when familiar words were used. The scrambled letters averaged about 55 ft/in. of letter height, whereas familiar words gave about 65 ft/in. of letter height.

EFFECT OF LETTER BRIGHTNESS ON LEGIBILITY

The luminance desirable for dark rural conditions has been reported (30) for letters 8 in. through 18 in. in size. Under the test conditions (from 0.1 to 100 ft-L for white letters on black backgrounds), maximum legibility for the Series E letters occurred at luminances of 10 to 20 ft-L. Satisfactory results were shown to be within a range of letter luminances from 1.5 to 100 ft-L. The reduction in legibility distance at 100 ft-L was attributed to halation or "overglow." At 1 ft-L, legibility was reduced to approximately 80 percent of maximum; 0.1 ft-L was shown to yield 45 percent of maximum.

Despite the relatively large luminance span from 1.0 to 100 ft-L, the corresponding legibility was shown to range from 63 to 74 ft/in. of letter height. A similar study (7) of "illuminated suburban" conditions (0.2 ft-L ambient and typical of an illuminated highway without oncoming headlight glare or competing advertising lighting) reported legibility distances essentially consistent with the dark rural conditions reported by Allen.

A test of an even greater range of brightnesses was reported by Allen et al. (1), who used internally luminated bright-on-dark and dark-on-bright background signs and familiar 3-letter syllables.

By using sign luminance values ranging from 0.2 to 2,000 ft-L (with and without headlight glare and with 3 different levels of ambient illumination), they found that legibility distances are substantially affected by headlight glare and competing illumination. Here again, resulting average legibility distances were generally from 40 to 60 ft/in. of letter height in the range between 2 and 20 ft-L, but ranged from 12 to 65 ft/in. in glare and in high ambient illumination. For rural sign brightness, 10 ft-L was recommended; for lighted areas, 100 ft-L was considered optimum.

Allen et al. (1) reported 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. Additionally, they observed that a driver does not ordinarily observe a highly luminous sign continuously on his approach as did their subjects.

NEED FOR CONTRAST

The need for 40 to 50 percent contrast for day luminance and 50 to 60 percent contrast under night driving luminance levels is indicated in a study by Richards (29). He measured the visual ability of subjects to discriminate letters, not their response to sign legibility distances. He found a great need for high-contrast targets by older subjects.

GLANCE LEGIBILITY

When time is limited to a short glance of about 1 sec, as in much seeing by drivers on the highway, Forbes (8) found that the legibility distances reduced from 10 to 15 percent and only about 3 or 4 short, familiar words could be recognized. The limit for familiar words with about 1-sec exposure was confirmed in a study by Hurd (18).

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 (26) in the United States and in England by Odescalchi et al. (28) and Moore and Christie (27). To accomplish this, time to read signs plus warning time needed for maneuvers must be known or assumed.

LEGIBILITY SUMMARY

It has been shown that legibility distance changes with the following parameters: letter height, width, spacing, contrast, and brightness. Each of these parameters interacts with and influences the others. Familiar words are seen at longer distances. Scrambled-letter determinations give better reliability, and the distances are probably more representative of the 20/40 vision of many drivers. Relatively high sign luminance is needed against comparatively bright surrounds, but usually not for ordinary rural roads.

TARGET VALUE

Target value is the capability of a sign to be visible against its background and to provide early recognition and discrimination of the sign type. This in turn prepares the driver for the potential message moments before actual reading of the legend. Major factors affecting target value are the sign color and brightness, producing contrast with the natural background or surround.

The visual factors of color and contrast are relatively well understood. As shown by Hanson and Dickson (15), the more contrast a sign has with its surround, the greater will be the distance for its discrimination and recognition. The importance of color is highlighted in 2 studies (5, 17). A conventional red stop sign was placed in a prominent location with the letters rearranged to read TOPS. Under the assumption that a stop sign registers primarily because of its color and shape, it could be expected that few people would note anything unusual. After passing the sign, 86 percent of the drivers admitted that the word TOPS had been overlooked. Drivers who used the road frequently took less notice (87 percent) than did strangers (79 percent). As Birren (5) observes, "To think continually in the process of seeing is quite contrary to human nature. Bright colors will mark danger spots far more effectively than words and legends. The reason is simple enough: visual reaction to color is involuntary while words require deliberation." Hulbert arrived at a similar conclusion in a 1965 test of "do not enter" signs used to control wrong-way freeway entries. Black-on-white and white-on-black "do not enter" signs were compared with white-on-red-background signs. After testing 81 subjects in a driving simulator, the experimenters concluded that white-on-red signs can be seen from a much greater distance than can black-and-white signs. Forbes et al. (10, 13) found that the range of effectiveness of a given sign color depends on its brightness contrast with the prevailing surround. To maximize sign effectiveness on a system-wide basis of utilizing a single relatively uniform color, careful consideration of all potential backgrounds should be made. The diversity of natural backgrounds with which a sign must compete is very broad.

In an inventory of more than 4,000 Interstate guide signs, Hanson and Woltman (16) found the most frequent surround to be dark trees, occurring 23.1 percent of the time. Sky and bridge surrounds were the next most frequent surround, occurring 19.1 and 15.8 percent respectively. Overhead signs had a somewhat higher incidence of sky surrounds than did shoulder-mounted signs, which were predominantly seen against a dark tree surround.

A 4-year study of attention value was reported by Forbes (9), indicating that signs with good attention value must have good contrast within the sign and good contrast with the surround. Several mathematical models were advanced to describe the factors of detection and identification of the sign against many natural surrounds. The contrast levels between the legend and sign background, and between the sign background and its surround, were found to be of equal importance. Of significance is the total luminance of the sign, other things being equal. An evaluation of the relative merits of sign position favored the overhead location.

ANGULAR POSITION

Although target value is greatly influenced by background, it is somewhat dependent on the sign's position with respect to the driver's central point of fixation. For optimum attention and identification, Matson (24) suggests that a sign should fall within a visual cone of 10 to 12 deg on the horizontal axis and 5 to 8 deg on the vertical axis throughout the intended range of sign effectiveness. Greenshields (14) states that 5 deg to the left or right is ideal but that practical considerations may force a wider visual field. He suggests a value of 10 deg to the left or right for the maximum angular displacement.

In areas where the terrain is flat, sign positions were found by Hanson and Woltman (16) to be within the suggested angular limits. In metropolitan areas and on gently rolling terrain, sign positions of 10 and 37 percent respectively had greater than optimum angular displacement. The mountainous area was most severe, with 53 percent of the shoulder-mounted signs falling outside the optimum range of 10 deg horizontal displacement.

LUMINANCE CHARACTERISTICS

Sign luminance for illuminated signs is directly measured with footcandle meters and comparatively straightforward instruments of little complexity. The determination of the luminance of reflective signs is less straightforward and must generally be calculated in the manner first described by Straub and Allen (30). Elstad, Fitzpatrick, and Woltman (7) employed planes to describe luminances for several signing positions for sign-viewing distances from 1,200 to 75 ft. King and Lunenfeld (19) used computer analysis to investigate the effects of horizontal and vertical roadway curvature on sign luminance.

These techniques employ careful determination of reflective luminance in absolute values. Reflective efficiency varies widely with divergence angle, the angle subtended by the headlights, the sign, and the reflected light beam at the observer. This angle undergoes significant change as the motorist approaches the sign and greatly influences the resulting luminance. The separate values for each headlight necessitate separate calculation of the luminance for each headlight and for each divergence angle.

Illuminance depends on the alignment of the sign with the headlight beam, and its determination requires the location of the reflective device in the appropriate area of the headlight isocandle diagram for both high and low beams and for typical conditions of highway alignment. (Calculation for each lamp is required, as is change in sign position, alignment, or distance.) Luminance values are then obtained by application of the inverse square law.

As a result of computer analysis of luminance variables, King and Lunenfeld (19) found the following:

1. There was only a negligible change in brightness for the different types of cars;
2. The farther the sign is located from the traveled way, the dimmer it appears to the driver;
3. A substantial difference in sign brightness results between high- and low-beam usage;
4. The overhead sign in the right lane is brighter than the signs located in the median or over the median lane;
5. Brightness is only slightly affected by degree of curvature;
6. As the grade change becomes larger, brightness increases for crest vertical curves and decreases for sag vertical curves;
7. A slight headlight voltage change has a minor effect on sign brightness; and
8. A vertical misaim of 1 deg upward increases the brightness of the sign; a misaim of 1 deg downward reduces sign brightness.

Only recently have field photometers of portable size, high sensitivity, and small angular resolution become available to make in situ luminance measurements of signs, thereby resolving the inherent question of the relation between real-life data and theoretical calculations. An extensive study by Youngblood and Woltman (33) of guide signs of contemporary reflective legend and background materials, for both day and night driving situations, was made to evaluate sign luminances.

Sign legend luminances of more than 1 ft-L were found on low beams for encapsulated lens and button reflective materials on unlighted overhead signs for the legibility distances available. Three legend materials were in excess of this level for the shoulder-mounted location on low beams. With high beams, luminances of 10 to 20 ft-L, equivalent to those exhibited for illuminated overheads, were found for several materials on both overhead and shoulder-mounted signs. The effect of adjacent vehicles in the traffic stream is to raise sign luminance for low beams from 2 to 5 times for adjacent vehicles on low beams and up to the level of high-beam luminance if adjacent vehicles are using high beams.

Maximum reflective sign luminance was found to occur at distances similar to the maximum legibility distances for the letter sizes prescribed by the Federal Highway Administration (22). Such luminance depends on the headlight distribution pattern, sign offset, material efficiency, and letter sizes used.

THE INFORMATION SYSTEM

King and Lunenfeld (19) have extensively described reception and information processing capabilities. The present information channel is primarily visual. It has the farthest unaided range of all sensory channels. Because information can be presented externally and at a distance, it does not require the presence of equipment in the vehicle, and the signing system is relatively permanent and inexpensive.

However, the visual channel may be adversely affected by the differences between day and night, attenuation factors (such as fog), and speed of vehicle (which limits perceptual time). Drivers can attend to only one channel at a time, and information may be missed because it was not processed by the driver.

The authors list the following requirements of a basic information system: user-centered, applicable to the existing highway system, usable by all drivers at all times, fail-safe, compatibly evolutionary, and economically feasible. The system must be compatible with the worst-case driver.

SIGNS AS A COMMUNICATIONS TECHNIQUE

Signs are the main technique for accomplishing visual communication, and there are several cogent reasons for retaining and maximizing the use of the sign as the primary visual display technique. These include the following:

1. Expectancy—drivers expect to receive information from signs and willingly respond to messages displayed on signs;
2. Investment—sign panels and supports already exist; therefore, costs of any changeover to a new information system will be minimized; and
3. Implementation—personnel, organizations, technology, and equipment necessary to implement any sign system already exist.

SYSTEM ANALYSIS AND RECOMMENDED PRACTICE

The identification of deficiencies in the present system of signing, delineation, and marking has been made by D. L. Woods et al. (32). Using a diagnostic team study technique, they evaluated existing visual communication systems on freeways, arterial streets, and 2-lane highways. The following subsections give the visibility subjects that were investigated during the study and the practices or treatments that were recommended. (Some of the language has been paraphrased.)

Signs

Freeway directional signing is expected by the driver to have a green background, and, in instances where the background color is different, drivers have a tendency to overlook the entire sign assembly. A driver approaching an exit is searching for a green background sign, and only after reading all such signs will he scan the other signs in the area in search of his desired destination. The time lost during this scanning process can consume most of the lead time provided the driver.

The use of a diagrammatic sign to convey to the driver the necessary maneuver when he approaches a cloverleaf interchange was desired by many team members. Confirmatory route markers are most desirable just downstream from every major decision point.

The priority of control devices normally assumed in the design of signing is totally reversed on modern freeways. Directional signs are of the highest priority on freeways, with regulatory and warning devices assuming a much lower level of importance to the driver. When asked why the black-on-white regulatory signs were not read, one subject driver replied as follows:

> Those little black and white signs tell you anything: "don't throw litter on the highway," "don't park on the shoulder," almost anything. The one thing that is important to me is which lane I have to be in to get where I want to go.

Black-on-white regulatory signs will probably not be effective when they are located in the vicinity of a major overhead structure.

Team drivers reported that they frequently experienced difficulty in locating entrance ramps to freeways, especially at night when the total roadway environment is not visible. Drivers are often confused by side roadways intersecting in close proximity to the interchange. Better definition of entrance ramps could be accomplished either by route markers with directional arrows at the entrance to the ramp or by signs designed specifically to designate the freeway entrance.

