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## Appendix A

### Literature Review and References

(Reprinted from: *Evaluation of Roadway Lighting Systems Designed by Small Target Visibility (STV) Methods*, Final Report No. 0-1704-8, Department of Civil Engineering, Texas Tech University, Lubbock, TX 79409, by Bobby Green, Olkan Culvaci, Sanjaya Senadheera, Karl Burkett, and Douglas Gransberg)

#### A.1 CORRELATION BETWEEN ACCIDENTS AND ROADWAY LIGHTING IMPROVEMENT

##### Components of Stopping

To understand the correlation between lighting and accidents (crashes), one must first identify those parameters that affect a driver's ability to avoid accidents. This is normally expressed through the components of stopping. To bring a vehicle to a safe stop from some speed, four things must occur in order:

1. The driver must sample the driving environment for information requiring adjustment in driving behavior such as changes in speed and direction. This can be called sampling rate and has a probabilistic function associated with it. If a piece of data is sampled which would require a change to zero, the next three items will occur. This can be called *sampling time*.
2. The driver must see and acquire an image (for purposes of this discussion, the image will be called the target) that generates the thought that the vehicle should be stopped. This can be called *target acquisition time*.
3. The driver must process that target thought and react by stepping on the brake. This will be called *reaction time*.
4. The vehicle must rapidly decelerate from its initial speed to zero. This will be called *stopping time*.

Stopping time is merely a function of physics and can be computed with great accuracy if the initial speed is known or can be estimated. Reaction time varies among individuals, but highway safety literature generally accepts this to be constant at 2.50 seconds. Acquisition time is a more complex parameter and is a function of both visibility (i.e. the driver being able to see the target) and other more random factors such as the driver's immediate attention when the target becomes visible or the driver's ability to recognize the target as a hazardous image requiring an immediate reaction. If one were to assume that as the visibility of the target increases that the probability that an average driver will properly react to it also increases, then the aim of roadway lighting design for safety should be to create an environment of enhanced visibility.

##### Elvik Study

The Norwegian Institute of Transportation Economics conducted a study to validate the hypothesis that adding light enhances traffic safety (Elvik, 1992). The study looked at the correlation between accidents and roadway lighting in 37 different studies in 11 different countries. The study identified three types of traffic environment as urban, rural, and freeways and grouped safety data according to these

classifications. The author used meta-analysis to develop what he called a “criterion of safety” (CS effect) which is a ratio expressed as follows:

$$\text{CS effect} = \frac{\text{No. of night accidents after lighting} / \text{No. of night accidents before lighting}}{\text{No. of day accidents after lighting} / \text{No. of day accidents before lighting}} \quad (\text{A-1})$$

If the ratio is less than 1.00, then it could be concluded that lighting reduces the number of nighttime accidents. If it is greater than 1.00, then lighting increases the number of nighttime accidents. If lighting has no effect, then the ratio would be 1.00. This is an interesting approach in that it provides a means to prove or disprove the fundamental hypothesis. When one considers the effects of contrast on visibility, it becomes evident that adding light to an area can diminish the contrast of a particular target and essentially render that object invisible, which, in turn, may increase the potential for accidents. Elvik’s system can be used to test this argument as well.

Elvik’s study found that roadway lighting reduced nighttime fatal accidents by 65% and nighttime injury accidents by 30%. It also calculated a reduction of “property-damage-only” accidents of only 15%. It also found that these improvements vary by country and types of traffic environment. Elvik recognized that the studies he reviewed did not consider every conceivable source of error. He also found that there is “no doubt a large number of other variables with respect to which the effects of public lighting might be expected to vary.” However, he was able to satisfy the statistical requirements for meta-analysis for regression to the mean, secular accident trends, and contextual confounding variables. He found that the two most significant variables were accident severity and accident type. Unfortunately, he was unable to confirm that lighting satisfying current warrants was either more or less effective than lighting that did not satisfy warrants. It should be noted that he found, in some cases, nighttime accident rates went up after public lighting was installed.

### Box Study

A study of the relationship between illumination and freeway accidents (Box, 1971) concluded that the addition of lighting reduced accidents by 40%. This study used a simpler ratio than Equation A-1 to determine the effect of adding lighting:

$$\text{Safety ratio unlighted} = \text{No. of night accidents} / \text{No. of day accidents} \quad (\text{A-2})$$

$$\text{Safety ratio lighted} = \text{No. of night accidents} / \text{No. of day accidents} \quad (\text{A-3})$$

Thus the unlighted ratio is compared to the lighted ratio, and if the unlighted ratio is found to be greater than the lighted ratio, it is concluded that lighting reduces accidents. If the reverse is true, then it is concluded that lighting increases accidents.

Box concluded that freeway fixed lighting reduces accidents. It is interesting to note that his results for Interstate 20 in Dallas show a mean ratio of only 1.01 and confidence limits of 0.72 to 1.30. In fact, the best range in confidence limits was for Atlanta where the mean ratio was less than 1.00; that would indicate that lighting increases the number of accidents. The paper also speaks to the levels of illumination and concludes that it is impossible to determine an optimum level of illumination. Box also concludes that those areas with the lowest illumination range had the best night/day accident ratios. This lends credence to the argument that contrast may be the salient parameter in the visibility equation.

Roadways with typical in-surface illumination levels of 0.3 to 0.6 horizontal foot-candles (HFC) had the best accident rate ratios (Box, 1971). Great variation in luminaire output was found in the field. Data analyzed for over 800 mercury lamps revealed wide variations in lamp output. The erratic performance of systems invalidates any analysis of fine differences between various designs. The extent of variations may be enough to “wash-out” meaningful analysis of small variations in lighting design. As a group, lighted roadways had an average night/day rate ratio of 1.43 accidents of all kinds, and unlighted roadways had a ratio of 2.37. From Box’s data, a lighting level of 0.3 to 0.6 HFC produced the best ratio of night/day accident rates. It is also interesting to note that he found that 25% of the urban traffic occurs at night and

the primary accident problems involve collisions due to lack of adequate acceleration lanes. Therefore, on the issue of arbitrary target size, this study would seem to indicate a target that in some way models the rear end of a typical vehicle. That would support a similar finding by Kahl and Fambro of Texas A&M University (Kahl and Fambro, 1994) that the target height should exceed 150 mm.

### Fisher Study

An Australian study (Fisher, 1977) went as far as to identify a point of diminishing returns with respect to the relationship between the costs of upgrading roadway lighting systems and the savings accrued by accident reduction. Fisher calculated a variable which he called the accident reduction factor ( $r$ ):

$$r = \frac{\text{No. of night accidents after lighting} / \text{No. of day accidents after lighting}}{\text{No. of night accidents after lighting} / \text{No. of day accidents before lighting}} \quad (\text{A-4})$$

His equation is surprisingly close to the criterion of safety used by the Norwegian Elvik. He found  $r$  to be significant at the 0.1% level. He also found that accident reduction was significant at the 5% level with respect to lighting. This means that the change in accidents as a result of pure chance rather than as a result of upgraded lighting could only happen in 1 instance out of 20. More important, he found that only about 12% of the variation in the data can be explained by the variation in light level. Thus this study seems to have a very sound statistical base. Fisher calculated an optimum lighting upgrade with respect to accident cost savings. The lighting upgrade in his study was the replacement of mercury lamps by high-pressure sodium lamps. He used a function for the lighting upgrade as expressed by the following equation:

$$U = \frac{\text{Lower hemisphere flux per unit area after upgrading}}{\text{Lower hemisphere flux per unit area before upgrading}} \quad (\text{A-5})$$

He compared that to a cost function (SOC), which was the savings in accident costs over increased lighting costs due to the upgrade. Figure A-1 is a copy of the graph from Fisher's paper and clearly shows

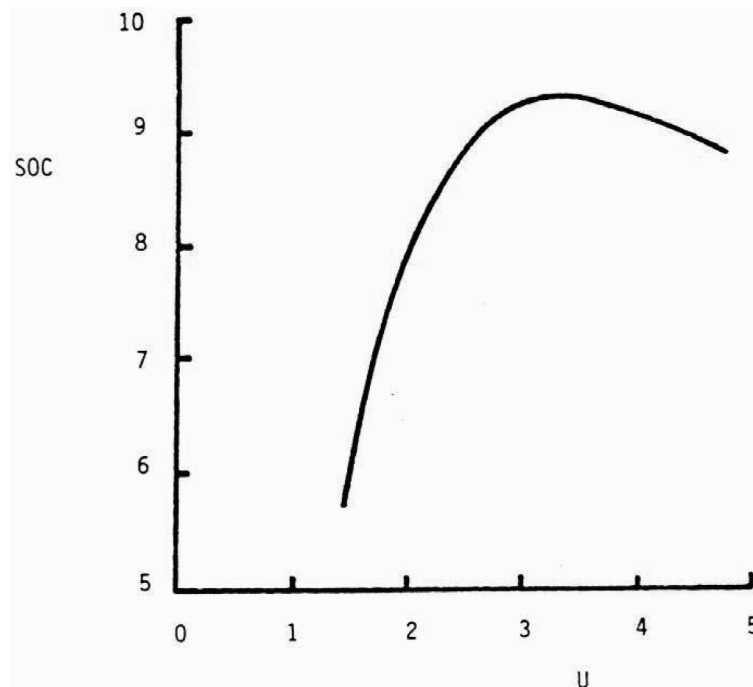


Figure A-1. Fisher's Optimum Lighting Upgrade Analysis (Fisher, 1977).

the optimum benefit occurs at a point around 3.3 times the increase in flux per unit area. In other words to add more light does not amortize the additional cost of construction by a commensurate amount of accident cost savings. Fisher also puts a very pragmatic spin on the subject of lighting and roadway safety in the final paragraph of his paper when he states.

Lighting does reduce night accidents and is a valuable accident counter-measure. However, there are limits to its application, and it must be regarded as one of the many counter-measures available. Lighting explains only a very small part of the phenomenon of accidents, and there is a diminishing return as roadway lighting is expanded and upgraded.

### **Highway Research Board Study**

A similar conclusion was reached by the Highway Research Board in a study on the effects of illumination on freeways (NCHRP, 1967). They found that there was no difference in the accident rate when illumination intensity was varied between 0.22 and 0.62 foot-candles. In fact, visibility only increased 41.1% with this nearly 300% increase in illumination because of disability glare.

### **Anderson et al. Study**

A University of Nebraska team evaluated the impact of lighting a rural at-grade intersection (Anderson et al. 1984) and found that the addition of lighting generally reduced accidents. However, the greatest reduction among various designs was only about 14%, and in one case in the study the accident rate actually increased 6% after the addition of lighting. Six different designs were studied and the variations in accident rate were less than 6% between differing designs. Between the two designs with the greatest difference in accident rate, the change in average horizontal illumination was 118%, which produced a 6% improvement in accident performance. It should be recognized that the scope of this study was very limited, but it nevertheless shows that attempts to improve safety performance by varying design provide only marginal differences at best.

