ILLUMINANCE VERSUS LUMINANCE

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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.

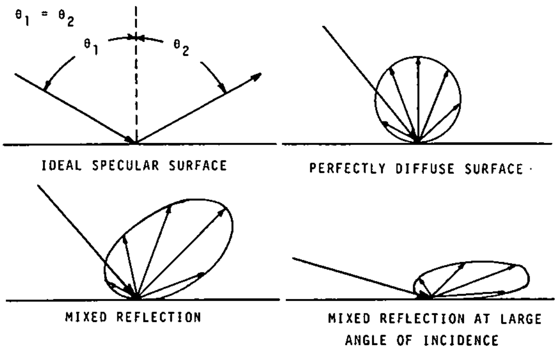


Figure 2. Luminous paths.

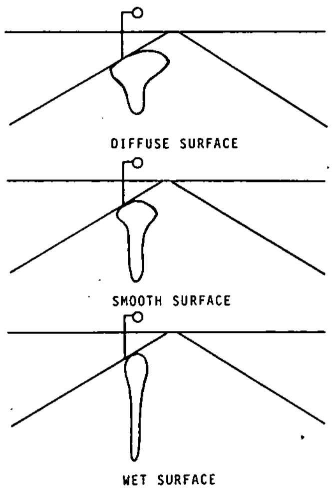
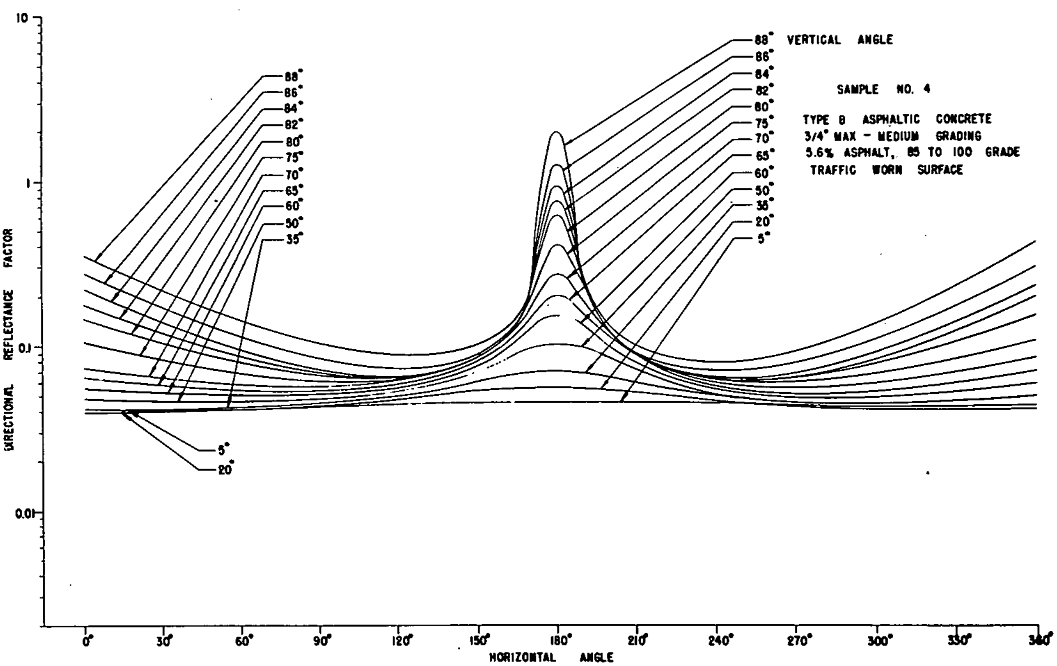


Figure 3. Directional reflectance factors for 50-ft viewing distance.



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

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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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