Signing of freeway entrance ramps on frontage roads is considered inadequate. Confusion at entrance ramps can be minimized by use of prominent and concise directional signing. More beneficial, however, are specially designed freeway entrance signs.

The use of route marker assemblies on a more extensive basis was strongly supported by the team members. Route markers were desired along the most direct route to the freeway in the desired direction. Trailblazing to hospitals offering 24-hour emergency service was considered desirable by team members.

Motorists traveling on freeway facilities have become accustomed to the freeway signing. After leaving this highway system, however, they are often confused because of a lack of continuity in signing or a complete absence of signing. A communications breakdown often occurs at this interface. An equally critical problem occurs in the reverse situation. To enable drivers to effectively maneuver along the desired route between freeway and arterial street systems, we must provide them with sufficient information.

Drivers report that arterial street name signing is not aiding them effectively, resulting in an inability to utilize turn lanes. The legibility of street name signs is inadequate for the posted speed limit, and lettering is generally too small on signs located at intersections. Such signs should be located on both the right and left sides of all arterial streets, with alternative locations in the median or overhead. When arterial streets converge at major intersections, drivers should be able to read the street names before reaching the intersection proper. This could be accomplished with larger signs at the intersection or a combination of advance and intersection signing. (Span-wire-mounted overhead signs are the most economical and would be the logical choice for use on such arterial streets.) The lettering should be a minimum of 6 to 8 in. in height for adequate legibility. With a few improvements in current techniques, street name signing could be very beneficial.

Visibility is an essential prerequisite to all other signing considerations. Drivers frequently pass intersections where they wish to turn simply because the sign is placed too far off the roadway. Signs placed too close to the point at which a driver must make a decision have also been criticized. Intersecting roadways are critical areas on 2-lane highways, and advance road name signing should be provided.

Urban Signing

The frequency of regulatory parking signs on urban arterial streets is often excessive and unattractive. The diagnostic team members felt that the problem was of sufficient magnitude to justify exploration of alternative methods of parking control. One suggestion was the concept similar to the "snow emergency route" designations to control parking, which might be combined with the use of pavement markings to designate the restricted area.

Pavement Markings

Many drivers felt that the view of the roadway surface ahead was their principal source of information to accomplish the driving task. The view of the roadway is especially important on a 2-lane highway where drivers are more dependent on road geometry for guidance.

The effectiveness of edge lines was suggested repeatedly by team members on all types of highway facilities. Despite a high contrast between the shoulder and through lanes, drivers are benefited by the presence of an edge line. Drivers recommend that edge lines be used on lighted freeways and on all entrance and exit ramps. Edge lines were recommended for use on arterial streets for guidance around obstructions, or when required to guide to the left. The majority of participating drivers expressed a desire for edge lines on all types of highways, except in urban areas where there are raised curbs. Edge lines apparently give the driver a greater sense of security in operating his vehicle, and, if this is in fact the case, edge lines should be provided in order to allow the driver to perform the driving task under more nearly optimum conditions.

The effectiveness of pavement messages on arterial streets is diminished by dense traffic, which limits the view of the message. Span-wire-mounted overhead signs were suggested as a more economical and effective means of conveying information.

Rural 2-lane highways present the driver with the task of tracking, and thus attention is focused on the pavement. Under these conditions, the pavement message can be very effective.

Delineation

The following practices were recommended for use at a hazardous structure: a combination of post-mounted delineators gently tapered to the obstruction, an edge line following the same general course, and a hazard board or equivalent treatment at the obstruction.

Guardrail delineation has been found to confuse some drivers when it is placed only at the ends. Continuous delineation is more meaningful to the driver.

The placement of post-mounted delineators in the medians of freeways was considered unnecessary. This is particularly true on a lighted freeway.

Drivers desire delineation on horizontal curves, especially on 2-lane roadways. This seems to be accomplished effectively by placement on the outside of the curve.

A wide variety of devices are now being used to delineate mailboxes and private driveways along rural highways. These devices startle drivers, provide incorrect information, and are responsible for additional visual "clutter." Specific requirements should be developed to replace the great variety of devices to establish uniform standards.

The standards for signing in the United States are prescribed by the Manual on Uniform Traffic Control Devices (22), which gives standard colors, sizes, and legends for signs, signals, and pavement markings.

The efficacy of urban signing was also questioned by Markowitz (23). He observes, "None of the sign systems of the world deal with the urban sign problem in any significant manner." The Manual (22) hardly acknowledges the problems and provides very little in the way of guidance for those responsible for the implementation of urban signs. In order to help reduce the proliferation of signs, and at the same time expedite communications, we explore the use of special subsystems of signs for particular user groups.

The urban signing problem is also dealt with by Ashley et al. (3). They provide many specific suggestions designed to improve the flow of information supplied by traffic and pedestrian signing of both an official and commercial nature. In nearly all cases, tests indicated that new sign designs were a significant improvement over the conventional. New signs furthermore were welcomed in the surveys conducted. Signs were generally larger and color coordinated and employed symbols for rapid detection and comprehension.

DIAGRAMMATIC SIGNS

A study of diagrammatic signs by Berger (4) recommends that they be installed at interchanges where unusual or inconsistent geometrics are involved and where high volumes or perceptual difficulties are encountered. The design itself should be simple and incorporate not more than 2 choice points where possible. Such signs should be of the aerial or plan view and be designed to indicate the correct lane for the appropriate exit maneuver.

The blockage of signs by trucks is described in terms of probability for the number of trucks and speed of traffic by King et al. (19). The geometry of the blockage problem was defined in terms of the line of sight from the sign determined by the extremities of the sign and by the extremities of the truck as viewed from the sign.

The driver will have his vision blocked if his line of sight falls within the truck's "shadow." The extent of this shadow is a function of truck speed, size, and position and size of the sign. The final probability is given for a random car in the shadow for a percentage of time greater than the total time it is on the roadway. The obvious implication of blockage suggests a redundancy of devices where amount of traffic or number of lanes is excessive.

FUTURE RESEARCH

No review would be complete without an observation on the direction of future research. Future work should appear to be directed to system-wide analysis with particular emphasis on user-oriented needs at the freeway-arterial street interface, arterial and major street identification, urban signing for parking control, and pedestrian needs. At these levels the solutions appear ready for implementation. Previous research of legibility and attention value has been timely and accurate. The diagnostic team findings level virtually no criticism of freeway signing where the principles of this research have been properly interpreted and deployed. Necessary information required by the motorist for such freeway facilities may still be lacking in terms of message content and sequence of information provided, however.

Specific visibility questions can still be identified in areas such as the extensive proliferation of various reflective devices along rural highways and of advertising devices along arterial streets and at points of traffic confluence. Of serious concern is the low-beam performance of reflective devices in view of more extensive low-beam usage.

Although the Manual (22) requires reflectorization or illumination of signs, delineators, and pavement markings, no values are specified and no minimal maintenance of luminance is suggested. The 3 classes of devices, for the several environments, require not only quantification but also identification of practical techniques for specification, field inspection, and maintenance.

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DISCUSSION

T. W. Forbes

The paper by Woltman gives a fine review of research reports on visibility factors in roadway signing. Well summarized are the research results of the use of dark letters on a light background versus light letters on a dark background. He notes that in some cases a light letter on a dark background was better, and in other cases the reverse was true. These results can be understood logically in terms of irradiation of light on the retina of the eye, which acts like halation on a photographic film. A bright feature, whether letter stroke or a bright space between letters, can be expected to spread as intensity increases. If the spacing between letters is greater, this spreading has more room to occur before encroaching on another letter. Therefore, one can expect different effects with different combinations of stroke, width, and letter spacing.

In reviewing legibility distances, we should remind ourselves that these distances depend on the visual acuity of people. Therefore, measurements of legibility are usually made with large groups of observers, and legibility distances are often given either as average values or as 85th percentile values. The average values are statistically most stable. These values allow valid comparison of different factors and conditions.

Because an average legibility distance is one at which 50 percent of a group of drivers can read a sign, for most applications to sign design, an 85th percentile value should be used so as to include most drivers. This results in larger sign letters and usually corresponds to 20/40 vision if legibility distances are determined on a group of observers whose corrected vision averages 20/20.

Thus an 85th percentile distance may be preferable to an average legibility distance for design purposes. This means that the legibility distances should be shorter and the letters larger than the average values would indicate.

In reporting a study of very high luminance in the range of 100 ft-L to 2,000 ft-L by Allen et al. (1), the very important comment is quoted that such high brightness levels in a dark rural surround may impair the driver's vision for low-luminance objects beyond the sign. This comment of the researchers should not be overlooked. Time for recovery from exposure to such high luminances may range from a fraction of a second to several seconds or more, depending on exposure. Needless to say, even 1 or 2 sec of blind driving may be serious at 50 to 70 mph.

A more recent study adds to Richard's report that 40 to 60 percent contrast is required for discrimination of letters and that much higher contrast is needed by older subjects. A study of low-contrast vision under simulated night driving conditions found that a few subjects in each 10-year age group had difficulty in discrimination of test letters (34). Further work (not yet published) seems to indicate that a reaction to glare may be involved.

Familiarity of place-names may give some rather interesting but misleading research results at times if not carefully controlled. For instance, familiar names of certain length or combinations of short and long words may appear to be recognized much farther than the actual legibility distance. But if other test words of the same pattern and length are presented, this excessive legibility distance will shrink dramatically. In other words, subjects think that they recognize a word, but they really recognize the wrong word. Control of the familiarity factor was achieved in one study participated in by the discussor. We used several sets of place-names having similar lengths and patterns, e.g., San Francisco and San Bernardino, and others that were short single words. Familiarity of test words still increased legibility distances slightly.

Studies of target value of signs are well summarized, and the importance of background characteristics noted.

A comment might be made on angles of effective clear vision assumed by different authors, which range from 5 to 10 or 12 deg. The basic consideration here is a 5-deg central cone of clear vision that is fairly well determined in psychological and visual studies. Earlier studies assumed a central 5 deg (plus 5 deg to each side) as the minimum field of view, and others have adopted other combinations. Ordinarily the eyes do not remain still; therefore, a minimum of a central 5 deg plus 5 deg to each side seems reasonable. Head movements, of course, will add to this angular field of vision.

The field measurements of actual sign luminance by Youngblood and Woltman furnished information that has been badly needed.

The information system is of great importance in transmitting information to the driver, and the inclusion of the study by King and Lunenfeld is helpful. Perhaps, however, their statement that the system must be compatible with the "worst-case driver" for practical purposes needs to be interpreted as the "90th percentile driver."

From the system analysis study of signs by Woods et al. (32), factors of special importance are information needs of the driver and expectancy, i.e., his idea of the type of sign for which he is searching. This systems analysis helps to interpret findings made several years ago by Schoppert, Hulbert, and others on California freeways, where many drivers did not recognize destination names and more than 15 percent were actually lost. One solution, the numbering of freeway interchanges, was initiated on the New Jersey turnpike some years ago and has been used on other toll roads; it now is being adopted on many freeways.

Another important finding is the objection by drivers that signs are often placed too close to interchanges or intersections. This is often justified and emphasizes the need for sign design allowing sufficient perception, judgment, and response time for the maneuver required. Reports of methods of determining sign letter size are quoted by the reviewer.

Reports of driver uncertainty from delineators and obstruction markers call for application of the basic principles of perception of lighted markers and beacons. A single marker or small group of markers may be ambiguous, but a line of markers with unique characteristics will be perceived as a line. However, as noted by Connally at a previous meeting, if delineators or other lighted markers are surrounded by a variety of other lights, this "visual noise" interferes with correct perception, thus causing errors.

Berger's recommendation of diagrammatic signs is in line with recommendations of others. A recent conference was held by the International Road Federation on this subject. The principle of symbol signs is most effective if the symbols are self-explanatory and can be kept simple and easily interpreted by the driver. A method of comparing effectiveness of different symbols for drivers from countries with a given cultural background was reported in a study of symbols for lane control signals.

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Richard A. Olsen

It is difficult to "reply" to Woltman's paper, which is an excellent review and condensation of literature spanning almost half a century and from several countries. Rather, it is more appropriate to give emphasis to some of the points brought out in the paper and to discuss some of the implications for future work. This should begin to order our priorities and increase the emphasis on applications of existing knowledge by operational personnel.