### **Problem of Contrast**

Taking the conclusions of the papers by Elvik, Box, Fisher, and Anderson et al. together, one can conclude that adding light to a road does enhance safety, and that the level of that light is hard to correlate with safety performance. By having a lower level of illuminance, an object will show higher contrast against both the background and the foreground when it is illuminated by the headlights of a vehicle. A paper published in 1945 by C.I. Crouch that indicated that visual acuity rises with illumination level and then drops off as levels of glare and brightness reach a point where the observer experiences discomfort. This identifies a key biological constraint that must be considered in the design of roadway lighting systems. In essence, we have two dichotomous conditions to try to optimize in the design. On one hand, increasing the level of contrast makes an object more visible. This would lead an engineer to increase the light behind the object to create a situation of negative contrast and thus maximize visibility. However, the placement of the lighting to achieve this condition would create glare thereby reducing the observers visual acuity and making it harder to acquire and safely react to the presence of the object in the traveled way. Additional complications arise when off-road fixed light sources are considered along with headlamps from multiple vehicles.

### **Jung and Titishov Study**

This dilemma was addressed after a fashion by Jung and Titishov (1987). They used a standard  $20 \times$

20 cm target, cut from a Kodak middle gray card (diffuse, 18% reflective standard) to conduct their contrast experiments. They discovered the fixed lighting has too many transient quantities that are difficult to characterize. In the case of luminance, there are only a few variables to characterize. The study considers luminance as reflected light in the luminance design standard and illuminance design standard as an incident light only design. It is difficult to reach agreement on standard values for visibility system parameters when the visibility factor is loaded with physical and human factors.

Jung and Titishov's solution is to concentrate on a less sophisticated parameter that can be computed easily at locations on the roadway using only dimensions and properties of the lighting system. Their parameter would be used in the same way as glare or illuminance to determine weaknesses in a roadway lighting system. They assume visibility of a small target is determined mostly by the negative contrast of a silhouette effect.

Jung and Titishov advocate backlighting the roadway to increase negative contrast while minimizing glare. In Jung and Titishov's opinion, the current illuminance and luminance standards are blocking development of backlighting because they do not reveal spots of bad visibility. According to them, it is necessary to perceive a critical object at a distance of about 90 m. Car headlights are not very effective at that distance, so objects are seen by silhouette vision (i.e. negative contrast) if the objects are backlit.

### **Hall and Fisher Study**

Hall and Fisher (1978) examined the design of roadway lighting systems by using empirically derived requirements of light technical parameters such as road luminance, luminance uniformity, and glare restriction. They also used a square target 200 mm × 200 mm with limited range of contrast. They found that lighting design based on a visibility matrix requires the introduction of simplifications. They caution that:

Inherent simplifications may not broaden our understanding but further rigidify our [technical] attitudes. For example, the thought that the [critical] task is the identification of simple objects on the carriageway is reinforced. This again prevents the consideration of the total environment, which includes the immediate surrounds of the carriageway. Indeed it may be argued that a visibility metric should include a weighting factor for spatial safety distribution over the carriageway.

These authors go as far as formally questioning the introduction of a contrast based visibility metric because of the difficulty of understanding the effect of inherent simplifications on the output of the design methodology.

### **Marsden Study**

Marsden (1976) studied road lighting, visibility, and accident reduction numerically and experimentally and focused to some extent on the issue of glare. For experimental investigation, disability glare is related to veiling luminance, which was measured with a Pritchard photometer. Horizontal illuminance near the road surface was measured by summing the outputs of photocells mounted on the ends of the vehicle. Vertical illuminance at road level was measured by a photocell mounted on the rear of the vehicle, and some instrumentation was mounted below the vehicle to record road reflectance data. They recorded all the information as well as the visual field of the driver on the tape. The tape was played in the laboratory and selected frames were frozen. An area of the shape can be defined (by operating brightening-up controls) for luminance analysis. This analysis was examined on the portion of the TV signal corresponding to the selected area. Analog processing gives the value of maximum, minimum, average, and standard deviation of luminance within the selected area by using a calibration luminance scale on the picture.

## Scott Study

In Scott's study (1980) a wide range of measures of lighting quality was investigated in order to determine which of them was most clearly related to accident frequency. A representative number of sites was examined to establish correlations with reasonable confidence. It was assumed that day and night accident frequencies would be equally distributed in all factors except road lighting quality.

Analysis was limited for dry road surfaces and major two lane roads with speeds greater than 30 mph. It was concluded that average luminance is strongly related to accident ratio. An increase of 1 cd/m<sup>2</sup> resulted in a 35% lower accident ratio. A non-pedestrian accident ratio correlated well with average luminance and overall uniformity ( $U_0$ ). A significant relationship with average luminance was found for minor accidents.

## Frantzeskakis Study

J.M. Frantzeskakis (1983) presented the results of two accident analysis studies conducted on two highway sections of the Greek National Roadway Network. It was found that overall accident rates increase during winter, on weekends, at night, and during the period before sunset. It is considered more appropriate to correlate accident rates to levels of service instead of traffic volumes.

## A.2 DRIVER PARAMETERS

### Introduction

Rackoff and Rackwell (1975) investigated the physiological components of driver reaction and target acquisition. They developed a vehicle-based television system to investigate driver eye movement pattern during night driving and to compare those patterns to daytime patterns on freeways and a rural highway. They determined the differences of visual search behavior at sites with high and low night accident rates and the effect of illumination on a driver's visual search. They discovered that nighttime visual search behavior is different from daytime visual search behavior, and the measure of visual search behavior is sensitive at sites with different day and night accident rates. The results demonstrate that the changes in visual search measures due to illumination not only demonstrate that illumination can affect visual search at the same sites, but also demonstrate that visual search behavior can be useful in associating the specific effects of various illumination designs on driver search patterns.

Walton and Messer (1974) discuss fixed roadway lighting from a driver visual workload measure of effectiveness of vehicle control. They were looking for a measure for determining when roadway lighting would be warranted. Their work compliments the concept discussed earlier with regard to target acquisition time, reaction time, and stopping time.

### Driving Tasks

Walton and Messer divide driving into three primary tasks, the information necessary to complete each task, and the priority level of each task. The tasks and priority levels are the positional level, the situational level, and the navigational level respectively. The positional level consists of speed and lane position and must be satisfied before any other task. The situational level is second and consists of changing speed, direction of travel, and position on the roadway. The navigational level consists of following a predetermined route from here to there and is the third level of priority after position and situation.

In a situation overload, a driver will shed lower priority tasks for high priority tasks. An environmental situation causing a driver to shed high priority tasks is not a suitable situation. Load shedding

is not determined by the amount of work a driver must do but by the rate at which the tasks must be accomplished. An emergency situation will cause sudden load shedding. From an information supply standpoint, the size of the information supply to the driver is inversely proportional to the speed at which he is traveling. Fixed roadway lighting improves information processing capability of drivers by increasing the amount of information available for processing by making a larger proportion of the roadway visible.

To quantify the amount of information available due to fixed lighting, we first need to determine the total amount of information available to the driver under ideal lighted (i.e. daytime) conditions. Then, we must determine the amount of information available in the same area at night without lighting, which then allows the computation of the contribution of the fixed lighting in terms of total information available to a driver. After the information contribution due to fixed lighting is assessed, it is then possible to determine the change in information available to a driver due to changes in fixed lighting.

Drivers are assumed to service information needs in a cyclic order dictated by priority of tasks. The cycle would be positional information search, situational information search, navigation information search and back to positional information search. From an information standpoint, the tasks involve sampling each task periodically with the period of the sample determined by the speed of the vehicle and complexity of the task. As a task becomes more complex, the sample rate increases.

The assumption of safe and effective vehicle positional control is based on redundant positional information of the roadway ahead and must be acquired each time the driver returns to a position information search and acquisition phase. During situational information search and navigation information search, the driver is assumed to be traveling without positional information. Information demand is the time required to complete a sequence of position, situation, navigation, and position information searches.

### **Positional Information Acquisition**

Most night time positional information is gathered from lane lines, edge lines, curb lines, position of other vehicles, and a general view of the roadway. Much of the positional information under good (daylight) driving conditions can be obtained with peripheral vision. During nighttime driving, the driver fixates on position markers rather than using peripheral vision. Time required to identify a task is about 0.2 seconds. The time for eye movement is from 0.1 to 0.3 seconds. So, the time required to sample a position source is about 0.3 seconds or more.

### **Situational Information Acquisition**

It is assumed that a driver scans situational areas to ensure safe operation when a potential hazard is visible about 25% of the time, but if there are no hazards, the situational load drops. Increased complexity of the scene being viewed increases the mean fixation time of the situational information gathering tasks.

### **Navigational Information Acquisition**

A driver can search for navigational information only after the positional and situational needs are fulfilled. Navigational information consists of reading signs and other navigation tasks. The complexity of the tasks is determined by a level of familiarity with the route and with the situation. New signs and situations require more time and increase stress levels. A word on a sign requires about 0.35 seconds to locate and read. Multiple unfamiliar signs are confusing and increase stress levels during navigation tasks. As navigational task time increases, positional and situational task times suffer. Roadway lighting increases the positional information supply by increasing the visibility distance. Decreasing speed also increases visibility distance.

## Addressing Drivers' Information Needs

Walton and Messer's approach to warrant fixed roadway lighting is based on the driver's information needs to perform night driving tasks in a particular driving environment. Fixed roadway lighting is warranted when the information demand exceeds the information supply without fixed roadway lighting.

Adrian (1997) adds to the knowledge base with respect to driver physiology. He discusses rod vision and cone vision and the 2° central field of view and blue shift in the eyes sensitivity. He also found that as light levels decrease, the spectral sensitivity of the eye changes, but the sensitivity curve remains approximately the same shape. However, the peak of the curve shifts away from 550 nanometer (nm), to a slightly bluer 520 to 530 nm. Low light level contrast sensitivity is shifted into the blue with higher contrast sensitivity in blue than in red.

## Target Size and Composition

The proposed RP-8 (IESNA, 1990) specified that size and composition of the "small target" to be 18 cm square and of 20% diffuse reflectance (change to 50% before adoption in 2000). This reference is silent as to the reasons why this particular target is chosen as the standard. It is clearly an attempt to create a series of parameters that can be related to visibility and, therefore, correlated to experimental and computed data with for the purpose of quantifying visibility. A study led by Freedman (Freedman et al. 1993) proved that the probability of detecting a target strongly depends on its type and that older driver's generally showed a significantly lower probability of target detection. Thus, the selection of a target's size, shape, and composition should not be arbitrary. Other studies have used targets of different size than the STV target (the term target will be used to define a standard object used experimentally to relate to some other parameter of visibility, recognition, or other such factor). Roper (1953) used targets 40.64 cm square with a reflectance of 7.5%. Haber (1955) used a much larger target with a mean linear dimension of 91.4 cm and a reflectance of 15%. A German group (Waetjen et al. 1993) used a target composed of a Landholt ring with a stroke width of 8.7 cm and a height of 43.5 cm. Jung and Titishov (1987) conducted their work with a 20 cm square target with a reflectance of 18%. Zwahlen and Schnell (1994) used targets of varying reflectances that were 60.96 cm square and installed 30.48 cm above the pavement. They did further detailed studies on this type of target with a constant reflectance of 15.5%.