It was gratifying to see that several speakers at this workshop have made the point that roadways designed to Interstate specifications, safe and efficient as they are, will never replace the great majority of 2-lane, 2-way roadways throughout the nation. A great deal of information on visibility and driver behavior in relation to signs and markings has yet to be established firmly enough such that it can be applied to the poorer quality roads on which the great majority of the fatalities occur. It would be highly questionable to assume that future study can be confined to new roads.

Another important assumption is that it is not accidents that need study but driver behavior. It remains difficult to point to "causes" of accidents, but evidence is beginning to grow on factors that contribute to erratic maneuvers, critical incidents, near misses, and other intermediate criteria of system operation, many if not most of which are influenced by visual information needs.

It is obvious that visibility factors are more important in night driving than in day driving, and, in a few cases, there seem to be contradictory requirements for day and night. For example, irradiation with bright reflective signing using white letters on a dark background calls for a smaller stroke width in the lettering at night as compared to the optimum for daylight use. This apparent incompatibility may not be real because it should be possible to develop an opaque white material that appears white in the daytime but that does not allow retro-reflection at night. Under headlight illumination, the opaque white portion would appear black because no light gets to the beaded surface, whereas the normal translucent white portion of the lettering would continue to reflect the same legend but with a narrower effective stroke width.

It was pointed out in the discussion of sign contrast that the contrast provided by urban, urban freeway, 2-lane rural, and Interstate roadways can vary over a broad range. In some research on vision, a slightly different set of terms is used from that described by Woltman. In addition to the lettering or legend, there is the background on which the legend is placed. Immediately outside of this is the surround, and beyond this is the general environment. Because environments are very diverse, the provision of an artificial surround, such as flat black expanded metal screening, could provide a break in a cluttered environment by isolating the sign and thus providing a better target or priority value. Such surrounds have been used in the past, but they reduce standardization and may increase the cost as well as the mounting requirements because of additional wind resistance.

Another point that has been raised in previous discussions is the desirability of very high speeds. It is my opinion that speeds beyond 70 to 80 mph are not cost-effective with manual driving control. In the few places where it is feasible to drive at very high speeds, information requirements are inherently low. Even at ordinary freeway speeds, the time available to read a sign of reasonable size allows use of only a few short familiar words, depending on the "mental set" of the driver. There is much to be discovered about the "chunking" of information, messages fed in segments to the driver to establish his expectancies or mental set and to provide information gradually over a period of time. Problems arise as to how big a chunk, how much redundancy, and how many segments there should be in such messages. Where unusual situations or even unusual place-names appear, the driver must be reassured that what he perceived on the first sign is actually the case by confirmation with additional signs.

A general conclusion of Woltman's paper is that overhead signing is probably best. It, too, is speed-limited, and such things as the tinted strip in windshields may further reduce the reading time available. Where it is possible to design a roadway for cars only, overhead signs can be lowered to reduce the vertical angle and increase exposure time as well as improve the illumination from headlights.

The topic of sign brightness brings up the problem of locating a spot in space. On a meandering road, a sign that is visible from a distance can "wander" in space because of the lack of cues to its actual position. Post-mounted reflectors, especially when each is a single small bright point, provide no size cues, and even a pattern of such points can make the apparent course of the roadway ambiguous. A pattern of two such spots separated vertically by a standard distance (probably 12 to 18 in.) on the same post would provide the information needed to estimate distance realistically.

As Woltman pointed out, signs will probably remain the most practical communication technique for some time. Although the complicated calculations of reflective luminance now can be handled by computer techniques, communication by signing is hampered most by lack of clear-cut descriptions of the users: the lack of specification of the worst-case driver or design driver. Several committees of the Highway Research Board are beginning to study the design-driver concept, though a set of design drivers for specific situations will probably be necessary. Because classified driver licenses are now being advocated, a corresponding set of design-driver specifications for each category seems feasible.

Pennsylvania State University has recently completed two studies (35, 36) that were not available in the literature covered by Woltman. As part of the latter study, a film was made that outlined the problem, the analysis in which erratic driver behavior was examined and driver interviews were used, and some techniques for solution.

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VEHICULAR LIGHTING SYSTEMS FOR TWO-LANE RURAL HIGHWAYS

G. E. Meese

In this attempt to express the state of the art, we will direct our attention primarily to headlighting and a condensed history of domestic progress to 1970 (Fig. 1).

Through World War I the development of the motor vehicle industry was much the same in Europe and Great Britain as it was in North America. However, since 1917, distinct differences in the political, social, economic, and geographic environments have led to very rapid expansion of the industry in the United States and Canada, while growth has been seriously retarded overseas (1, 2). Therefore, until very recently, the automobile has existed in a grossly different environment in the United States and Canada as compared with the rest of the world. Domestically, we have been experiencing serious vehicular traffic congestion in both urban and rural areas since the middle 1920s, whereas in Europe most citizens, until recently, have used other forms of transportation such as bicycles. This has resulted in a distinct difference in philosophy in the design of headlighting systems. Broadly, it might be stated that, because of the low vehicle population and the great preponderance of cycle and pedestrian traffic in Europe, great emphasis was placed on very low levels of headlight glare. Priority was given to the development of fixed overhead lighting, and in urban areas vehicles were prohibited by law from using headlights. Conversely, on the open highway at night, there was little or no traffic and, consequently, little restriction on the luminous intensity of the high beam. The result was a 2-beam system: a low-glare, low-visibility, low beam; and a high-candlepower, long-range high beam that could legally develop up to 300,000 candelas.

In the United States, because most street and highway traffic has consisted of automobiles, a greater tolerance developed for the brightness of headlights, and designers could therefore place more emphasis on providing better illumination for when cars meet. Good street lighting was not as extensive as in European cities, and, with our greater traffic density, vehicles drove in the cities with low beams lighted. Also, because nighttime suburban and rural traffic was relatively heavy, particularly on weekends near urban centers, there was a great need for good low beams. Conversely, this same traffic density caused a continuing public clamor against high output, clear-road beams, which would annoy oncoming drivers at great separation distances. As a result, when the original sealed-beam headlighting system became nationally standardized in 1939, the Uniform Vehicle Code (National Committee on Uniform Traffic Laws and Ordinances) established a limit of 75,000 candelas for the total high beam, and this has been enforced by the states ever since.

It is interesting to note that since the mid-1950s Europeans have experienced very rapid growth in motor vehicle sales and use, and increasingly they have been encountering many of the same types of lighting problems that were faced in this country years ago. They have recognized the need for better illumination when cars meet and have made some improvements in the design of their lower beams. Also, with the advent of the tungsten-halogen regenerative-cycle lamp bulbs, more cars are achieving total high-beam intensities approaching 200,000 candelas. This has caused growing concern about public annoyance created by these more powerful sources.

Figure 1. Automotive headlight history.

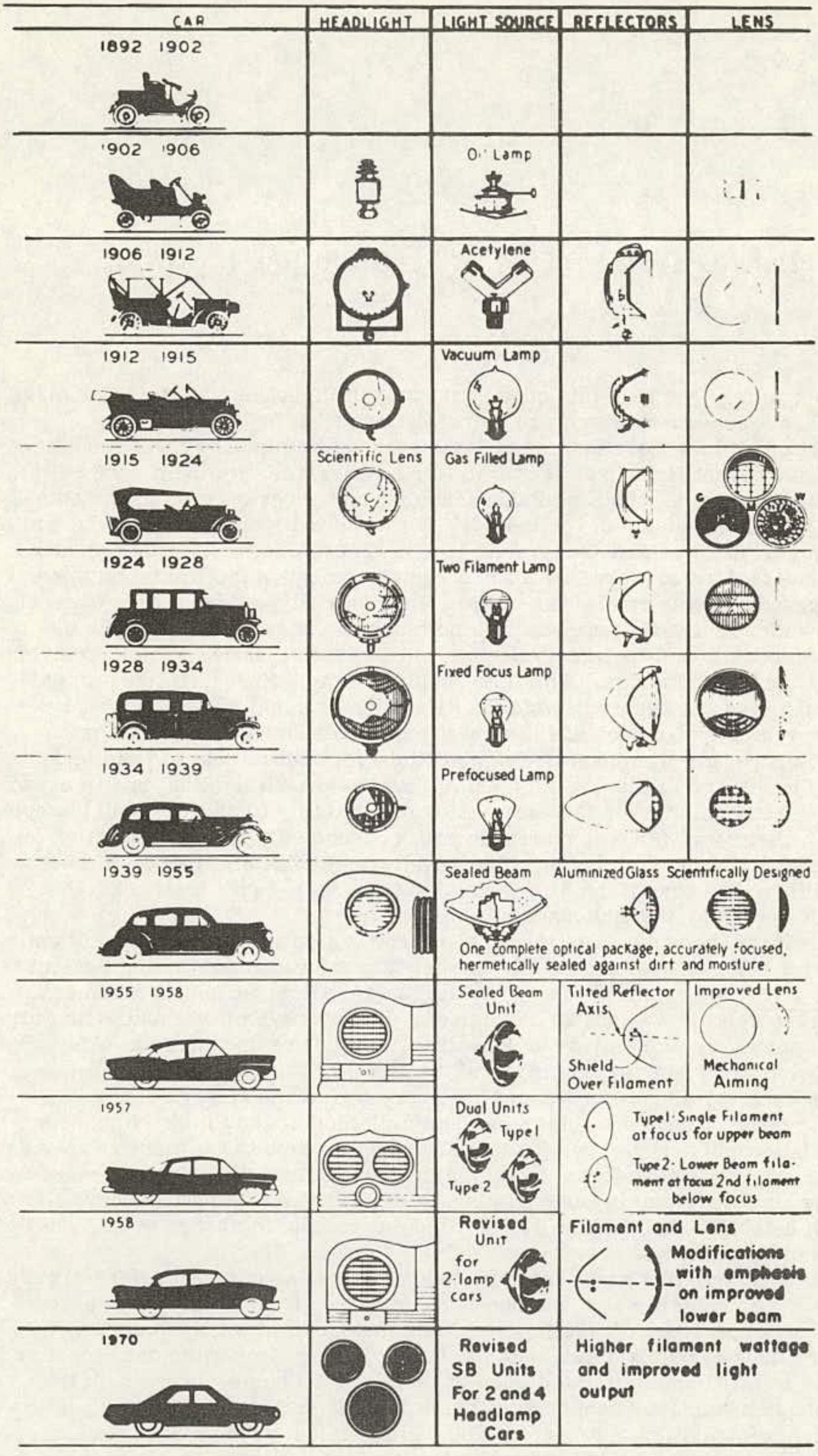


Figure 2 shows the lighting problem during the encounter of 2 vehicles on a straight, level, 2-lane highway (3, 4, 5). To obtain acceptable seeing distances in one's lane of travel, one must develop relatively high intensity just below the horizontal and just to the right of the oncoming driver. This would seem to suggest that the low-beam pattern has almost "knife-edge" cutoffs at the top of the beam to keep the eyes of the oncoming driver relative in darkness. Such a beam would, of course, be less than ideal for a clear road, where the highest intensity should be directed down the center of the road for distant seeing but with enough light in lateral and vertical spread to accommodate curves and hills.

In the United States, the light patterns for the upper and lower beams have been achieved with a parabolic reflector having 2 filaments in close relation to the focal point (Fig. 3). By its orientation, the upper filament can supply downwardly directed light for a low beam and the other light for a high beam. A frontal lens, having a complexity of elements for spreading and bending particular groups of light rays from the reflector, distributes the light to serve the needs of both beams. By using the full reflector for both beams, the greatest amount of light is gathered for each beam but at the sacrifice of a very sharp cutoff at the top of the low beam.

If sharpness of cutoff is the prime criterion, there are many possible optical approaches that can be used to achieve it. Foremost has been the Graves "anti-dazzle" system as used by European manufacturers (Fig. 4). It presents a reasonable compromise among adaptability to repetitive manufacturing techniques, system efficacy, and cost. This last item is very important in terms of overall public benefit. Gated elliptical systems as well as other more complex systems, usually involving objective lenses, can do a fine job of focusing a sharp cutoff pattern down the highway. As shown in Figure 5, these systems involve several optical elements that contribute to greater variances in manufacture, and costs become very high in terms of value received. These systems are generally in the 10 to 30 percent range of useful light output.

In the Graves "anti-dazzle" approach, the parabola of revolution would pick up from 55 to 65 percent of filament lumens, but to achieve the sharp cutoff for the low beam almost the entire lower half of the reflector is purposely blocked by the filament shield. This reduces the efficacy to the order of 35 percent or less. With our domestic sealed-beam designs, the reflectors pick up from 50 to 62 percent of the generated lumens, and almost all of this is directed into the beam. Because of simplicity, manufacturing cost is lower, and uniformity among lamps is considerably greater.

One of the most sophisticated attempts to solve the problem of providing abundant light ahead without bothering the oncoming driver is that advanced by Evan P. Bone in the late 1930s. This consists of a gated elliptical system somewhat like the one shown in Figure 5. In this case, the gate is replaced with a movable mask that can move laterally and be brought across the gate area. This causes a shadow to move across the beam from the left and, in fact, can block the entire beam if desired. A separate objective lens system and "photosensor" determine the presence of the headlights of an oncoming car and cause the mask to move in from the left just to the point where the oncoming car is in shadow. The remainder of the highly intense beam continues to light the highway ahead. As the oncoming car approaches the point of meeting, the mask slowly recedes to the left but always keeps that car in the shadow. Once past, the mask is dormant and the full beam shines ahead.

Advances in sensors and electronics have improved, and the "Auto Sensa" has become the most recent example of this approach with prototypes manufactured in Great Britain. As with most sensor-operated devices, they react to predetermined stimuli but are unable to "anticipate" or accommodate all of the myriad situations found in the normal highway environment. As a result, cost benefits are difficult to reconcile.

In any system where an attempt is made to develop both the symmetrical upper beam and the nonsymmetrical lower beam from the same optical system, compromises must be accepted in lighting performance (6). It is for this reason that the 4-headlight system was introduced in the United States in 1957. Two sealed-beam units were designed and used expressly for the lower beam, and the other 2 were designed for the upper beam. A second off-focus filament in each low-beam lamp is operated along

Figure 2. Vehicle encounter lighting problem.

Figure 3. Parabolic reflector.

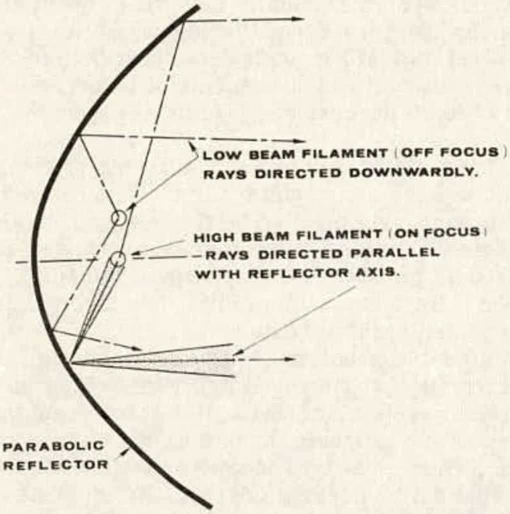


Figure 4. Graves "anti-dazzle" system.

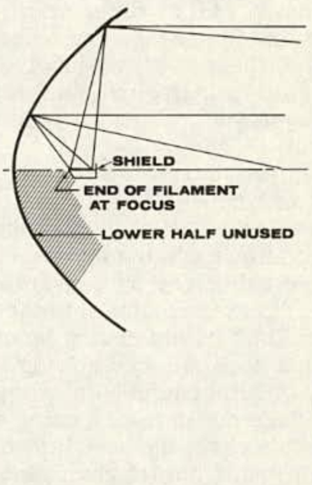


Figure 5. Gated elliptical system.

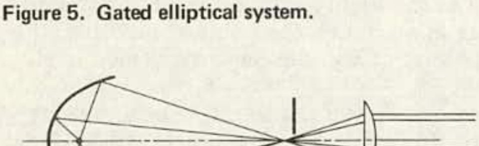
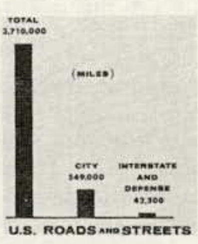


Figure 6. U.S. highway and street mileage.



with the upper-beam lamps to supplement the overall light output. This separation of function is also used to some extent in Europe, not only with an array of 4 separate headlight units but also with 2 separate lamp bulbs and reflecting systems contained behind 1 lens plate at each side of the car in nonsealed assemblies.

Roads are not straight and level, and vehicles are not stable mounting platforms for precision light projection devices. The best laboratory designs for headlights face serious problems in the practical world (7). Normal undulations of the vehicle due to uneven road surfaces cause beams to rise and fall. Lamps having a sharp cutoff will present to oncoming drivers very abrupt changes in brightness that tend to be annoying (8, 9, 10). On the other hand, lamps having a soft cutoff present changes that are less sharp. Similarly in seeing ahead, on undulation, the sharp cutoff will approach and recede rapidly on the roadway surface ahead of the vehicle. This is not as obvious or annoying with the soft cutoff.

Other investigators have noted that, during dynamic vision tests, the soft cutoff seems to aid in revealing obstacles at greater distances ahead (7, 8, 9). With the sharp cutoff, as the vehicle proceeds, obstacles are not revealed until they suddenly appear in the beam as they change from an unlighted, below-threshold state to a lighted state. On the other hand, with a softer gradient at the top of the beam, the eye seems able to apprehend the obstacle at a lower level of contrast and hence at a greater distance.

Headlight aim on the vehicle constitutes the greatest single source of variance in performance (11). Even with perfect aim, however, we are confronted with a change in attitude from the unloaded to the fully loaded state of more than a degree on certain standard-sized American cars. It becomes impossible to aim the lamps with a single setting that will accommodate such a broad range, but fortunately the extreme is rarely reached.

In U. S. practice the lamps are designed for 0.4 deg lower than ideal aim when the vehicle is unloaded. The assumption is that, with average loading, beams will approach the nominally best attitude for highway driving. For prolonged use with very heavy loads, it is assumed that the driver will re-aim the lamps. In Europe there appears to be no official recognition of loading allowance in standards and regulations.

Changes in load present more of a problem with a sharp cutoff low beam than with a soft cutoff. Also, smaller cars with short wheelbases generally present greater deflections from no-load to full load. As a result, there has been considerable interest in Europe in the development of schemes for manually adjusting the aim of headlights from within the vehicle and also automatic devices intended to maintain the aim of the headlights with respect to the highway, regardless of vehicle loading. Many designs and patents have emerged, but these must be precision mechanisms. When one considers that they must be supported in the front-end sheet metal of the vehicle body and work successfully for the life of the vehicle, one must question their practicality. In this location the mechanisms are most vulnerable to body damage, mud, salt, water, and icing conditions. At least one of these devices is now being installed in a European car, and it will be interesting to evaluate its performance in service.

There are also total vehicle leveling systems that are related to the vehicle suspension system. In these, ride, performance, handling, and other objectives are sought, and headlight leveling becomes an ancillary benefit. Because they become an inherent part of the basic vehicle, reasonably good maintenance in service should be expected. However, the attendant cost necessitates careful evaluation in terms of real public benefit.

In considering a headlighting system, one must also take into account the highway system within which it must perform. Although great strides have been made worldwide in highway construction and most notably with the Interstate system in the United States (1), the driving situation, as it affects headlighting, has not changed greatly since the 1930s. Some may take exception to this statement and cite the limited-access highway where average speeds are high and drivers are assumed to be overdriving their headlights. However, surveys show a 7-mph higher average speed on such highways, and I submit that drivers are far safer and there is relatively less need for headlight improvement here than on the ordinary bidirectional highways of the country. Please note that I did not say that better headlighting is not needed, but simply that, for the same reason that drivers are safer in daytime, there is less opportunity for unexpected trouble to appear at night on limited-access highways.

Of the total of 3,710,000 miles of streets and highways in 1969, 549,000 miles were in municipalities and only 29,638 miles were Interstate highways (Fig. 6). Also in 1969, the miles driven on rural roads just about equaled urban mileage—526 billion to 544 billion. Of this total of 1,070 billion, less than 200 million miles were driven on Interstate roads. Obviously the hazards are far more numerous and the need for better headlighting much greater on these millions of miles of streets and highways carrying bidirectional traffic, particularly because so few of these miles have even mediocre fixed highway lighting.

The need exists and the technical problems persist. The clear road is of little concern to the optical designer other than the allowance by the vehicle designer of enough electrical power and enough "real estate" on the front end to mount lamps of adequate size. But with regard to the meeting situation, we are still trying to find better ways of lighting the lane ahead without blinding oncoming or immediately preceding drivers.

During the 1960s, because of the feeling that motorists were overdriving their low beams on Interstate highways, improvement was attempted by experimentally interjecting a third beam between the low and high. Purpose was not well defined, but it fell into 2 general categories. First, it was thought that a beam similar to the high beam was needed but with a sharp cutoff latterly to restrict high candlepower from crossing the median toward oncoming traffic. One new lamp would supplement the low beam but provide sufficient illumination for 70-mph driving. Second, some researchers felt that light from this type of lamp would be too annoying, entering the rear windows and mirrors of preceding cars. This group suggested instead that this lamp (to supplement the low beam) should be little greater in glare than an existing low-beam lamp but have as high output as possible at and just below horizontal. Such a design was felt to be more useful in that it could even be used to improve seeing in most meetings on normal bidirectional roads.

Both of these "schools of thought" were advanced as modifications to the 4-headlight system. The inboard lamp on the driver's side would provide the intermediate beam. This leaves only the inboard lamp on the curb side to generate the very intense portion of the high beam for clear-road vision far ahead. Although this beam can be used only a minimal amount of driving time, high performance is needed because it is the sole source of light when the car is alone on the open highway.

Variations of these approaches are currently under consideration. The 3-beam concept seems to have appeal, but there is a very real human-factors question concerning the ability of the average (and less than average) motorist to understand and properly use each beam. There are also attempts to improve the 2-beam system, and headlight and car manufacturers are working on this problem. Whether these approaches can be evaluated properly, and whether improvement can be sufficient to justify a new standard, remains to be seen.

Unfortunately, the subject is politically extremely volatile. Many seeing-distances studies show that greater amounts of light projected ahead with the accompaniment of rather large increases in glare will net greater seeing distances in certain meeting situations. What these studies have not measured is the subjective reaction to the increased glare. Although it appears that the public will accept some modest glare increase to permit better seeing performance, there is little definitive information available (12). Hemion at the Southwest Research Institute made a good survey, but much confirming data are needed from highway tests before any major changes in glare limits are made. Should regulatory bodies move in this direction and exceed the nebulous public tolerance level, serious repercussions could result and we could find ourselves in a situation similar to the chaotic 1920s and 1930s with "glare wars" between motorists. Having been a driver during this period, I can readily understand how the emotions of affected drivers can quickly be felt in state and federal legislatures, not to mention the "press," and real public benefit would be doubtful.

I believe that the greatest need in the face of urban growth and increased vehicle density is improved visibility of oncoming vehicles. It is obvious that, because of economics, the majority of rural and urban travel will continue to be made on bidirectional, essentially 2-lane roadways. Although refined optical systems, beam modes, and leveling devices may offer some small improvement, only polarized headlighting offers the advantage of the use of a clear-road high-intensity beam that does not bother drivers as they approach each other in a meeting situation. The advantages and disadvantages of polarized headlighting were first studied in depth between 1939 and 1948 (13, 14). Jehu of the British Road Research Laboratory examined problems of introduction in 1963, and since 1968 considerable work has been done in Sweden by Erickson of the Institute of Optical Research and Johansson and Rumar of the University of Uppsala, which has evoked much interest in Europe. Also during the last 4 years, Hemion of the Southwest Research Institute has conducted a thorough investigation of the subject on behalf of the Federal Highway Administration and under the guidance of R. N. Schwab (15). Problems of available power, wiring, and switching are less critical now than 20 years ago although some deterrents remain. Undoubtedly the biggest is the fact that the polarized headlight system will work well only if all cars are properly equipped. This implies an extended transition period during which cars become equipped, either through normal attrition or with the use of conversion kits or both.

Before we move into such a program, with its great economic impact, more knowledge of anticipated public acceptance and use is needed. The large-scale testing programs that have been proposed will require federal sponsorship. This is currently under consideration by the National Highway Traffic Safety Administration. The system holds promise for more comfortable, safer nighttime travel, but we need more research on the tolerance level of drivers to headlight glare.

This subject is far more complex than the basic points that have been presented. Adverse weather, accumulation of dirt, and depreciation from any number of causes must be recognized. Merrill Allen of the University of Indiana has attempted to quantify the effect of pitting and scratching of glass windshields and lamp lenses. Many researchers have been working on the development of headlight cleaning devices, and standards have been written for implementation in Sweden and perhaps for Europe. These and many more are items worthy of serious consideration, but we still face the fundamental task of finding a way to adequately illuminate the road ahead without annoying other highway users.