A team led by Janoff (Janoff, et. al, 1986) used a target composed of styrofoam hemisphere with a 0.15 m diameter skirt and an 18% reflectance. The lighting system in controlled field conditions consisted of 200 watt high-pressure sodium (HPS) lamps mounted 30 ft high at spacings of between 68 and 88 ft. They chose 6 different lighting conditions: full lighting, 75% power, 50% power, every other luminaire extinguished, one side extinguished, and no lighting. They measured photometric data for each condition. Subjects were required to drive the vehicle at the 55 miles per hour (88 kph) constant speed limit. Results of the controlled field experiments show that drivers tended to dislike reduced lighting on ramps or interchanges as opposed to reduced lighting on straight mainline roadway sections. By using the six conditions, they found a linear relationship between detection distance and horizontal illumination, and between pavement luminance and visibility index

Zwahlen and Yu (1990) studied two types of investigations to determine the distances at which the color and outside shape of targets can be identified at night under vehicle low-beam illumination for flat targets with three different outside shapes and with six different retroreflective color sheet coverings. First, the color and the shape recognition distances were investigated. Second, only the color recognition distance was determined. They used colors (red, green, yellow, orange, blue, and white) and target shapes (circle, square, and diamond) having the same surface area (36 in<sup>2</sup>) as independent variables. In both experiments the center, front of the vehicle is positioned above the centerline of the road, and the longitudinal centerline of the vehicle also positioned at a 3° angle to the left of the road centerline. The results show that the color recognition distance was twice as long as the shape recognition distance. Also, they concluded that a highly saturated red color of the retroreflective targets was the best. Hall and Fisher (1978) examined design of roadway lighting system by using empirically derived requirements of light

technical parameters such as road luminance, luminance uniformity, and glare restriction. They used a 200-mm square target with limited range of contrast. They found that lighting design based on visibility matrix gives better results than others. Finally, the 1990 Green Book (AASHTO, 1990) uses a target 150 mm in height as a standard from which to calculate stopping sight distance requirements for highway geometric curves. Thus it can be seen that target size and composition has been quite variable.

While roadway lighting can be installed for a variety of purposes, the consensus found in the literature seems to indicate that safety is the primary reason for making a capital investment in lighting systems. Thus, it would seem logical that the size and composition of the standard target used for design would be directly related to the dynamics of nighttime driving safety. A study done by Kahl and Fambro (1994) provides an excellent analysis of the comparison of targets to accidents. This pair correlated types of accidents with the size of the object involved and then compared it to the standard Green Book 150 mm target. They found that only 0.07% of reportable accidents were attributable to collisions with small objects in the road. They then concluded that the frequency and severity of these types of accidents did not justify the use of the 150-mm object height in the critical Stopping Sight Distance model. In fact, they found that only 2% of all accidents involved objects or animals in the roadway. In urban areas, 10.4% of the objects struck were less than 150 mm in height, and on rural roads only 1.8% were 150 mm or less in height. They also found that “more than 95% of the accidents resulted in low-severity injuries; therefore, a small object is not the most critical, hazardous encounter in the Stopping Sight Distance situation.” They also make two recommendations of interest in the STV discussion:

- The object height should be a function of and related to the smallest realistic hazard typically encountered on the roadway.
- The taillight height of an average vehicle (380 mm) is probably a good measure for the height of a typical hazard.

This correlates well with the results of Zwahlen and Schnell (1994) who found that a 60.96-cm square target with 15.5% reflectance placed at 30.48 cm above the pavement could be spotted by subjects at an average distance of 104 m with a standard deviation of 16.6 m through the filter of a windshield. When this is compared to the STV model of the 18-cm target visible at 83 m, there appears to be a potential that the STV target might be too small to be detected by the average observer, and that the use of it as a design standard does not directly correspond to those hazards related to visibility for which the lighting is being installed. The Zwahlen and Schnell target provides nearly three times the reflective surface at nearly the same distance (if one were to subtract the standard deviation from the mean distance) as STV. It should be noted that the Zwahlen and Schnell experiment was a static one in that the observer was not moving as would normally be the case in most roadway hazard situations. Also, the observer’s only data collection task was to search for the target. Jung and Titshov (1987), while using a target that was very close to that specified by STV, found that once “luminance levels meet standards for uniformity, spots of unsafe low contrast are clearly revealed . . .” They also seem to advocate the use of several standard values of reflectivity.

### **A.3 PAVEMENT PARAMETERS**

#### **Background on Pavement Luminance in Roadway Lighting Design**

Until the 1983 IES/ANSI Standard Practice for Roadway Lighting (RP-8) was proposed, roadway lighting in North America was based on horizontal illuminance. In the 1983 RP-8, pavement luminance was introduced as the preferred basis of design with illuminance criteria included as an acceptable alternative (IES 1983). High mast and walkway-bikeway lighting systems were two exceptions where illuminance was presented as the only criterion for design.

Along with pavement luminance, disability glare (veiling luminance) was also identified as a significant factor that affects the nighttime visual performance of a driver. At the time when RP-8 (IES 1983) was introduced, the IES/ANSI recognized that “luminance criteria do not comprise a direct measure of

the visibility of features of traffic routes such as traffic and fixed hazards.” However, they decided that “visibility” criteria proposed at the time were based on limited research and evaluation and, therefore, could not be adopted at that time. Nevertheless, RP-8 (1983) had a complete appendix (Appendix D) dedicated to visibility concepts for information purposes. This Appendix used the concept of visibility index (VI), which was developed based on research by Blackwell and Blackwell (1977) and Gallagher (1976) where the visibility of a gray-colored rubber traffic cone was considered as the target.

According to literature, the “visibility” concept was first introduced in England by Waldram (1938) who identified the concept of “revealing power.” He calculated the visibility for 24-inch square targets set on a grid pattern on the roadway, and determined when a target became a dangerous obstacle for observers driving at 30 mph. Also in England, Smith (1938) conducted a study of the reflectance factors and revealing power of objects. He showed that 50% of the pedestrian clothing had a reflectance of less than 5%, and 80% of the clothing had a reflectance below 15%. Based on these results, it was possible to show that a 10% reflectance target will always be darker than the pavement that can act as a background for a pedestrian wearing such clothes. Such a scenario provides negative contrast (pavement brighter than the target), and the target that is least visible on the roadway will be the one located where the pavement has the lowest luminance.

Based on research such as those mentioned above, CIE (International Commission on Illumination) adopted the following positions in its standard practice for roadway lighting design:

- “Quality” of a lighting system is always higher when average pavement luminance is high.
- “Quality” of a lighting system is always higher when “empty street” pavement luminance uniformity is excellent.
- Glare needs to be considered in the design.

It was interesting to note that contrast was not considered as a design criterion. Keck (1996) observed that CIE at the time felt that objects are almost always darker than the pavement, and therefore, by considering factors 1 and 2 above, would provide a simple design method.

## Reflective Properties

In terms of reflective properties, all surfaces, including roadway pavement surfaces, are generally classified into three major groups. These are the ideally specular surface, perfectly diffuse surface, and mixed reflection surface. Descriptions of each follow.

***Ideally Specular Surface.*** The ideally specular surface reflects all the luminous flux received by a point at an angle of reflection equal to the angle of incidence and in the same plane. The reflected ray, normal to the surface at the point of incidence and the reflected ray all lie in the same plane. These surfaces form a similar geometric image. Some examples of almost ideally specular surfaces are mirrors, highly polished metal surfaces, and liquid surfaces.

***Perfectly Diffuse Surface.*** The perfectly diffuse (matte) surface reflects light as a cosine function of the angle from the normal, regardless of the angle of incidence. Since the luminance of a surface is equal to intensity divided by the projected area, and since 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 the surface is independent of the luminance of the source of light but proportional to the illumination of the surface. These surfaces form no geometric image. Surfaces such as white matte finished paper or white painted walls closely approximate the perfectly diffuse surface. However, these surfaces behave as diffuse only if the angle of incidence is close to zero.

***Mixed Reflection Surface.*** Most surfaces encountered in everyday life fall into the category of mixed reflection that is somewhere between the ideally specular and perfectly diffuse surfaces. These surfaces form no geometric image but act as a diffuse surface to some extent with some preference to direction of

reflection. Therefore, the apparent brightness of such a surface changes with the angle of incidence and the observer's viewing angle. King (1976) illustrated these surfaces with the luminous intensity distribution curves shown in Figure A-2.

Pavement surfaces that encounter viewing angles between 86 and 89 degrees and incident angles between 0 and 87 degrees (both from the normal) exhibit characteristics of mixed reflection. Generally, a single luminaire over the pavement surface produces a single luminous patch that appears to the traveler to be shaped like a "T" on the surface of the roadway with the tail of the "T" always extending towards the observer irrespective of the observer's position on the roadway. This brightness (luminous) patch is almost completely on the observer side of the luminaire since very little of the light incident in the direction away from the surface is reflected back to the observer. The size, shape, and the luminance of the patch depends to a great extent on the surface reflection characteristics of the pavement.

Figure A-3 illustrates the shape of a luminous patch produced by a luminaire on diffuse, smooth (specular), and wet surfaces.

### Studies on Pavement Reflectance

In one of the earliest studies done on reflection characteristics of pavement surfaces, Christie (1954) of the Transportation and Road Research Laboratory (TRRL) in England found that a reduced range of data presented in a single family of curves is sufficient to calculate the luminance in important regions of a street lighting installation with an accuracy level of 15%. Christie adopted the view that brightness (luminance) in a lighting installation is built up from the bright patches produced by individual luminaires. This technique was used to assess the reflection characteristics of three types of pavement surfaces commonly used in England. The three surfaces were rolled asphalt with precoated chippings, "non-skid" rock asphalt, and machine finished Portland cement concrete. After calculating the luminance factors, a family of curves for these surfaces was drawn. Since these curves do not present an immediate picture of how the surface is brightened, a perspective drawing showing the bright patch was developed using the luminance factor curves.