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DISCUSSION

Philip Maurer

As Meese has well indicated, automotive lighting is a complex subject that goes far beyond the simple task of designing a set of lamps that project an arbitrary selected beam pattern ahead of the car. In addition to the strictly physical design factors involved, there are other parameters that have to be considered, such as the design of the rest of the automobile, highway design, physiological and psychological considerations grouped under the broad title of human factors, and cost-benefit ratio.

I agree with Meese's analysis of how the American and European beams developed differently. Each, when seen in its own locale, seems to be fairly well suited to the driving task but when mixed show a decided contrast. European lighting experts admit that the U.S. system seems to be very satisfactory here but appears very glaring when observed in Europe among a great majority of cars equipped with European beams. It is interesting to note that, as European rural expressway night traffic increases, Europeans are beginning to have doubts about the 300,000-candela maximum for high beams. At the same time, we in the United States are thinking about increasing our 75,000-candela maximum. Perhaps we will meet somewhere in between.

It is also noteworthy that Sweden, after extensive testing, is beginning to favor the U.S. low beam; however, because of the high tourist car interchange with the rest of the continent, Sweden feels that it cannot make such a change alone.

Aim

I would like to point out that the importance of good headlight aim cannot be stressed enough. A great deal of emphasis has been put on this subject by some states and by the automotive companies. The inspection and regulation of headlight aim is accomplished by state-owned or state-licensed inspection stations in those states that have an inspection program. Automotive manufacturers are exploring various ways to further ensure proper aim on all cars. Mandatory state inspection should ensure maintenance of such aim in service as well as rule off the road some of the "baling wire wonders" that are still seen on the roads of states that do not have mandatory inspection.

Load Levelers

The need for a load adjustment device for headlights is being discussed in European lighting circles, and we may see a legal requirement there in the future. Such a need is not as great in the United States because our low beams are less annoying when raised slightly, our larger, longer wheelbase cars do not change level as much either statically or dynamically as do European cars, and our load factor is much lower. Because of these factors, neither headlights nor full-car load levelers seem to have a good cost-benefit ratio for general use, although one U.S. luxury car already has a full-car automatic load leveler as standard equipment.

The simplest method of headlight leveling control that is being considered is a manually operated device, e.g., a lever that would tilt the headlights and have positions for "1 to 3 passengers," "4 to 6 passengers," and "heavy load." Knowing something of the psychology of the average motorist, I fear most controls would be set according to the driver's opinion of his best seeing condition and then would be left there through all kinds of loading.

Three-Beam System

I agree with Meese that, although we may sometimes overdrive our headlights on limited-access superhighways, the risk is minimal because the road is generally clear of unexpected obstacles. A few years ago we had much discussion about a so-called "turnpike beam," and I was one of the first to point out that what we really need, as dictated by accident records, is an intermediate beam usable on 2-lane country roads. As Meese mentioned, considerable work is being done in this area by both industry and government, and our next step in headlighting improvement may well be in that direction.

Control of such a 3-beam system is of paramount importance. The present foot switch no longer meets the requirements of ease of control, understandability, and ease of reaching any beam quickly. It appears that a hand-operated control of some sort would be a better answer.

I think that Meese is overly concerned about glare acceptance because a properly designed intermediate beam may have only slightly more glare than our present lower beams and because there is always the option of signaling an offending driver to switch to his lower beam. I would agree that considerable cooperative testing between the National Highway Traffic Safety Administration (NHTSA) and the automotive and lighting industries should be conducted before an "across-the-board" change is made.

Polarized Headlighting

I differ with Meese somewhat on his assessment of polarized headlighting. In my opinion, although it has some good theoretical advantages, there are still many unanswered questions that make its future use at least questionable. I took part in both the 1946-47 Automobile Manufacturers Association's (AMA's) evaluation and the 1971 evaluation at Southwest Research Institute, and my conclusion is that there has been very little progress in the interim. In fact, in several areas we are worse off today than we were in 1947; e.g., windshields are curved and raked backward more, and rear windows are made of tempered glass with its stress concentrations. Both of these conditions cause depolarization with accompanying glare.

Because of the high optical losses in polarized lighting, it probably becomes impractical to equal or exceed current high-beam output in seeing light returned to the driver, so open road improvement may not be achieved with the system used in these 2 tests unless some further breakthrough is achieved. Furthermore, it appears that the best polarizing material available in large enough quantities for high production use deteriorates rapidly at the elevated temperatures to be expected in high-output lamps.

One European manufacturer is reported to have achieved considerably higher efficiency in a new system based on the application of Brewster's law. Either plane or circular polarized light can be produced. Such work needs to be carefully evaluated.

Besides the system experimented with in this country, which polarizes only the upper beam, there have been proposals for polarizing only the lower beam, for polarizing both the upper and lower beams, and for polarizing only a meeting beam of a 3-beam system.

A few of the problem areas that have not been resolved are as follows:

1. Street lighting effectiveness is reduced;
2. Glare to pedestrians and cyclists is excessive;
3. Glare through side windows must be controlled at intersections where cars are approaching on side roads;
4. Polarized headlights do not cause any atmospheric glow when approaching the top of a hill, thus giving no advance warning;
5. The problem of introduction of polarized lighting and intermix with present lighting is very complicated and must be given a great deal of further study; and
6. The added current consumption will necessitate larger generators on some cars, which becomes a cost and space problem.

I have not enumerated all the problems, but my point is that polarized lighting is not ready for large-scale testing. First, we must better determine an optimum system, and, if possible, this should be done in cooperation with European standard-making organizations, or we will again find ourselves with mismatched headlight systems of even less compatibility than today's.

When we look at these difficulties, we can see that it probably will be several years before polarized headlighting could be considered for use. In the meantime, we should endeavor to improve our present system such as by converting to a 3-beam system.

Headlight Cleaning Devices

Headlight cleaning device standards are being seriously worked on in Europe, and it appears that the use of headlight cleaners will be mandatory overseas. Such devices have been offered for sale in this country as an extra-cost option but without much success. I am sure that both NHTSA and the industry will be watching this development in Europe closely because a good reliable headlight cleaner could certainly help visibility under the most adverse conditions.

AUTHOR'S CLOSURE

I would like to thank Maurer for his discussion of my paper, which admittedly constitutes only a brief overview of a very complex and difficult lighting problem area. The questions with respect to the practicability of polarized headlighting require some further clarification.

It is a fact that the excessive sloping and contouring of windshield glass tends to cause depolarization, which can be accommodated to some extent by proper orientation of the basic plane of polarization.

It is not an impractical matter to overcome the light losses inherent in polarization. As indicated in the body of the report, clear-road lighting systems are in existence today that develop up to 300,000 candelas. Reducing the intensity of such systems by polarization would still net usable illumination that is considerably in excess of that allowed by current domestic regulations. The point that is missed in this criticism is that, when cars having polarized systems meet, visibility distance remains close to that of clear-road conditions. In addition, our experience with polarizing materials has shown that they are readily capable of withstanding the temperatures of "high-output" lamps. Work is continuing on bonding materials, which also indicates compatibility.

System design details concerning number of beams and which sources to polarize can be readily solved through national or, preferably, international convention and standardization.

I know of no serious proposal that includes the use of a fixed polarizing screen that would remain in the line of view during daytime driving or driving under lighted city streets and highways. Therefore, I foresee no reduction in street lighting effectiveness.

Pedestrians and cyclists are subject to severe glare from present high beams. Under polarization, the wearing of simple polarized half-spectacles could increase comfort.

Glare through side windows can be annoying at intersections, particularly if one is attempting to make a left turn across the beam of a car intersecting from the left. If the driver is wearing spectacles, however, this presents no problem. Attention to design of the visor or polarizing screen fixed to the car could alleviate this momentary condition.

The statement concerning atmospheric glow is invalid when one considers that it is not present in daytime driving nor is it present under clear atmospheric conditions at night. Regardless of the lighting system used, motorists should stay on their own side of the road and be cautious of blind curves and hills.

From the appraisals of the past 35 years, I see no serious problems with regard to the introduction of polarized lighting and its intermix with current lighting systems. However, this is merely an opinion, and the consideration of introduction and intermix is a necessary part of any program.

Added current consumption and larger generators have not seemed to present any problem when the object has been that of supplying air-conditioners, window lifts, and other useful accessories; therefore, these objections hardly seem insurmountable.

I agree with Maurer that further investigation of this subject should be done on an international basis because the benefits can be best realized under international standardization of the fundamental elements of the system. With respect to the complaint that there has been little progress since the 1946-47 AMA evaluation, I find it unfortunate that no contributions have been forthcoming from the vehicle manufacturers. I can see no other remotely practicable means for accomplishing a significant improvement in visibility. The other avenues for improvement using ordinary light can yield only minimal increments in an area where major gains are needed.

STATE OF THE ART IN WARRANTS FOR FIXED ROADWAY LIGHTING

Neilon J. Rowan

The basic motivation for using artificial lighting at night has remained unchanged over the years. Application of artificial lighting to streets and highways has also resulted from the same basic motivation, but emphasis on the application or objectives has changed. In order of chronological development, the objectives of street and highway lighting are as follows: crime reduction, civic improvement, and traffic safety.

The history of street lighting dates back to the fifteenth century, when citizens of London and Paris began to carry lanterns at night. The provision of street lighting by the government was begun in Paris in 1866, when lanterns were hung on ropes stretched across the streets. This practice also became popular in England and throughout Europe. Changes in lamp innovations for street and roadway lighting took place over the years. Today, a number of light sources with efficiencies of 25 to 175 lumens per watt are being used successfully in street lighting applications.

All of the earlier artificial lights for street lighting were normally mounted at heights of 10 to 20 ft. The power of the electric arc lamp gave rise to a number of early installations involving extremely high poles or towers. In 1881 the city of Cleveland installed 4 steel masts, 250 ft in height. Because it had been decided by 1883 that higher mounting heights produced inefficient light, the one tower that remained was reduced to a height of 100 ft. Many other cities installed towers as high as 90 to 165 ft although none are now in existence, except those in Austin, Texas.

Modern practice has seen mounting heights increase from 20 to 60 ft. Many states are now employing high-intensity lighting sources and, consequently, are returning to mounting heights of 60 to 200 ft for special lighting situations, such as complex interchanges.

WARRANTS FOR FIXED LIGHTING

The literature is abundant with information on the technology of fixed lighting, benefits of these installations, and visual environments; however, it is almost totally void of any research dealing with warranting conditions. The lack of adequate research on fixed lighting warrants is evidenced in the rather arbitrary nature of most published warrants. These warrants are based primarily on engineering experience and judgment and have little, if any, factual basis.

Existing warrants for the installation of fixed lighting do not reflect adequate consideration of the many factors that affect the driving task. The principal requirement of the driving task is an informational requirement: The driver must be able to see the roadway, environmental, and traffic elements that affect the driving task in sufficient time to respond safely and efficiently.

This paper will deal with a detailed evaluation of the currently available published information (1, 2, 3) on guidelines and warrants for fixed lighting.

AASHO WARRANTS

The most widely accepted set of warrants for roadway lighting is that published by the American Association of State Highway Officials (AASHO). The purpose of this review is to critically examine the following warrants suggested by AASHO (1) from the point of view of reasonably fulfilling the driver's needs.

Warrants for Continuous Freeway Lighting

> Case A-1: Continuous freeway lighting is considered to be warranted where for a length of 2 or more miles it passes through a substantially developed suburban or urban area in which one or more of the following conditions exist: (a) local traffic operated on a complete street grid having some form of street lighting, parts of which are visible from the freeway; (b) the freeway passes through a series of developments such as residential, commercial, industrial and civic areas, colleges, parks, terminals, etc., which include roads, streets, and parking areas, yards, etc., that are lighted; (c) separate cross streets, both with and without connecting ramps, occur with an average spacing of ½ mile or less, some of which are lighted as part of the local street system; and (d) the freeway cross section elements such as median and borders are substantially reduced below desirable sections used in relatively open country because of the high costs of right-of-way due to proximity of existing land developments.