Comparing his brightness patch for the rolled asphalt surface with precoated chippings with results published by Waldram (1934), Christie concluded that the old surface (Waldram's test section) gave a much larger brightness patch than the new surface (Christie's test section). In comparing the rolled

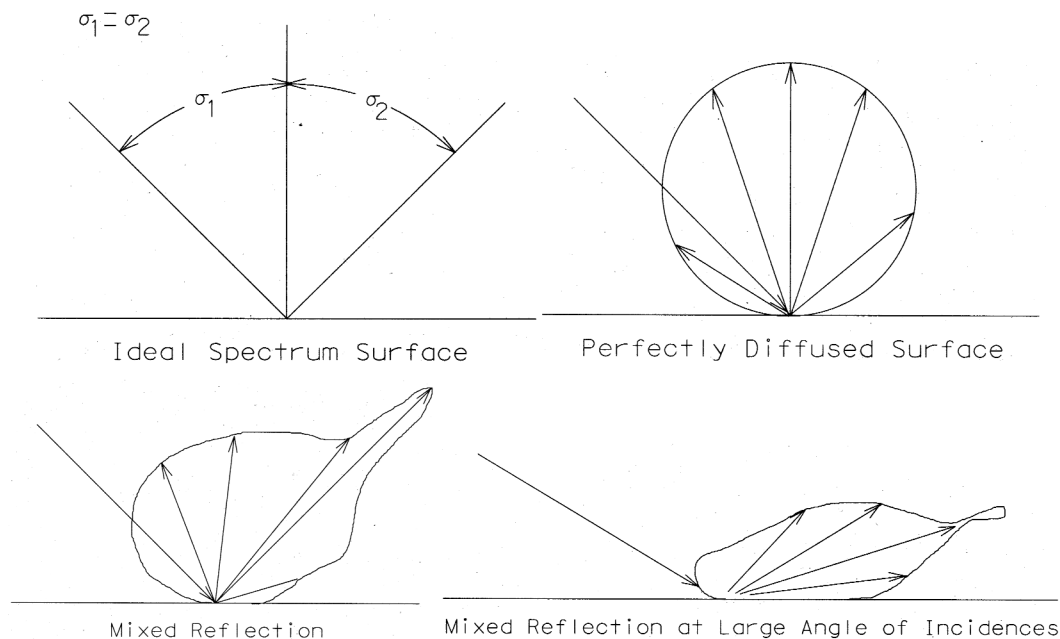


Figure A-2. Luminous intensity distribution curves for different types of reflection (King 1976).

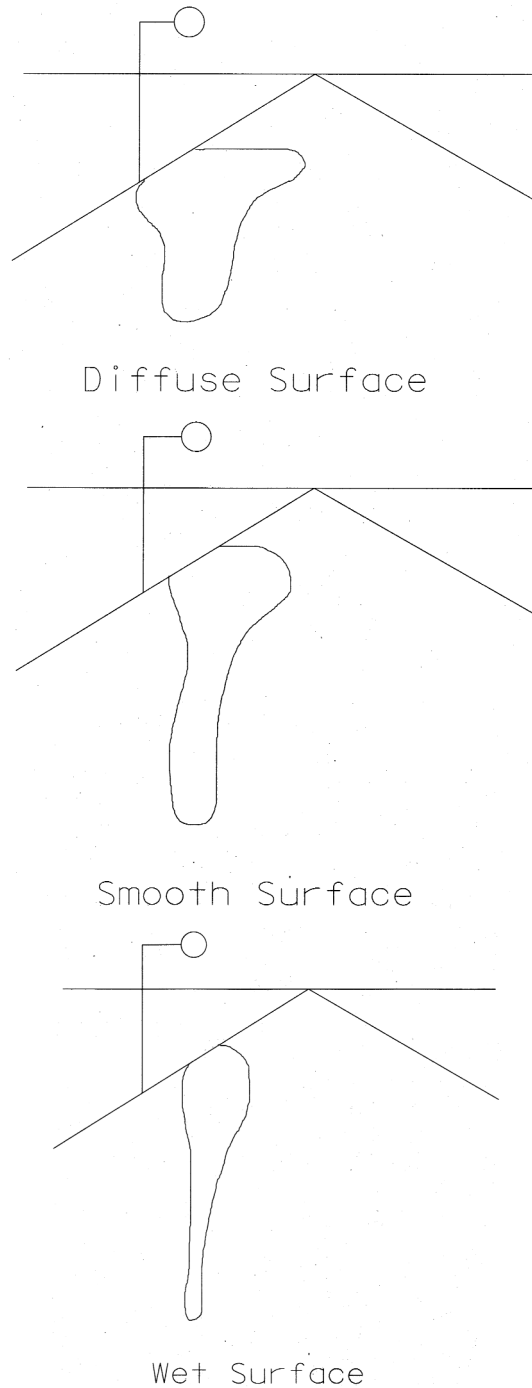


Figure A-3. Luminous patch produced on different roadway surfaces (King 1976).

asphalt surface with the “non-skid” rock asphalt, Christie observed that the efforts to make pavement surfaces “non-skid” have seriously reduced their power to reflect light. Christie also found that in addition to coarse surfaces, fine textured surfaces with protruding small aggregates also produce short brightness patches. His explanation of this phenomenon was that within limits, what matters is the shape of the surface, not the size of its features (coarseness). He concluded that sharp projections necessary to prevent skidding tend to destroy the specular reflection of obliquely incident light that makes possible the formation of long patches. Christie also observed that in coarser surfaces where specular reflection is reduced, brightness has to depend more on diffuse reflectance than in the case of smoother surfaces. Since diffuse

reflectance depends on the lightness of color, he said that the benefits of using light colored materials should be substantial. Christie also commented on how the type of luminaire can be changed to overcome problems involving smaller brightness patches. On skid resistant coarse surfaces, he suggested that high angle beam luminaires are not very satisfactory and medium angle luminaires with maximum intensity at 75 to 78 degrees are preferred.

Finch and King (1967) appear to have introduced the first direct reading reflectometer for roadway lighting purposes. Until then, reflective characteristics of pavements were evaluated using visual photometry and other photographic techniques. This device allowed full flexibility in changing all three angles relating to reflectivity. It operated on 115-volt AC power, and it used a stray light rejection curve for the telephotometer where the light acceptance angle was approximately 3 minutes. The problem associated with this device is that it took approximately 3 hours to set up the equipment at site and another hour to take one set of reflection data corresponding to a set of angles. If measurements were taken at 5° intervals for the vertical source inclination and the horizontal angle, it would result in 864 readings at one location and require 864 hours of data collection. King and Finch (1968) later developed a reflectometer for use in the laboratory where 12-inch diameter pavement cores were used to simulate the pavement. By automating the data collection procedure, they were able to make rapid automatic readings of the directional reflectance factor, thus enabling the collection of large volumes of data over a very short time. This device was able to simulate up to 600 feet of viewing distance. One significant feature of this reflectometer was that the color response was corrected to approximate that of the human eye.

Even after the development of their automated pavement reflectance measurement device, King and Finch (1968) observed that there was little application of it outside the research laboratory, primarily due to the specialized nature and complexity of calculations involved. They suggested that one way to expand the use of reflectometry is to use a pavement surface classification system and proposed that the classification be based on directional reflectance properties of the pavement surface.

Towards the latter part of the 1970s, the University of Toronto (Jung et al. 1984) built a photometer for the road surface reflectance measurement based on concepts developed earlier by CIE (1976). This reflectometer features automated control of positioning and reading and recording data. It is capable of testing pavement cores 6 to 8 inches in diameter and at least 3 core samples from a given pavement are required to classify the pavement type. Jung et al. (1984) conducted a study to measure reflectance properties of many types of pavements in Ontario. The measurements were made on 6-inch diameter cores taken from 36 different pavements where more than 400 core samples were processed. When factors such as traffic level and the position of the lane were considered, this accounted for about 100 different surface types.

Pavement surfaces were classified based on the average luminance coefficient  $Q_0$ , and the ratios  $S_1$  and  $S_2$  as defined by IES Roadway Lighting Committee (1976).  $Q_0$  is considered as a measure of the overall brightness of the pavement as it appears to the viewer, whereas  $S_1$  and  $S_2$  describe the degree of specularity of the pavement surface. Over the years, two systems of four standard reflectance tables have been proposed for dry pavements. These two systems are indicated by “R-Series” and “N-Series” classifications. This Guide adopts the R-Series classification for its pavements and its features are indicated in Table A-1.

## Theoretical Basis for “R-Series” Classification of Pavement Surfaces

The classification is based on specularity of the pavement as determined by a ratio,  $S_1$ , and a scaling factor,  $Q_0$ , as determined by the overall “lightness” of the pavement. The normalized  $Q_0$  is given in table 18.2 for each of the pavements described. Greater accuracy in predicting pavement luminance can be achieved by evaluating specific pavements as to their  $S_1$  ratio and specific  $Q_0$ , and then choosing the correct R-table.

The  $S_1$  ratio and specific  $Q_0$  for a pavement can be determined in one of two ways:

- A core sample can be removed from the pavement and photometered by a qualified laboratory.
- A field evaluation can be made.

The characteristics  $S_1$  and  $Q_0$  were adopted by CIE as basic quantities for evaluation of the reflection properties of a road surface (CIE Publication 30, 1976). The average luminance coefficient (scaling factor)  $Q_0$  is given by the following equation as a measure of the lightness of a road sample:

$$Q_0 = \frac{1}{\Omega_0} \int_0^{\Omega_0} q(\gamma, \beta) d\Omega \quad (\text{A-6})$$

In the formula 18-6,  $\Omega_0$  is the relevant solid angle of incident light at a specified point on the road.  $\Omega_0$  is defined by a rectangular 'ceiling' at the mounting height  $h$  extending  $3h$  to the right and left to the specified point,  $4h$  toward the observer and  $12h$  behind the specified point. The special quantity  $S_1$  given by:

$$S_1 = \frac{r(\tan \gamma = 2, \beta = 0)}{r(\gamma = 0, \beta = 0)} \quad (\text{A-7})$$

The angles  $\gamma$  and  $\beta$  are as shown in Figure A-4.