The 4 conditions defined in Case A-1 are all situations that could justify the installation of fixed illumination. In condition a, the reasons for excluding street systems that are other than a complete grid system are not apparent; however, the other warranting conditions would include any design configuration. In condition b, reference is made to a series of developments that are lighted along the facility. This situation could occur along virtually any section of an urban freeway. The question is, rather, to what degree the roadside development contributes to the need for fixed external illumination. Three situations could exist in this regard, 2 of which would not justify the provision of external illumination:

1. The level of illumination, in combination with the geometric and terrain conditions, does not result in a situation in which the roadway appears darker than the general environment. Fixed illumination, therefore, would not be required as a result of the environmental lighting circumstances.
2. The level of illumination associated with the roadside development is sufficient to produce a situation in which the roadway appears much darker than the surrounding area. Under these conditions, lighting of the facility would most certainly result in greater confidence on the part of the driver while on the facility.
3. The spillover from the lighting associated with the roadside development is sufficient to outline the geometric features of the roadway for most of the roadway length; thus, the need for continuous lighting would not exist.

Condition c states that continuous lighting is warranted when spacing between interchanges or grade-separated roadways or both averages ½ mile or less, some of which are lighted as a part of the local street system. The number of interchanges lighted and/or the degree to which they are lighted have not been specified. It appears that an assumption has been made that interchanges and/or grade separations so closely spaced would result in a rather complex geometric design that, in turn, would warrant continuous illumination. The fact that some of the separation structures are lighted (including degree of luminosity) seems incidental to the warranting condition.

In the design of freeways in urban and suburban areas, it is generally accepted that openings at approximately ½-mile intervals are desirable when it is practical to provide such openings. Therefore, most sections of urban freeways could warrant installation of fixed lighting by virtue of the basic design alone, if one or more of the crossing roadways is lighted. Condition c is, therefore, not a warrant per se; rather, it permits the installation of continuous lighting on urban freeways when the decision-maker is of the opinion that it is justified and also as funds for installation become available.

Condition d alludes to a warrant based on a reduction in desirable design features due to the high cost of right-of-way in urban areas. The phrase "substantially reduced below desirable sections" is used in the definition statement. Without some additional qualifying statements, this condition is too vague to provide the decision-maker with a tool for including or excluding as he sees fit almost any section of urban freeway in the warranted sections of roadway. There is little doubt that virtually every mile of urban freeway is built to a lower standard than would be used in open country. The key word is "substantially," and, because each individual has a different connotation as to that which constitutes a substantial reduction regarding design standards, the decision to warrant fixed illumination under Case A-1, condition d, is based on personalities rather than on objective decision-making.

Case A-2: Continuous freeway lighting is considered to be warranted on those sections wherein three or more successive interchanges are located with an average spacing of 1½ miles or less, and adjacent areas outside the right-of-way are substantially urban in character.

Case A-2 is a repeat of Case A-1, condition c, without the requirement that one or more of the interchanges be lighted as a part of the local street system. This appears to be a recognition of the fact that closely spaced interchanges create a difficult and complex driving environment in which the driver should be kept informed of geometric conditions ahead. It is again worthwhile to note that current practice calls for openings at approximately ½-mile intervals; thus, many miles of urban freeway could warrant fixed illumination on the basis of the basic design criteria.

Case A-3: Continuous freeway lighting is considered to be warranted on those sections in and near cities where the current ADT is 30,000 or more.

The concept that the benefits derived from lighting a freeway are directly related to the volume of traffic using that facility has resulted in attempts to justify, on the basis of traffic volume alone, the installation of fixed illumination. It is apparent, however, that traffic volume alone cannot justify lighting. A section of freeway that has no merging or diverging areas, is essentially straight, and has well-defined lanes of adequate width would probably not need external illumination, whereas a complex series of interchanges could require external illumination for traffic volumes well below the cited value.

Other difficult situations for the driver can be alleviated by the use of external illumination. For example, on a multilane freeway section during wet conditions, the painted lane lines are lost, and the headlights do not illuminate the extremities of the roadway sufficiently to permit the driver to discern the lane lines. The driver is essentially lost in a mass of pavement with few, if any, clues to guide him. Although other treatments may be more effective in increasing the lane line visibility, the definition of the extremities of the roadway can be effectively accomplished using external illumination.

The use of a definite traffic volume as a warrant for fixed illumination must be considered questionable. The value of 30,000 ADT was reported to have been selected so that only a few sites would warrant fixed illumination. This was done because many highway administrators feared that public pressure would result in freeways being lighted on the basis of traffic volume alone. The philosophy is undoubtedly valid, and the other warranting conditions would cover the other cases. The difficulty in using a specific traffic volume as a warrant occurs when an individual responsible for review of roadway lighting simplifies the decision-making process by using the volume warrant as an absolute measure rather than as a guide. All other warranting conditions, therefore, become secondary to traffic volume.

Case A-4: Continuous freeway lighting is considered to be warranted on those sections where the ratio of night to day accident experience is high (say, higher than the statewide average for all unlighted similar sections) and a study of conditions indicates that lighting may be expected to result in a significant reduction in the night accident rate.

The use of the accident rate as a basic warrant for continuous illumination is, at best, somewhat questionable. The number of accidents associated with the through segments of the roadway (i.e., other than interchange areas) is usually relatively small.

This fact, coupled with the requirement that the lighting should significantly reduce the night accident rate, means that the overall rate would be very low. For example, if the statewide accident rate on unlighted sections of similar character is 3.0 accidents per million vehicle-miles, the rate on any one section could exceed this value by 50 percent and still be within the normal variation about the mean value. Thus, if the average ratio of night to day accidents is 1.5, and a rate that is 50 percent greater than the average is needed in order to be significant, then the actual rate on any given section of roadway could be twice the average rate without being significantly different in a statistical sense.

This discussion points out a rather obvious fact: If the accident rate at night is due to a lack of adequate illumination, which is likely coupled with poor geometric design, the need for external illumination is usually rather apparent. The use of accident rates to establish the need for safety lighting appears justifiable; however, for warranting continuous freeway illumination, a logical question can be raised regarding the validity of this concept.

> Case A-5: Continuous freeway lighting is considered to be warranted where the local governmental agency finds sufficient benefit in the forms of convenience, safety, policing, community promotion, public relations, etc., to pay an appreciable percentage of the cost of or wholly finance the installation, maintenance, and operation of the lighting facilities.

This general warrant is designed to accommodate those special local situations that, in the opinion of the local governmental agency, justify roadway lighting on the basis of indirect benefits to the population as a whole.

<u>Interchange Lighting for Unlighted Freeways</u>

> Case B-1: Complete interchange lighting on unlighted freeways is considered to be warranted at locations where existing substantial commercial, or industrial development which is lighted during hours of darkness is located in the immediate vicinity of the interchange or where the crossroad approach legs are lighted for ½ mile or more on each side of the interchange.

The warranting of complete interchange lighting by virtue of the commercial lighting on the intersecting facility is certainly justified. Very often this situation will result in the actual freeway interchange being the darkest spot in the area. This results in a great deal more uncertainty on the part of the driver and, conceivably, could increase the accident probability. The most serious objection to this warrant is its failure to specify the level of lighting on the cross facility and the resultant effect on the freeway traffic stream.

> Case B-2: Complete interchange lighting is considered to be warranted where the total current ADT ramp traffic entering and leaving the freeway within the interchange area exceeds 10,000 for urban conditions, 8,000 for suburban conditions, or 5,000 for rural conditions.

The values specified for interchanging traffic volume, which will warrant complete interchange lighting, are undoubtedly the result of a group judgment by those individuals responsible for establishing the basic warrants. Professional judgment and experience are apparently the basis for selecting the values, and these values probably represent a fair evaluation of the least amount of ramp traffic that alone could justify complete lighting. It would be desirable, however, to have a more objective basis for selecting these constraints, especially when the decision regarding federal participation is so heavily related to values that were selected in an arbitrary fashion.

> Case B-3: Complete interchange lighting is considered to be warranted where the current ADT on the crossroad exceeds 10,000 for urban conditions, 8,000 for suburban conditions, or 5,000 for rural conditions.

This warrant seems somewhat inappropriate. The warranting condition is for the crossroad and not the freeway itself. It is difficult to understand how the crossroad traffic volume, independent of the number of vehicles interchanging between 2 facilities, could justify complete interchange illumination. This is not to say that the need for partial interchange lighting might not be so extensive as to justify the installation of complete interchange illumination.

Case B-4: Partial interchange lighting is considered to be warranted where the total current ADT ramp traffic entering and leaving the freeway within the interchange area exceeds 5,000 for urban conditions, 3,000 for suburban conditions, or 1,000 for rural conditions.

The justification for partial interchange lighting on the basis of interchanging traffic volume seems appropriate. The only question that could be raised involves the values selected. Again, it would appear that geometric conditions, in addition to interchanging volume, should be included in the warrant. This is discussed in the "special considerations" section of the interchange lighting warrant.

Case B-5: Partial interchange lighting is considered to be warranted where the current ADT on the freeway through traffic lanes exceeds 25,000 for urban conditions, 20,000 for suburban conditions, or 10,000 for rural conditions.

The use of through-traffic volume alone as justification for partial interchange lighting is subject to the same criticism as that for continuous illumination (Case A-4). If all the traffic is going through, there is no need for lighting other than that required for the through lanes. Conversely, if the interchange is complex, the need for illumination may be substantial even for relatively low traffic volumes.

Case B-6: Complete or partial interchange lighting is considered to be warranted where the ratio of night to day accident experience is high (say, higher than the statewide average for all unlighted similar interchanges) and a study of conditions indicates that lighting may be expected to result in a significant reduction in the night accident rate.

The problem involved in evaluating the need for fixed illumination on the basis of accident experience has been discussed in some detail previously. A similar discussion of this warrant is of somewhat more limited value here. The only possible difference between the 2 treatments is the number of accidents associated with the interchange areas. These occurrences are usually considerably more frequent than for segments of a through roadway; thus, the relative error involved in establishing a significant deviation from the statewide average is greatly reduced.

Case B-7: Complete or partial interchange lighting is considered to be warranted where the local governmental agency finds sufficient benefit in the forms of convenience, safety, policing, community promotion, public relations, etc., to pay an appreciable percentage of the cost of or wholly finance the installation, maintenance, and operation of the lighting facilities.

The warranting of interchange lighting by indirect benefits is implied in this case. It is apparent that the importance of these indirect benefits was not considered to be of great importance by the individuals who prepared the warrants.

Special Considerations: Where there is continuous freeway lighting, there should be complete interchange lighting. When continuous freeway lighting is warranted, but not initially installed, partial interchange lighting is considered to be justified under the continuous freeway lighting warrants A-1 or A-2. This would preclude the requirements of satisfying the partial interchange lighting warrants B-4 or B-5.

Where complete interchange lighting is warranted, but not initially fully installed, a partial lighting system which exceeds the normal partial installation in number of lighting units is considered to be justified.

Lighting of crossroad ramp terminals should be considered, regardless of traffic volumes, where the design requires the use of raised channelizing or divisional islands.

These special considerations seem to be logical and consistent with the needs of the driver. The last one, in effect, is the statement that would permit the designer to provide lighting for special geometric conditions that require it. However, the warranting of partial interchange lighting for these special considerations would probably be somewhat more difficult than with one of the more definitive warrants.

Warrants for Arterial Street Lighting

> Warranting Conditions: It is not practical at this time to establish specific warrants for the installation of roadway lighting to satisfy all prevailing or anticipated conditions. In general, lighting is considered to be warranted for those locations where the respective governmental agencies concur that lighting will contribute substantially to the efficiency, safety, and comfort of vehicular and pedestrian traffic. Lighting should be provided for all major arterials in urbanized areas and for locations or sections of streets and highways where the ratio of night to day accident rates is high (say, higher than the statewide average for all similar locations) and a study indicates that lighting may be expected to significantly reduce the night accident rate. Where such determinations to install lighting have been made on the basis of experience and accident data under certain existing conditions, extrapolation should be made of these conclusions to other similar highway sections. The latter should include similar geometric layouts on which experience or accident data is not available and also highway sections where anticipated increase in vehicular and pedestrian traffic (either normal growth or sudden changes) will present problems within a few years. Lighting also should be considered at locations where abnormal or unusual weather conditions exist, such as the frequent occurrence of fog, ice, or snow. In other situations, lighting may be warranted where studies indicate that the resulting benefits, both tangible and intangible, are in the interest of the general public.

The general warrant statement can be divided into the 4 following areas of interest for purposes of analysis: population, major arterial streets, sections characterized by high accident rates, and weather conditions (fog, ice, and snow).

The first area is similar in content to the general warrant specified for freeways; it is stated that lighting is considered to be warranted if the respective governmental agencies agree that lighting is needed. Such a general statement cannot be applied on an objective basis because of the continual change in governmental representation.

The second area states that lighting is justified for all major arterial streets. This is somewhat more specific than the previous statement because a facility must be classified as a major arterial in order to meet the warrant. However, this has become a question of semantics. For example, a major arterial street near a central business district may have the characteristics of a local street once outside the central city. Thus, the classification referred to in the warranting condition is a functional, rather than an administrative, classification. This warrant could be a very valuable guide if judiciously applied. There can be little doubt that the lighting of major arterial streets serves to deter crime as well as improve driving conditions.

The third area deals with sections that have unusually high accident rates. The method of establishing the accident rate and the rate that, when exceeded, indicates a critical condition are not specified. The problem of evaluating accident exposure in urban areas is well known and documented in the literature. There still exists the possibility that a large number of accidents may be corrected by the addition of external illumination, and, if such trends are established, this should be considered as a warrant for lighting. The key is proper analysis of accident data, not comparison of accident rates. Both intersections and continuous illumination are included in this consideration.

The final area pertains to the frequency of adverse weather conditions (fog, rain, or snow and ice). Although some advantages are apparent from the standpoint of visibility, when external illumination is used during adverse weather conditions, the degree of improvement and the benefits associated with this improvement are questionable.

WARRANTS SUGGESTED BY KETVIRTIS

Ketvirtis (2) presents a set of conditions that warrants illumination for fixed sources, based on 3 classes of lighting circumstances:

1. Class I, Partial Illumination—Luminaires are located only at the critical decision points (beginning of acceleration and deceleration lanes, nose of channelization point, and so forth).
2. Class II, Intermediate Illumination—Luminaires are located as required by class I, with additional units on the ramps connecting to lighted roadways or at intersections with lighted highways.
3. Class III, Full Illumination—Full illumination refers to complete lighting of the facility, including all interchanges and at-grade intersections.

In addition to the 3 basic types of illumination, Ketvirtis utilizes a 4-level functional classification of the highway system. This classification includes the following: freeway and expressway, arterial, collector, and local.

In the following discussion of Ketvirtis' work (2), some of his warrants have been paraphrased.

Freeways and Expressways: Urban and Rural Main Lanes

> Lighting is warranted when the ADT exceeds 40,000 vehicles per day (class III).

The selection of a specific volume level as a warrant for lighting the main lanes must be considered questionable. As the traffic volume increases, the need for information about the main lanes is reduced because the major driving cues come from the vehicle immediately preceding the subject vehicle. It is conceivable that increasing volume could require a greater number of lanes and thus create a greater degree of driver disorientation. The geometric condition, rather than the traffic volume, would logically be the warranting condition in this case.

> Lighting is warranted where the ADT is less than 40,000, but one of the following conditions is met: the distance between the limits of illuminated interchanges is less than 1 mile; the section of the road is adjacent to high illumination levels such as shopping centers, theaters, or high-volume service roads (class III).

The first condition is apparently an attempt to account for the driver's discomfort by frequent changes from illuminated to unilluminated situations. The apparent assumption is that the interchanges are completely lighted. It is possible that class I illumination would not create any great degree of driver discomfort and, therefore, would not justify continuous illumination. The second condition is notably vague regarding the level of roadside illumination and the effect of spillover that must be considered in warranting conditions. The point is well taken that an increase in the level of roadside illumination will reduce the effectiveness of available light on the roadway; therefore, to maintain an equal level of effectiveness, additional illumination would have to be provided.

Freeways and Expressways: Urban Interchanges

> Illumination is warranted at interchanges where the through traffic on either road is in excess of 25,000 ADT (class III).

It is difficult to understand how the interchange area, having a through-traffic density lower than that for the freeway main lanes, could warrant roadway lighting when it is not warranted for the main lanes. The requirements for the driving task certainly are not changed to the degree indicated by the reduction in the warranting condition.

> Interchange illumination is warranted where traffic on any ramp branching off or connecting to an illuminated road is greater than 250 vehicles per hour (class II).

Roadways branching off from an illuminated roadway need illumination even for very light traffic volumes, whereas roadways connected to lighted facilities may not need any additional illumination in order to be effective. A value of 250 vehicles per hour may be too high for the former case and too low for the latter one.

Freeways and Expressways: Rural Interchanges

> Rural interchange illumination is warranted where the through traffic on either road is in excess of 15,000 ADT (class II).

The use of any level of through traffic to warrant illumination seems a questionable practice, as previously noted.

Arterials: Main Lanes

> Illumination is warranted where the distance between the limits of illuminated interchanges or intersections is less than ½ mile (class III).

The vague nature of "illuminated intersections" means that this warranting condition is almost boundless. Anything from a single incandescent bulb up to rather complete illumination of the intersection would seem to fit this definition. Some lower limit on the level of illumination should be established to make the warranting condition realistic.

Arterials: At-Grade Intersections

> Illumination is warranted when the accident rate is high (3 or more per year) (class I or II).

The concept seems logical; however, the accidents that are to be included should be only those that could conceivably be corrected by illumination. Even then, the level (3 or more per year) seems very low. A better relation might be a ratio of night to day accident rates of 2:1 or greater.

> Illumination is warranted at all signalized intersections (class I or II).

This warranting condition seems somewhat illogical. There does not appear to be a direct relation between the requirements for traffic signals and the need for external illumination of the intersection. However, an indirect relation may exist because of the complex nature of the vehicular movements in the intersection area. It is doubtful whether all signalized intersections warrant extensive illumination simply by virtue of warranting signalization.

> Illumination is warranted at all channelized intersections (class I or II).

If the intent is toward channelization using raised curb for all intersections, the warranting condition seems appropriate.

Railroad Grade Crossings: Rural Areas

> Illumination is warranted at rural crossings where the ADT is greater than 1,000 (class I).

The warranting condition does not account for exposure to trains. The warrant should probably be based on the product of the number of trains per day as well as the ADT level.

Tunnels and Underpasses

> Tunnels up to 400 ft in length should have night illumination only when the associated road is illuminated.

It is assumed that the deflection angle is sufficiently small such that the tunnel end is apparent to the driver. Should this not be the situation, the warranting condition should include both day and night operation.

INTERNATIONAL RECOMMENDATIONS FOR THE INSTALLATION OF ROADWAY LIGHTING

The Commission Internationale de l'Eclairage (3) has established a general set of recommendations for the installation of fixed roadway lighting. These recommendations are composed of descriptive terms, rather than numerical values, and the values to be associated with each description were specifically left to national committees of each individual country. Although general in nature, the commission's recommendations could be considered as warrants.

> On the basis of the nature of the road, the nature and amount of vehicular traffic, and the presence of pedestrians, it is possible to classify lighting installations envisioned by the present recommendations into three classes, comprising in all five subclasses.
>
> The principal classes are as follows:
>
> Class A: lighting for very important routes with rapid and dense traffic, where the only questions are the safety and the speed of the traffic and the comfort of the drivers.
>
> Class B: lighting for roads with considerable vehicular and pedestrian traffic in which, in addition to the needs of drivers, the needs of pedestrians and shops and considerations of amenities and aesthetics are important.
>
> Class C: lighting for residential roads having light local traffic.
>
> Classes A and B have been divided into two subclasses according to the importance of the road.

By leaving to the individual countries the task of associating specific numerical values with the descriptive terms, the commission effectively obviated the problem of determining specific warranting conditions. It is apparent, however, that the commission is suggesting that lighting should be provided for all heavily traveled roadways, both rural and urban.

An examination of the warranting conditions of several European countries reveals the fact that few countries apply a volume warrant. Belgium has established an average daily traffic of 10,000 vehicles as warranting conditions for lighting on main roads. Belgium does not use this volume warrant on motorways (freeways); rather it uses an interchange spacing of less than 5 kilometers as a warranting condition. This minimum spacing (3.1 miles) is considerably more liberal than the 1½-mile criterion established by AASHO.

Several European countries apparently did not have specific roadway lighting warrants, whereas others utilized geometric conditions or economic returns as the method of establishing the warranting condition. For example, Holland specifies that continuous lighting is warranted in rural areas where 3 or more lanes are provided in one direction. England bases its justification on an economic analysis of the savings associated with an assumed 30 percent reduction in the night accident rate as compared to the cost of lighting the facility.

With regard to the geometric warrant being utilized in Holland, it is interesting to note that, for level-of-service C, a peak-hour factor of 0.83, a directional distribution factor of 0.6, and a peak-hour volume of 10 percent of the ADT, the design flow rate for 6 lanes would be 42,000 vehicles per day. This compares very favorably with the value recommended by Ketvirtis.

STATE HIGHWAY DEPARTMENT WARRANTING CONDITIONS

The warranting conditions recommended by AASHO are used, with minor variations, by most state highway departments. There are, however, some state highway departments that have developed their own warrants. Parts of one such set of warrants are discussed in the following paragraphs.

General: Contrary to traffic signals, properly designed highway illumination is not a liability if installed prematurely. Hence, the warrants for lighting are actually a method of establishing priorities based on available monies. If sufficient funds were available it would be desirable to illuminate continuously all urban highways and all rural highway intersections to reduce accidents and increase driver comfort.

This statement expresses the feeling of many professionals in the lighting field, i.e., that continuous illumination is always desirable but is sometimes unrealistic from an economic point of view. Thus, the warranting conditions are, in reality, an attempt to balance expenditures on roadway lighting and the funds available for such improvements.

The assumed reduction in accidents has been questioned, particularly when related to the main lanes of a traffic facility.

1. In rural areas only the intersections and pavement transitions may be illuminated.
2. In urban areas all intersections and pavement transitions shall have at least minimum illumination. Continuous illumination is desirable; however, it shall only be installed where the local agency has agreed to pay all maintenance and energy costs of lighting between intersections.

These qualifying statements are necessary in view of the extremely liberal warranting conditions specified by this state's policy.

Intersections

The minimum vehicular volume traffic signal warrant is met during any 1 hour of darkness on a typical day.

The interruption of continuous traffic signal warrant is met during any 1 hour of darkness on a typical day.

The minimum pedestrian volume traffic signal warrant is met during any 1 hour of darkness on a typical day.

Of 5 or more accidents at an intersection in a 12-month period, 50 percent or more are after-dark accidents.

These warranting conditions would appear to be rather liberal; however, there are no guidelines that would indicate how much reduction in the traffic signal warrants would be justified. It is apparent that, where there is sufficient conflict to justify the installation of traffic signals, lighting would be justified; but it could well be justified at a somewhat lower level. It might also be argued that illumination of the intersection area would make it more difficult to see an approaching vehicle because the contrast between the headlight illumination of the conflicting vehicle and the background would be reduced by the degree of fixed illumination.

The number of accidents does not reflect the fact that night accidents might not be eliminated by the installation of illumination. It may be reasonably assumed, however, that such accidents are in the minority and that an in-depth study to determine whether additional illumination might be effective would not be economical.

The MADT (Monthly Average Daily Traffic) for November, December, or January is at least 5,000 vehicles.

Five thousand vehicles per day is an extremely liberal volume warrant and would undoubtedly warrant illumination on all urban arterial streets and many collector streets. The area of illumination conditions previously presented would be vital for controlling the number of roadway sections to be lighted under this warrant.

The MADT for November, December, or January is 2,000 vehicles, and the 85th percentile speed is 40 mph or greater.

This warrant is very liberal, although it is doubtful that many urban facilities would have a 40-mph 85th percentile speed with an ADT below 5,000 vehicles per day.

> Of 5 or more nonintersection accidents in a ¼-mile section of roadway, in a 12-month period, 50 percent or more are after-dark accidents.

This warrant seems reasonable, although arbitrary. The magnitude of the warrant seems consistent with the accident warrants for traffic signals. A logical question can be raised concerning the effectiveness of lighting for reducing accidents in nonintersection areas.

Signals

> Whenever a traffic control signal or intersection beacon is installed, either at an intersection or mid-block, the area of conflict shall be illuminated (in the same manner as an intersection).

The lighting of signalized intersections may increase the target value of the intersection and thereby decrease the startle effect of the signal. Such an effect has not been established, however, and the warranting condition seems very liberal.

School Crossings

> All officially designated and marked school crossings may be illuminated.

The word "may" seems to be the key word in the application of this warrant. School crosswalks that are utilized during the hours of darkness should be illuminated. The current trend toward split shifts in schools could result in children traveling to or from school during hours of darkness. Also, the expansion of adult classes during the evening hours could contribute to a need for illumination of school crosswalks.