This function is derived from the angular distribution of the reduced luminance coefficient to indicate the shape of the reflection indicatrix:

$$r(\gamma, \beta) = q(\gamma, \beta) \cos^3 \gamma \quad (\text{A-8})$$

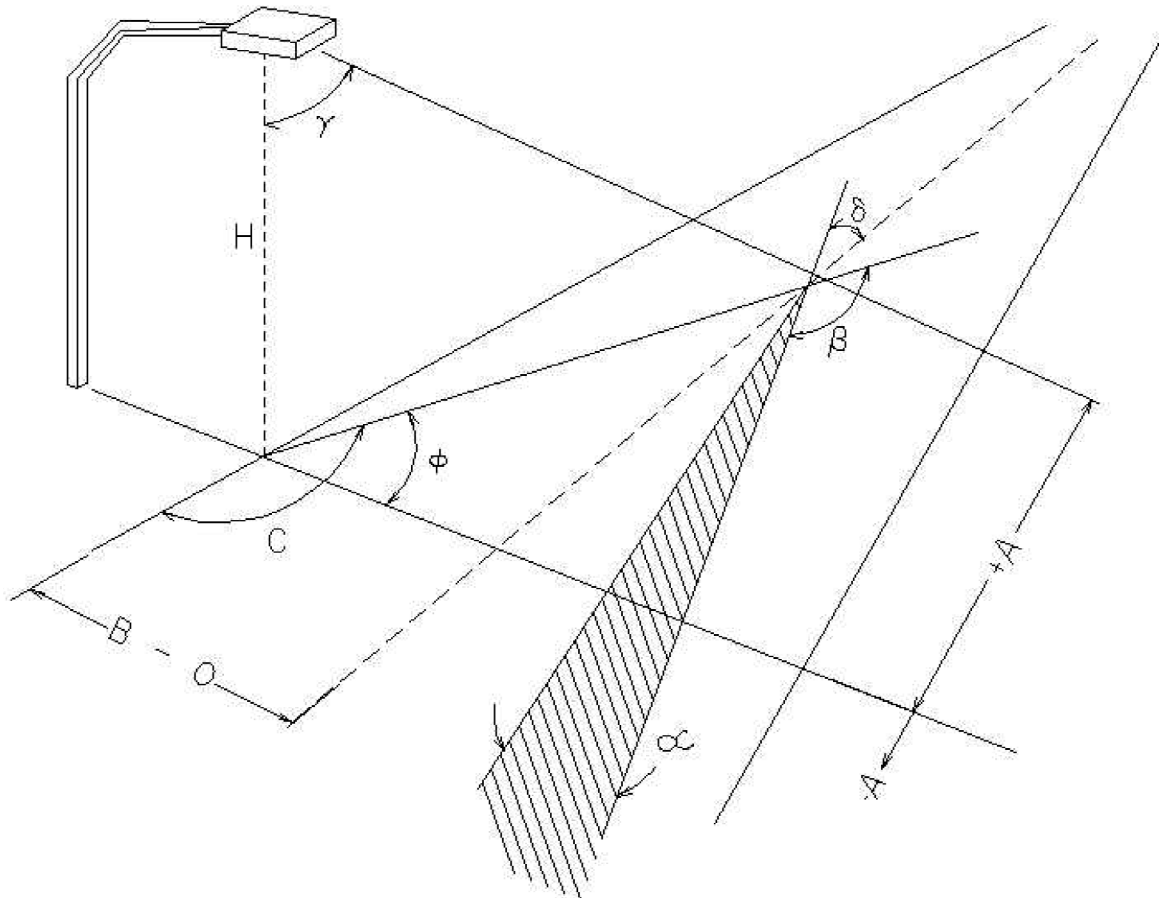


Figure A-4. Schematic diagram of roadway lighting.

It was found that  $Q_0$  is highly correlated with the average luminance  $\bar{L}$  on the road as follows:

$$\bar{L} = \frac{1}{A} \int_0^A L_p dA \quad (\text{A-9})$$

where  $L_p$  is the luminance at point P and A is the relevant portion of the road area (usually restricted to one luminaire spacing).

Based on calculations of 24 road surfaces, 24 luminous intensity distributions, and 72 one-sided lantern arrangements, the correlation coefficient between reflection characteristic  $Q_0$  and average luminance  $\bar{L}$  was found to be 0.96 (Schmidt, 1986). Bodmann and Schmidt (1986) conducted field experiments to compare calculated and measured luminance characteristics. The reflection characteristics,  $Q_0$ , were measured with the LTL 200 portable road surface reflectometer.

The average luminance  $\bar{L}$  was measured with the portable luminance meter. On average, the calculated values for  $\bar{L}$  were found to be 31% higher than the measured values. The experimenters estimated the results as a reasonable estimate. If one takes into account maintenance factors such as the decrease of light output with age and deterioration of reflecting and transmitting materials of the luminaires, the agreement between calculated and measured luminance can be evaluated as perfect.

Table A-1 identifies the values for the three reflectance parameters  $Q_0$ ,  $S_1$ , and  $S_2$ . The N-Series classification was developed in Germany by Erbay (1974). One note of caution by CIE was that variation of  $Q_0$  within one pavement class might be very high, so the  $Q_0$  value given within the standard must be scaled to correspond to the  $Q_0$  of the actual surface being chosen.

**TABLE A-1. Reflectance Parameter Values for “R” and “N” Classifications (Jung et al. 1984)**

Parameter	R-Series				N-Series			
	R1	R2	R3	R4	N1	N2	N3	N4
$Q_0$	0.10	0.07	0.07	0.08	0.10	0.07	0.07	0.08
$S_1$	0.25	0.58	1.11	1.55	0.18	0.41	0.88	1.61
$S_2$	1.53	1.80	2.38	3.03	1.30	1.48	1.98	2.84

### Pavement Reflectance Studies

Table A-2 outlines the range of Log ( $S_1$ ) values obtained for three different types of coarse aggregates. Jung et al. (1984) attributed the different values to different levels of resistance to polishing under traffic. This data quite clearly indicated a relationship between the  $S_1$  ratio and the type of coarse aggregate used on the pavement surface.

**TABLE A-2. Relationship between Coarse Aggregate on Pavement Surface and  $S_1$  (Jung et al. 1984)**

Coarse Aggregate	Range of Log ( $S_1$ )
Igneous or Trap Rock	-0.29 to -0.17
Limestone	-0.10 to -0.06
Blend of the Above Two Aggregates	-0.23 to -0.08

As for  $Q_0$ , a wide scattering of values was observed. Table A-3 outlines the range of  $Q_0$  values obtained for three different types of coarse aggregates. Jung et al. (1984) attributed the different values to different brightness levels of aggregate and on a concurrent increase in specularity of the surface. The appropriate value to be used in design depends on the road surface materials, their composition and changes to the pavement surface with time and traffic exposure. Jung et al. (1984) also noted that with time, asphalt pavements tend to brighten and Portland cement concrete tends to darken. They also observed that with coarse aggregates that are polishable due to traffic, there might be a shift in the specularity class, for instance from R2 to R3.

**TABLE A-3. Relationship between Coarse Aggregate on Pavement Surface and  $Q_0$  (Jung et al. 1984)**

Coarse Aggregate	Range of Log ( $Q_0$ )
Dark Trap Rock	0.074 to 0.088
Bright Limestone	0.102 to 0.124
Blend of the Above Two Aggregates	0.086 to 0.097

Some notable observations made by Jung et. al, (1984) included changes in specularity between different lane wheelpaths and that asphalt pavements become more specular as reflected with increased values for  $Q_0$ ,  $S_1$ , and  $S_2$ . In the end, it was reported that with regard to specularity only, the four pavement classes were regarded as sufficiently accurate for design purposes. However, the authors cautioned that, due to high variability observed,  $Q_0$  should be estimated more accurately by considering the surface course composition and the aggregate type. Nevertheless, based on their extensive measurements of pavement reflectivity, the authors published recommended (and amended) design values for different combinations of coarse aggregate type and mix design commonly used in Ontario, Canada.

Bodmann and Schmidt (1989) showed the marked variation in the reflection characteristics of road surfaces with time and traffic and highlighted some problems associated with the CIE recommended standard classes of pavement surfaces. They also pointed out that the decision on the class of surface to be used in the design is often based on assumptions and the standard r-table represents the individual road surface irrespective of temporal and local variations due to age and wear. Furthermore, the authors indicated that the classification of surfaces into four CIE “R” classes is justified neither by test calculations nor by measurements on real streets. Based on these observations, the authors highlighted the positive aspects of the “C-Series” classification where only two standard surfaces are considered. The two classes of pavement surfaces are C1 and C2, C1 corresponds to the R1, and C2 corresponds to R2, R3, and R4 in the “R-Series” classification. The authors contend that the “C-Series” classification for dry road surfaces is more realistic and much more practicable. However, even under the “C” classification, the prediction of  $Q_0$  remains a problem at the design stage.

Nielson et al. (1979) studied the reflectance characteristics of 41 different road samples, 24 of which were asphalt concrete, and the rest were hot rolled asphalt with coated chippings. The surface materials were cast into 30 cm × 35 cm rectangular specimens and were tested in the laboratory. In addition to the mix type indicated above, the maximum size of the aggregate, aggregate type, and the climatic conditions were included in the experimental design. The results from this study can be summarized as in Table A-4.

**TABLE A-4. Summary of Observations by Nielsen et al. (1979)**

Factor(s) Investigated	Conclusions and Observations
Parameter Relationships	$Q_0$ and $S_1$ are inversely correlated. Retroreflection $Q_R$ does not change significantly with the observation distance. Specular reflection $Q_S$ on dry roads increases with meeting distance to oncoming vehicle. Specular reflection $Q_S$ increases from dry to wet pavement by a factor of two. For worn samples, $Q_0$ and $Q_R$ are directly correlated.
Surface Wear	The brightness measured by $Q_0$ and $Q_R$ develop slowly with wear. Residual bitumen (after aggregate is polished) increases $S_1$ . Reflection properties increased slightly when summer tires are used, but improved during subsequent exposure to studded tires.
Composition	Brightness of aggregate affects $Q_0$ and $Q_R$ . Brightness not affected by coarseness of aggregate.

According to Bodmann and Schmidt (1986), if a decision has to be made as to whether or not a particular road lighting installation meets prescribed values, the tolerance  $(1 \pm 0.1)\bar{L}$  can be recommended.

Analysis of computer predicted luminances was conducted by (Janoff, 1993). The illuminance calculations performed in the past using computers were quite accurate when given all input parameters. However, in 1983 the roadway lighting standard changed based primarily on pavement luminance (Janoff, 1993). This change brought about more complex calculations. It also required the exact reflectance properties of the pavement surface. This made the computer programs accuracy very dependent on factors such as the r-tables, the formulae for computing pavement luminance, lighting geometry, and the luminaire intensity distribution (Janoff, 1993). A standard practice based on visibility was proposed in 1990 (Janoff, 1993). The visibility level (VL) can be determined using photometers to measure target luminance, pavement luminance, and veiling luminance. A predictive computer program thus becomes an important tool for deriving target, pavement, and veiling luminances for a road lighting design in progress. In 1992, the only predictive computer program available was STV. A study was performed to compare the target, pavement, and veiling luminances, as well as VLs, to measured values. This experiment consists of two different targets. Each target was a 7 inch square, with one placed upstream of the closest luminaire and one downstream (Janoff, 1993). The targets consisted of three different reflectances: 5, 30, 80%. During this study there were 48 measured points. For accurate measurements all street lights were cleaned, aligned, and 12 new calibrated lamps were installed closest to the target locations. The results indicated that the predicted values did not match up with the measured values. There were significant differences between the target, pavement, and veiling luminances (Janoff, 1993). For example, during one experiment the veiling luminance ( $L_v$ ) was measured and predicted at 275 feet for each target. The results are shown in Table A-5.

**TABLE A-5. Veiling Luminance**

Variable	Target Reflectance	Target Position	Measured	Predicted	Result Ratio
$L_v$	—	1	2.10	0.16	13.1
$L_v$	—	2	2.86	0.22	13.0

The measured value at target position 1 was 2.10 and the predicted value was 0.16. It was concluded that “. . . many of the problems may not be in the computational parts of STV, but rather in the (inaccurate) choice of r-tables, choice of nominal target reflectance, specification of proper candlepower distribution, or failure to include light reflected from pavement onto target.” (Janoff, 1993).

An effect of headlights on luminance and visibility was studied experimentally. There are at least two relevant parameters to consider in roadway visibility. The first is headlight intensity in the direction of the road ahead, and the other is the intensity in the direction of the eyes of the driver (Alferdinck et al. 1988). A study was performed to evaluate the increase of visibility due to the addition of vehicle lighting. A number of measurements were made under 20 different lighting conditions to determine increases in visibility. The reported measurements taken used 5, 30, and 80% target reflectances. The measurements were taken with and without headlighting. Measurements were taken first at 75 feet then every 50 feet up to 275 feet; then they were taken every 100 feet up to 775 feet. The study concluded that at distances less than 275 feet, there is a significant change in photometric visibility resulting from headlights (Janoff, 1992). However, at distances greater than 275 feet there is no effect of headlights on either small target visibility or recognition distances derived from subjective estimates provided by the drivers (Janoff, 1992).

Adrian et al. (Unpublished Data) studied the influence of light reflecting from the road surface on to the target on STV. Their results showed that this indirect portion of illuminance can contribute up to 15% of the total target illuminance. This will significantly alter the *Visibility Level* (VL) required to see the target under positive contrast.

**A.4. REFERENCE SUMMARY**

No.	RP-8 Ref.	Reference	Abstract	Assumption/ Limitation	Main Conclusions
1	1	<b>Uniformity of Illumination in Highway Lighting</b> , D. M. Finch and A. E. Simmons (1950), <i>Journal of the IES</i> 45, p561, Univ. of California, Berkeley.	A review of design procedures adopted by many highway departments and local government agencies are analyzed in terms of parameters associated with good lighting design. A simple method was developed whereby the designer could quickly get all essential design information.	Glare not considered.	When recommended procedures such as the average illumination are used, wide variations in roadway illumination and brightness pattern may result even though the average illumination is maintained. Minimum illumination criterion should be used rather than the average.
2	3	<b>Comparison of Accidents and Illumination</b> , Paul C. Box, (1972), <i>HRR 416</i> , pp.1–9, Syracuse, NY.	The economic impact on the city of Syracuse for upgrading street lighting to national standards is determined. The methodology developed during this research may be the state-of-the-art for similar future studies.	Street light glare and ambient light not considered.	Street classification appears to be more significant in accident-illumination relations than the abutting land use classification. Streets with high illumination levels tended to have above-average night-day accident ratios and accident cost ratios.
3	5	<b>The Relationship Between Road Lighting Quality and Accident Frequency</b> , P.P. Scott, (1980), <i>TRRL Laboratory Report no. 929</i> . London, U.K.	An investigation of a wide range of measures of lighting quality was conducted to determine which were most clearly related to accident frequency. Also, a sufficient number of sites were selected to establish relationships with reasonable high confidence.	Day/Night accident frequencies would equally reflect between site variations in all factors other than road lighting quality. Analysis is limited to dry road surfaces and major two lane roads with speeds > 30 mph.	Average luminance is strongly related to accident ratio. An increase of 1 cd/m <sup>2</sup> result in a 35% lower accident ratio. A non-pedestrian accident ratio correlated well with average luminance and overall uniformity. A significant relationship with average luminance was found for minor accidents.
4	7	<b>The Specification of Street Lighting Needs</b> , V. Gallagher, B. Koth and M Freedman (1975). FHWA Rep. RD-76-17 Franklin Institute, Philadelphia.	Objectives of the study were to: <ul style="list-style-type: none"> <li>• Develop a visibility metric for roadway lighting design,</li> <li>• Determine the precision of this metric as a measure of driver visual performance,</li> <li>• develop spec. for driver visibility needs,</li> <li>• develop a method to predict visibility with lighting geometry, luminaire specs and pavement type</li> </ul>		

No.	RP-8 Ref.	Reference	Abstract	Assumption/ Limitation	Main Conclusions
5	8	<p><b>Effectiveness of Highway Arterial Lighting</b>, M. S. Janoff, B. Koth, W. McCunney, M. Freedman, C. Durek and M. Berkovitz (1977), FHWA Report RD-77-37 Franklin Institute, Philadelphia</p>	<p>Cost-benefit analyses of arterial highway lighting treatments were conducted with regard to traffic safety and energy usage. Regression equations were developed to predict nighttime accident history based on population density, area classification and visibility. A design guide was prepared to assist in conducting cost-benefit analysis of lighting improvements.</p>		<p>Total nighttime dry-weather accidents are inversely proportional to visibility. HPS luminaires are more cost beneficial than mercury luminaires. However, both types provide a cost/benefit ratio greater than 1. When visibility and accident reduction are constraints, 400W HPS luminaires gave optimum designs. When cost and energy use are constraints, 150W HPS luminaires gave optimum designs.</p>
6	9	<p><b>Cost-Effectiveness Evaluation of Rural Intersection Levels of Illumination</b>, Kyle A. Anderson, Weldon J.Hoppe, Patric T.McCoy, Ramon E. Price, (1984), <i>TRR 996</i>, pp. 44-47. Omaha, Nebraska</p>	<p>There are no generally accepted design criteria that define the levels of illumination required at rural intersections. The objective was to evaluate the cost-effectiveness at different levels of illumination.</p>		<p>At each wattage level, traffic operations were safer under a two-luminaire system than they were under a one-luminaire system. Two 200-watt HPS had the lowest total annual cost at intersections with main highway ADT &gt; 3750 No lighting system was warranted at ADT &lt; 3250</p>
7	10	<p><b>Freeway Lighting and Traffic Safety—A Long Term Investigation</b>, R. Lamm, J. M. Kloeckner and E. M. Choueiri, (1985), <i>TRR 1027</i>, pp.57-63. Frankfurt, Federal Republic of Germany.</p>	<p>A case study on traffic accident characteristics was conducted that utilized a suburban freeway area in Germany to assess the effectiveness of freeway lighting.</p>	<p>The savings in energy costs after switching off lights as compared with savings in accident costs was not determined (it deals only with safety)</p>	<p>Accident rates were reduced due to lighting and increased after lights were switched off at night to save energy (Partial Lighting).</p>
8	11	<p><b>Effects of Turning Off Selected Roadway Lighting as an Energy Conservation Measure</b>, Stephen H. Richards, (1981), <i>TRR 811</i>, pp. 23-25. Austin, Texas.</p>	<p>To save energy, continuous roadway lighting were turned off and two years of before-data and two year of after-data were collected and analyzed.</p>	<p>Ramp and frontage road lighting were excluded. Little conclusive data on public reaction to light cut back.</p>	<p>The savings in power consumption associated with a cut back are offset to a large extent by a significant increase in accident frequency and severity.</p>

No.	RP-8 Ref.	Reference	Abstract	Assumption/ Limitation	Main Conclusions
9	13	<p><b>Fifteen Years of Road Lighting in Belgium,</b> G.De Clercq, (1985), <i>ILR 36(1)</i>, pp. 2–7.</p>	<p>Data were studied during the 12 months prior to and 12 months following the introduction of energy saving measures.</p>		<p>In all cases saving measures unfavorably influenced the accident patterns.</p>
10	14	<p><b>Accident Analysis on Two Non-Controlled Access National Highways in Greece,</b> John M. Frantzeskakis, (1983), <i>ITE Journal 53(2)</i>, pp.26–32.</p>	<p>The main findings of two accident analysis studies conducted on two highway sections of Greek National Roadway Network are presented.</p>		<p>Overall accident rates increase during winter, week ends, at night and at the period before sunset. It is considered more appropriate to correlate accident rates to levels of service instead of traffic volumes.</p>
11	18	<p><b>Subjective Ratings of Visibility and Alternative Measures of Roadway Lighting,</b> Michael S. Janoff, (1988), <i>Journal of the IES 18(Winter 1989)</i>, pp.16–28, Christianburg, VA.</p>	<p>A series of panel rating experiments were conducted that provided measurements of the subjective appraisal of visibility for a wide range of lighting conditions.</p>	<p>The roadway surface was new bituminous concrete. The (log) transformed linear regression technique has been applied in all analyses relating to VI and VL to mean panel rating (MPR) which may not be the best form.</p>	<p>VI and VL are highly correlated with MPR but for VI, both target size and contrast conditions, and for VL, only the target contrast affects the form of relationship. Contrast has a much larger effect on visibility than luminance.</p>
12	19	<p><b>The Effect of Visibility on Driver Performance: A Dynamic Experiment,</b> Michael S. Janoff, (1989), <i>Journal of the IES 19(Winter 1990)</i>, pp. 57–63. Philadelphia.</p>	<p>A dynamic experiment was conducted to determine two driving performance measures; detection distance (DD) and recognition distance (RD).</p>	<p>All luminance measurements were made at fixed distances from the target.</p>	<p>Contrast, VI and VL are highly correlated with DD and RD. It appears that VL=2(VI) for small targets. Relationships are better if the data sample is restricted to only negative contrast conditions. VL is superior under 2-200 watt HPS per pole 200 ft. opposite system.</p>
13	13	<p><b>The effect of Headlights on Small Target Visibility,</b> Michael S. Janoff, (1992), <i>IES Journal 21(2)</i>, pp. 46–53 Philadelphia.</p>	<p>The relative effect of roadway lighting and roadway lighting in combination with low beam vehicular lighting on photometric visibility and on distance at which drivers can detect and determine the orientation of a small target placed on road surface were determined.</p>	<p>All measurements were made at distances from the target of 75 to 775 ft.</p>	<p>At a distance greater than 275 ft. there is generally no effect of headlights. At distance less than 275-ft. headlights may increase recognition distances in positive contrast but no such relationship found for negative contrast.</p>