System

> Whenever the majority of intersections in a series on a through highway meets illumination warrants, the remaining intersections should be illuminated to avoid entrapment at the otherwise nonilluminated locations. In like manner, sections of nonilluminated roadway less than ½ mile in length between continuously illuminated sections should be continuously illuminated.

The system warrant seems to be reasonable, particularly because the intersection warrants can only be satisfied at major intersections, which would probably not include a majority of all intersections. For those cases in which the number of major intersections is a majority, illumination of the remaining intersections would probably be justified, and continuous illumination should be considered.

Transitions

> All transitions from 2-lane roads to divided highways shall be illuminated. Lane-drops on multilane highways may be illuminated.

The lighting of all transitions is desirable but, through careful design, the need for illumination can be greatly reduced. The rather complex nature of the driving task in the transition areas cannot be denied, and fixed illumination could contribute substantially to the driver's orientation when approaching the transition. Nonetheless, the term "shall be" appears too restrictive.

Freeway Interchanges

> All freeway interchanges shall be illuminated as follows: off-ramp gore, on-ramp merging area, through roadway just beyond gore (1 light), off-ramp just beyond gore (1 light), and loop ramps (continuously). Intersections of ramps with the surface street shall be considered for lighting if the warrants for intersection lighting are met; if one ramp intersection is illuminated, all ramp intersections at the interchange shall be illuminated.

The freeway interchange warrant is consistent with the safety lighting concept now prevalent throughout the country; however, local rural interchanges with very light traffic may not justify the installation of safety lighting from an economic point of view. It can be argued that, if sufficient turning traffic exists to justify an interchange, sufficient justification exists for safety lighting because the driving task complexity at interchanges is as great as that that the driver will face on the freeway.

CONCLUSIONS

Review of the roadway lighting warrants currently in use reveals that 3 broad policies are being employed in establishing roadway illumination warrants. These policies are as follows:

1. Minimize sites warranting lighting—Fixed illumination is desirable on all classes of roadways, but, because of limited available funds, only a few sites should be warranted so as to have a firm basis for refusing to light a section of roadway. Thus, the warranting conditions should be set very high.
2. Maximize sites warranting lighting—Fixed illumination is desirable on all classes of roadways, and available funds will provide for illumination on relatively few. In order to encourage the allocation of local funds to pay the installation, maintenance, and energy costs associated with fixed illumination, the warrants should be very liberal so that all roadways with a substantial volume of traffic warrant lighting.
3. Act only where economically justified—Fixed illumination should be provided only at those points on the roadway that are complex, from a geometric point of view, because fixed illumination cannot be economically justified for most sections of roadway.

It is also apparent that virtually all of the warrants currently in use are very arbitrary and are frequently without substantial foundation. This is not to say that the warrants were not established by logical engineering evaluation of a problem. Rather, it appears that the warrants have been established from a broad philosophic position and logical deduction. Often the process of arbitration results in a set of warrants that is based on several philosophies rather than just one. This suggests the possibility that several different sets of basic warrants may be desirable, each developed to be consistent with a particular design strategy. Such a system of warrants would be somewhat cumbersome to administer, especially on a national scope.

Finally, all of the sets of warrants reviewed could justify lighting for any roadway carrying a substantial volume of traffic; therefore, the functional value of the warrant concept may well have been lost. The warrants appear to be utilized more for establishing the actual governmental agencies that will participate in the financing of the lighting system than for establishing the minimum conditions for which illumination can be expected to be effective.

PROPOSED FRAMEWORK FOR WARRANTS

Existing warrants do not deal directly with the principal function of the fixed lighting system, that is, to facilitate visual communication on traffic facilities through improved night visibility. There is a need to develop a more rational set of warrants based on driver informational needs as related to the roadway, traffic, and environmental conditions of the traffic facility. Such a set of warrants is being proposed in conjunction with a research project within the National Cooperative Highway Research Program (NCHRP). In fact, it is proposed that the total design process—warrants, guidelines, priorities, benefits, and cost-effectiveness—be developed around one common framework or concept.

This proposed framework for the total design process consists of a numerical rating system that ties the total process together in one package. Beginning with warrants, the features of the facility (geometric, operational, and environmental), which constitute the visual information needed by the driver, are rated numerically on a scale (1 to 5) such that the magnitude of the sum of the ratings or points of each of the features is an indicator of the severity of the visual communication problems. When this sum is compared to a number of points representing acceptable conditions, the warranting condition is established (e.g., 145 points > 95 points as a minimum value).

· The relative priority of installing lighting is established by setting the sum of the rating points in a ratio with the minimum number of points to justify lighting (e.g., 145/95 = 1.55). This priority index, when compared to other projects, indicates the relative severity in provision of driver informational needs with the installation of fixed lighting.

The guidelines for design, specifically the level of illumination, are determined by using the ratio developed for priorities as a multiplier of the minimum average illumination value as recommended by the Illuminating Engineering Society (IES). For example, the IES recommendation of 0.6 hfc for freeways would be increased by a factor of 1.55 if the previous example was applied.

The benefits are reflected in the solution of visual communication problems through fixed lighting. It is implicit that reducing the numerical rating of a given facility through the installation of fixed lighting results in benefits through an improved night driving situation.

Conventional methods use a monetary value for analysis of the effectiveness of a project. A method is established for cost-effectiveness analyses where supplying informational needs is a measurable effectiveness quantity.

The warrants package provides a logical framework for the total design process for fixed lighting. It should be recognized that the concept reported to NCHRP is tentative, and it has been proposed that the package be tested by a selected group of agencies for a period of time to ascertain its value to the profession and to identify needed modifications for practical application.

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DISCUSSION

W. H. Edman

With the advent of the automobile, "public lighting" took on a new meaning. To my knowledge, the first research of practical significance was initiated in 1910 to 1913 by Sweet. The research was conducted under the auspices of the Railroad Warehouse Commission at Madison, Wisconsin, and dealt with measurements of disability glare. Following this, an extensive research project was conducted in Philadelphia in 1914 under the leadership of Preston Millar. As a result of these studies, there was developed the concept of seeing by silhouette, reverse silhouette, glint, and shadow. The first use of the term "revealing power" of a street lighting system was also conceived, and this work was further added to by Waldram of England in the late 1930s.

No professional organized group existed until the IES Roadway Lighting Committee was formed at the request of the International Congress of Illumination and the Bureau of Standards. This was a request made in 1925 to prepare a circular on street lighting. This first report on principles of street lighting appeared in 1927 followed by the first code in 1930. Subsequently, there have been revisions made in 1935, 1937, 1940, 1945, 1953, 1963, and 1972. The first American Standard Practice appeared in 1947.

The first major installation that can be associated with the results of research was made in Milwaukee, Wisconsin, shortly before World War I. It was the first fully planned city street lighting system. It was then looked on as too radical with respect to the high mounting heights of 30 ft, first fully controlled light distributions, and other innovations.

The principal activity in street lighting during the 1920s was developing white-way lighting for the business streets. Little attention was paid to residential and traffic streets. In the 1930s began the era of traffic safety lighting after the number of motor vehicle accidents began to soar, especially night accidents.

This resulted in the development of more efficient luminaires with controlled distribution and the introduction of high-pressure mercury and low-pressure sodium sources. During World War II all progress was stopped. After World War II there began a slow conversion to the use of mercury sources. A number of utilities were slow in accepting this efficient source, but its acceptance gathered momentum in the late 1950s with an accelerating pace in the 1960s.

With regard to research, the newly formed Illuminating Engineering Research Institute (IERI) in 1944 requested subjects for roadway lighting research. However, interior lighting received priority at that time. About the mid-1950s, the Night Visibility Committee of the Highway Research Board, under the leadership of Burton Marsh, developed a program for research on highway lighting. The first major project was conducted on the Connecticut Turnpike, and subsequent to that both IERI-funded and federal-funded research projects have been undertaken and are currently under active pursuit.

D. Fischer

I should like to make some comments on the paper by Rowan. These comments are of course mainly based on the situation as it exists in Europe.

Rowan mentions the following as the objectives of street and highway lighting: crime reduction, civic improvement, and traffic safety. I should like to add three more objectives: visual comfort, increased road capacity at night, and optical guidance.

Street lighting installations of medium height and adequate quality already reduce the probability of traffic accidents to such a level that further improvement in the lighting can hardly be expected to give any further significant reduction in the number of accidents.

However, investigations and assessments of practical installations show that street lighting can be improved beyond this level to the advantage of the road user by ensuring a greater degree of visual comfort to the driver. I think that visual comfort on the road should not be regarded as a luxury but as a means of allowing the road user to play his part in the traffic without strain. Additionally, improved visual comfort is likely to reduce driver fatigue and thus add to general traffic safety.

Only under comfortable seeing conditions can one expect a smooth flow of traffic, even on a very busy road, that allows full advantage to be taken of the traffic capacity of the road. In many countries the rush hour for road traffic occurs during the hours of darkness during much of the year. Seen from this point of view, the requirements for good road lighting are not merely to offer the possibility of safe driving by ensuring easy and reliable perception, but also to bring the car-carrying capacity of the road at night up to the same level as was planned for it during the day. Road capacity is already a very pressing problem on a large number of roads leading in and out of large towns and cities. In view of the enormous sums of money that are being invested in the construction of new traffic routes, the problem of good road lighting is one of great economic importance. This is the reason that, in Europe, it is thought that traffic-volume requirements alone can justify the installation of fixed road lighting.

The third objective I should like to add is the need for optical guidance. Good correspondence and harmony between the run of the road and the line of the lighting helps the optical guidance of drivers, especially in fast traffic on main thoroughfares, and thus contributes to their safety and orientation. This is especially the case for roads having many curves or where there are rather short distances between interchanges on motorways.

Optical guidance at complex traffic junctions cannot, however, be achieved with conventional street lighting installations. A better solution for these areas is thought to be the simulation of daylight by means of a high mast installation, lighting the whole complex to a more or less uniform illuminance level.

Another means of achieving optical guidance with a street lighting installation is to use different lamp colors for through roads and for local arteries.

J. Stuart Franklin

Warrants, as presently written, appear to deal primarily with the location of lighting. They say little about the quantity or quality of the lighting that will be installed.

Existing codes and guides for street and highway lighting specify quantity (levels and uniformity), leaving the definitions of quality somewhat vague.

Recently, some cities and municipalities have been enacting ordinances restricting the spill light from all types of lighting equipment. Some of these are very restrictive in terms of light intensity and luminance.

If the quantity of lighting is specified on the national and international levels and the quality is spelled out on the local level, nothing but frustration and conflict will result.

A. Ketvirtis

In his paper, Rowan is critical of some major conditions that warrant illumination. He particularly objects to traffic volume being used as a measure of indicating the need for roadway illumination. In my opinion, although other traffic system characteristics should be taken into consideration, volume is one of the most important factors in establishing priorities for highway illumination. Other factors that should be included in these considerations are roadway geometry, accident frequency, presence of pedestrians, road geographic location, and visual distractions. In recent reviews of existing warrants, some traffic engineers are advocating that traffic density be used as a supplementary factor to traffic volume.

It should be remembered that warrants are used mainly by traffic engineers and highway administrators for objective allocation of public funds. Therefore it is imperative that they include the following characteristics:

1. As a general guide for warrant definitions, a traffic facility should be regarded as an integrated roadway system emphasizing intended levels of service;
2. For easier use of the warrants, major traffic-system characteristics such as volume, geometry, geographic location, and accident rate should be taken into account;
3. The warrants should need a minimum of subjective interpretation—any ambiguity would destroy them; and
4. Complicated calculations and lengthy procedures to arrive at warranting conditions should be avoided.

Richard E. Stark

Current warrants use traffic volume as the primary determinant in installing roadway lighting. A road having poor geometric design and experiencing low traffic volumes may not warrant lighting because the number of events and conflicts are few. On the other hand, a roadway having perfect geometry can experience events that are not related to geometrics but to volume. As volume increases, events such as vehicle breakdowns, multiple-vehicle accidents, debris falling from trailers and trucks, and erratic pedestrian occurrences all begin to increase and occur on a regular basis. Higher volume usually means higher numbers of pedestrians. These are motorists who have left their vehicles because of disabilities and accidents as well as occasional hitchikers. In 1 year approximately one-half of the fatalities that occurred on the Chicago expressway system involved pedestrians. It is my thought that volume should be included along with operational factors.

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