No.	RP-8 Ref.	Reference	Abstract	Assumption/ Limitation	Main Conclusions
14		<b>Standard Target Contrast: A Visibility Parameter Beyond Luminance to Evaluate the Quality of Roadway Lighting,</b> F. W. Jung and A. Titishov, (1987), <i>TRR 1111 pp. 62-71.</i> Ontario Ministry of Transp. & Communications, Canada.	A less sophisticated parameter to represent a visibility index that can easily be computed at each road location on the roadway surface by using only the physical dimensions and properties of the lighting system, is proposed.	20 cm × 20 cm middle gray card (perfect diffuser) of 20% reflectance is kept 80-100 m away from the driver.	With symmetrical luminaires the overlapping of the main beams is important to avoid spots with low or zero contrast. Increased negative contrast can be achieved with non-symmetrical luminaires directed toward the driver without having main beams touch or overlap and with good distribution of luminance.
15		<b>A Proposed Procedure for Predicting Performance Aspects of Roadway Lighting in Terms of Visibility,</b> O. M. Blackwell and H. R. Blackwell, (1976), <i>Journal of the IES (April 1977), pp. 148-166.</i> Institute for Research in Vision, Ohio State Univ., Columbus.	A method was developed to specify roadway lighting required to provide the visibility needed for driver performance by using a 15:1 scale model roadway in both concrete and bituminous pavement.	To measure $V_{L_{eff}}$ transient adaptation factor (for moving eye) is neglected because of the absence of an agreed upon method to measure it.	Disability glare factor to measure $V_{L_{eff}}$ has little effect. Physical contrast measures based on "average contrast" formula (excluding shadow) is found to be the best predictor of visibility.
16		<b>Reflection Properties of Road Surfaces in Headlight Illumination. Dependence on Measuring Geometry,</b> National Swedish Road and Traffic Institute, (1982), <i>Nordic Research Cooperation for Night Traffic, Report No. 4, 1982,</i> Linköping, Sweden.	This investigation concerns the dependence of the geometry on the specific luminance of road surfaces in headlight illumination. The analysis of data is based on model considerations of the reflection leading to expressions for the influence of geometry.	The surface can be divided into a large number of small, plane facets.	SL will be the same function of the angles for most road surfaces. SL's for humid conditions are a fraction of the SL's for the dry condition. The accuracy of the complete description system, as based on an assumed standard geometry of 50-meter spacing is found to be acceptable.
17		<b>Methodology for Determining Pavement Reflectivity for Roadway Luminance Calculation,</b> R. N. Helms (1983), <i>TRR 904,</i> Univ. of Colorado, Boulder.	This paper describes the instrumentation and methodology for making automated in-situ pavement reflectance measurements using gonio-reflectometer.	No presentation of data or analysis results because problems with reflectometer electronics invalidated the data.	Study incorporated factors such as surface macrotexture and microtexture, aggregate size, surface finish, grading, mixture design and climatic conditions. Recommends reporting of complete hemispherical data rather than reduced luminance coefficients.

No.	RP-8 Ref.	Reference	Abstract	Assumption/ Limitation	Main Conclusions
18		<b>Light Reflection by Road Surfaces</b> , <i>Mededeling 53</i> , (1984), Germany	This paper is the result of a long-term study of the relationship between the light reflection properties and civil engineering properties of the pavement. 423 dry pavement surfaces in Eindhoven, Copenhagen and Berlin were investigated.		A new pavement reflectance parameter system SCW-KEMA, (similar to the CIE-R and CIE-N systems) is introduced. It is recommended that a one- or two-parameter system is sufficient to characterize a pavement. These parameters can be $S_1$ and $Q_p$ . The authors also recommend that two groups of road surfaces (instead of four in CIE-R) be used. From a photometric standpoint, a preferred road surfaces can be defined by $S_1 \leq 0.4$ and $Q_p \geq 0.8$ Cd/m <sup>2</sup> /lux. These properties are given by: <ul style="list-style-type: none"> <li>• Asphalt pavements with at least 30% mineral aggregate consisting white chippings</li> <li>• Portland cement concrete pavements</li> <li>• Surface treatments with white chippings</li> </ul>
19		<b>A Standard Practice for Roadway Lighting Based on Driver Performance</b> , Michael S. Janoff, <i>Journal of IES</i> , 19(1), 1990.	Alternative approaches to Table 2 luminance values in IES RP-8 (1983) are considered because existing values are not based on proven research. The alternative approaches are based on panel rating experiments conducted in Christianberg, VA, in 1987. Also, field experiments were conducted in Philadelphia to determine the time separation gap or TTT.	Assumption: A maximum of 80% performance (reliability) is required for complex driving conditions.	Equations were developed for negative contrast relating required visibility index with driver performance level (reliability).
20		<b>Visibility VS. Response Distance</b> , Michael S. Janoff, <i>Journal of IES</i> , 22(1), 1993	Expressions for total stopping distance is developed based on speed, VI and VL.	A one-second correction to the reaction time is adopted to convert Gallagher's data (drivers not alerted) to compare with Janoff's data (drivers alerted).	Equations are developed for a 2 second reaction and response time in addition to the braking time (distance)

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## Appendix B Lighting Basics

### Purpose of Roadway Lighting

The general purpose of roadway lighting is to provide improved safety, security, and aesthetics for the various users of the roadways and associated facilities.

*User.* The term users may include vehicle operators (autos, trucks, buses, motorcycles, bicycles), pedestrians, and other citizens of the community.

*Roadway.* Roadways are defined as freeways, highways, and city streets of various types.

*Associated Facilities.* Associated facilities include appurtenances of a traffic and non-traffic nature. Traffic appurtenances include physical features along the roadway such as traffic barriers, bridge piers, roadside ditches, curbs, channelization, etc.

Identifying roadways that need lighting and designing lighting systems to improve driver visibility requires an understanding of what drivers need to see. Driving safely and efficiently requires a constant flow of information relative to the roadway, traffic, and environmental conditions.

### Physical Characteristics of Light and Vision

#### *Light as Radiant Energy*

Light may be defined as that portion of the electro-magnetic spectrum detectable by human vision—between 380 nanometers (nm) and 780 nm. The detection of radiant energy within those limits depends on many factors, including the relative sensitivity of the eye to the incident flux. While the unit of radiant power is the watt, the unit used to describe the effective power of light is known as the *lumen* (lm). The lumen is a measure of the time rate of flow of radiant energy into the eye, multiplied by the sensitivity of the eye, for each wavelength of the incoming radiant energy.

Knowledge of the luminous flux (total lumen output) of a source does not provide information on the distribution and eventual usefulness of the emitted light, nor is it instructive regarding our perception of the light source. The *luminous intensity* of a light source is a measurement of the luminous flux of the source in a given direction, per unit solid angle (steradian), in units of *candela* (cd). The *illuminance* is a measurement of the total luminous flux striking or passing through a given area. Illuminance is measured in lumens per area—either lux ( $\text{lm}/\text{m}^2$ ) or footcandles ( $\text{lm}/\text{ft}^2$ ), abbreviated fc. Thus, the amount of light striking a road surface from a system of fixed roadway lighting luminaires is the illuminance provided by the luminaires. When light is emitted from an extended area, such as from a fluorescent lamp fixture or light reflected off a wall or road surface, the eye cannot sum all of the observed flux into a single value of luminous intensity. Instead, the eye reacts to the luminous intensity emitted in the direction of the observer over some discrete observation area. For measurement purposes, we speak of the *luminance* of a source, which is the luminous intensity per unit area of the source, in units of  $\text{cd}/\text{m}^2$  or  $\text{cd}/\text{ft}^2$ . Luminance is often described as the “brightness” of an object; however, the two are very different. Luminance is a

physical phenomenon, and is independent of the observer or surrounding conditions. Brightness is a physiological phenomenon used to describe the sensation of what is perceived. It depends on the adaptation of the eye and the relative luminance of the object and its surroundings. For example, the moon looks bright against the dark night sky and dim when seen against the daytime sky but its measured luminance is a constant value. When assessing colors, the saturation of the color—that is, how nearly monochromatic the stimulus is—also influences the sensation of brightness.

Note that luminous intensity is a measurement of the light emitted from a source in a given direction, per steradian, and does not change with the distance from the source. The illuminance provided by a light source is, however, dependent on the area illuminated. As the source is moved towards or away from a given surface the illuminated area changes and the illuminance, likewise changes. The luminance of a source is the luminous intensity emitted by a unit area of the source *in a given direction, and does not change with distance.*

## Transmittance

The luminous transmittance of a substance is a measure of its capability to transmit light through the material. The nomenclatures for luminance transmittance are:

- transmittance
- transmission factor
- coefficient of transmission
- transmission coefficient.

These terms are used interchangeably. The transmittance is the ratio of the total transmitted light to the total incident light. Transmittance must be used cautiously because materials may be wavelength selective in transmitting light; so a spectral analysis of incident and transmitted light is sometimes called for if a material is selective in a wavelength of interest. For this study, the wavelengths of interest are restricted to visible light, so we will easily recognize a wavelength selective filter. In general the transmission coefficient should refer to materials displaying non-selective absorption characteristics.

## Reflectance

The ratio of reflected light to incident light is referred to by any of the following:

- reflectance
- reflectance factor
- reflectance coefficient.

Reflectance is a measure of the light that bounces off a surface and is not transmitted. If half of the incident light is bounced off the surface, the surface reflectance coefficient is 0.5 or 50%. If a beam of light reflects from a smooth surface, the reflection is known as specular and reflects away from the surface as a single beam of light. If the surface is very rough, the reflections for a beam of light are scattered by the multifaceted surface. The light reflects in all directions away from the surface, and the reflection is called diffuse.

## Refraction

The speed of light in a material,  $v_m$ , and the speed of light in free space,  $c_o$ , are related to the index of refraction,  $n$ , by the following:

$$n = \frac{c_o}{v_m} \tag{B-1}$$

The index of refraction,  $n$ , is always greater than 1; therefore,  $v_m$  is always less than,  $c_o$ .

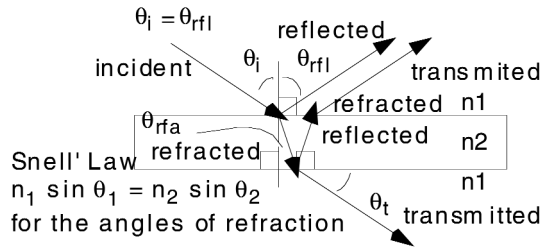


Figure B-1. Specular ray tracing model.

- Incidence radiation,  $I_o$ , @ Incidence angle,  $\theta_i$ ,
- Reflected radiation,  $I_{rf1}$ , @ Reflected angle,  $\theta_{rf1}$ ,
- Transmitted radiation,  $I_t$ , @ Refracted angle,  $\theta_{rfa}$ ,
- The angle of incidence is equal to the angle of reflection,  $\theta_i = \theta_{rf1}$ .

Refraction takes place at a boundary where indices of refraction change. The incident angle and the refracted angle are related by Snell’s Law, and reflect differences in speeds of light in the respective mediums.

Snell’s Law:  $n_1 \sin \theta_1 = n_2 \sin \theta_2$ .  
 Transmission angle,  $\theta_t$ ,

**Absorption**

Each time refraction takes place at a boundary, a portion of the incident light passes from medium,  $n_1$ , to medium,  $n_2$ , and the portion is transmitted. If the material is glossy some of the energy is converted from visible radiation to infrared radiation (heat) and lost (from the visible spectrum). The losses are absorption losses.

Absorption losses are exponential with distance such that

$$I(x) = I_o e^{-kx} \tag{B-2}$$

where

- $I_o$  is the incident radiation entering the material
- $x$  is the distance traveled through the material
- $k$  is the loss coefficient for the material
- $e$  is 2.718281 . . .

Absorption losses are losses due to energy transformation from higher energy, visible light to lower energy, infrared non-visible light. Changing the radiation from the visible spectrum to the non-visible spectrum is thought of as a loss to the visible spectrum and a loss to an observer.

**Diffusion**

Diffuse reflections are due to first surface roughness and reflections at the boundary surface.

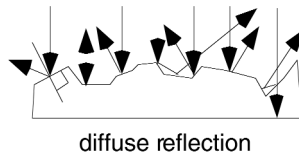


Figure B-2. First surface diffuse reflections.

Diffuse transmissions are due to second surface roughness and refraction at the second surface boundary.

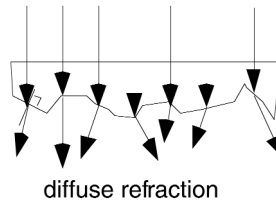


Figure B-3. Second surface diffuse refraction and transmissions.

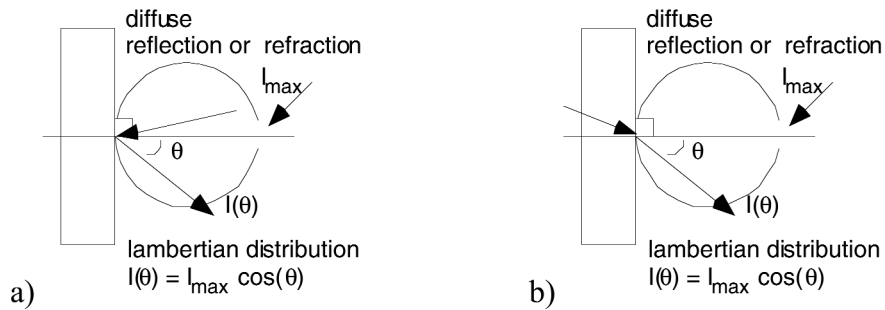


Figure B-4. Lambertian reflection or refraction/transmission distribution.

Lambertian distribution,  $I(\theta) = I_{max} \cos(\theta)$ , is a diffuse reflection distribution or refraction distribution due to the surface characteristics of a material. The roughness of the surface determines the reflection and refraction directions.

Surfaces are not flat, so the reflections, refractions, and transmissions have a partial specular characteristic and a partial diffuse characteristic as shown in Figure B-5.

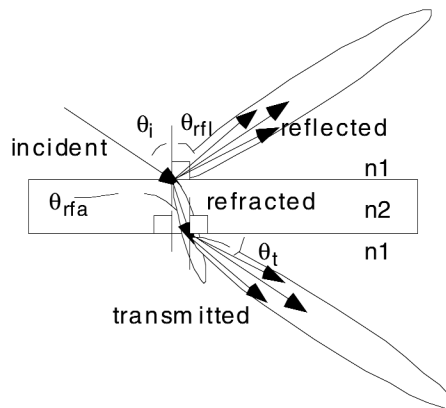


Figure B-5. Reflection and transmission distributions.

Most surfaces are somewhat smooth and somewhat rough, so we get both a diffuse reflection and a specular reflection. The reflectance is a measure of the total light reflected from the surface of any material. The reflectance does not depend on whether the surface is diffuse or specular; all the reflected light is measured. The ratio of incident light lost in a material is called the absorption coefficient. The absorbed light is not lost, it is simply changed from visible wavelengths to lower energy, non-visible wavelengths usually in the infrared. The sum of the transmitted, reflected, and absorbed light is equal to the incident light. The transmitted light may also be diffused after it passes through some material, but the total amount of light passing through the material is used in the transmission measurement to determine the transmission coefficient. Just as the total reflected light is used in the reflectance measurement to obtain the reflection coefficient.

## Vision and Visibility

Humans rely primarily on visual information to interact with their environment.

## Anatomy of the Eye

The process of vision begins with the eye, the sensory organ responsible for detection of light. The photoreceptors within the eye are located in the *retina*, a thin covering on the back, inner surface of the eye. There are two types of photoreceptors, rods and cones, which form the basis of two-receptor systems.

While the processes that link detection of a visual signal within the eye to comprehension of that signal by the brain are not well understood, there are models that provide good correlation between stimuli and reported observations. One precept for these models is the *duplicity theory* of vision, which postulates that the receptor systems of the rods and cones are independent, with their own particular properties. Note that detection of a visual stimulus is evaluated over the entire receptor system, including the receptors and the neural network that processes, encodes, and transmits signals to the brain.

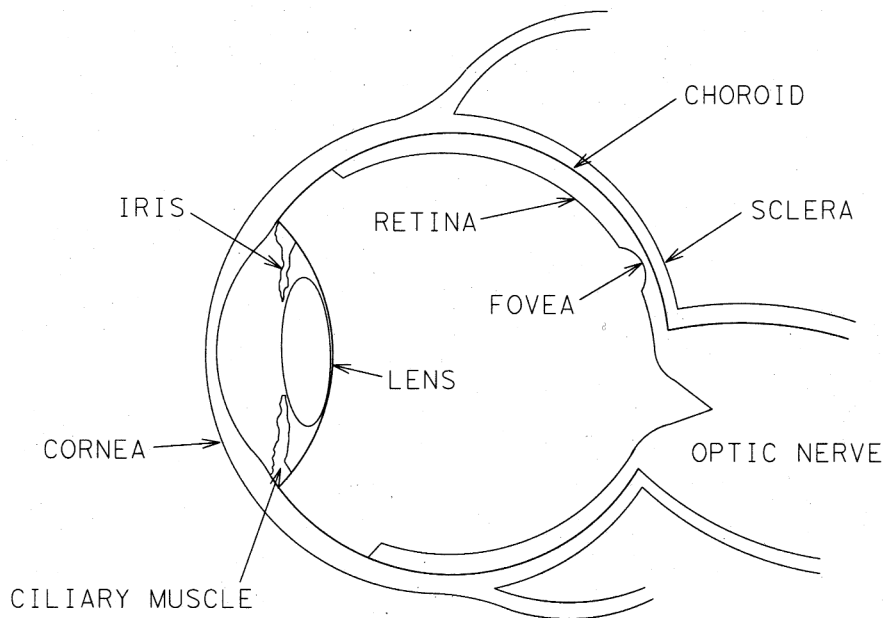


Figure B-6. A horizontal cross-section of the human eye.

- Approximate length from cornea to fovea of retina is 24 mm.
- Thickness of choroid is about 0.05 mm, and the sclera 1.0 mm.

There are approximately 120 million rod receptor cells and 6.5 million cone receptor cells in the human eye. The rod receptor system is more sensitive at very low light levels, but generally provides poor visual acuity and no color discrimination. The peak sensitivity of the rod system is at a wavelength of 507 nm. The cone system is comprised of three different cone receptor cells (commonly called blue, green, and red cones), with different sensitivity functions, and is responsible for color vision. The overall sensitivity curve of the system is at about 555 nm. The cone system also provides relatively high visual acuity, but requires significantly higher light levels to function.

## Visual Functions of Rods and Cones

The three visual functions provided by the two receptor systems (rods and cones) are scotopic, photopic, and mesopic vision. Descriptions of each follow.

**Scotopic vision.** At luminance levels below about  $0.05 \text{ cd/m}^2$ , there is insufficient light to activate the cone receptor system, and vision is provided solely by the rod system. Scotopic vision is commonly called “night vision.” There is no sensation of color in scotopic vision.

**Photopic vision.** At luminance levels above  $3 \text{ cd/m}^2$ , the rod system is effectively shut down through interaction with the cone system, and cones are the principal active elements. Central (foveal) vision is good, and normal color vision is possible.

**Mesopic vision.** At luminance levels between those suited for scotopic and photopic vision, both receptor systems provide visual information. Which system provides specific visual cues depends on the actual luminance level and the relative spectral sensitivities of the two systems. Typically, at the lowest mesopic levels, the cone receptor system only functions at longer wavelengths. As the luminance level increases, the cone system essentially turns the “gain” down on the rod system, preventing glare and allowing the cone system to predominate over increasingly shorter wavelengths. Thus, at very low mesopic levels, red will be the first color a person can detect, with blue the last color detectable as the luminance level increases.

## Color Vision

A model of human color-vision is based on the *opponents theory*. This theory postulates that signals from blue cones are compared against the summed signals of green and red cones to provide a value along a blue-yellow axis. Signals from the green cones are compared against that of the red cones to provide a value along a green-red axis. Finally, the summation of the green and red cone signals provides a luminance value. These three values allow the brain to identify the color in a color space. Note that although there are three types of color receptors, there are only two chromatic channels and one luminance channel for our color vision system.

## Distribution of Visual Sensitivity within the Eye

Cone density is greatest in the fovea, a small area at the visual axis of the eye, and drops off rapidly to a minimum at about  $10^\circ$  of eccentricity. Cone density remains fairly uniform from  $10^\circ$  eccentricity to the limit of the retina. Rods are absent in the fovea, and then increase rapidly in number to a maximum density at about  $18^\circ$  of eccentricity. Beyond  $18^\circ$  the rod density falls gradually, but remains significantly higher than cone density. Clusters of rod and cone receptor cells are linked to individual ganglion cells, which provide the actual signals to the brain. Thus, each “pixel” of the retina, which creates an image of what we are observing, will have more than one receptor cell contributing to the production of a neural signal. This clustering of receptor cells increases the sensitivity of the visual system, but puts a limit on *visual acuity*. In the fovea, where there is a very high density of cone receptor cells and no rods, the area

occupied by a cluster of receptor cells is extremely small, resulting in the smallest pixels within the retina. The fovea provides the highest resolution capability of the eye, and is the section of the eye where we will instinctively try to focus a task-image. With no rods, and the smallest number of receptor cells per ganglion cell, the fovea is also the least sensitive area of the retina, requiring the highest level of luminance for vision and a complete insensitivity under scotopic conditions. Towards the periphery of the retina, the clustered receptor cells occupy larger areas, resulting in lower image resolution.

## Night Driving Conditions

Most night-driving situations occur under conditions of mesopic vision, although a well-designed roadway lighting system can approach the photopic vision range in luminance.

## Visibility

Visibility is the quality or state of being perceptible to the eye. In many applications, visibility is defined in terms of the distance at which an object can be just perceived by the eye. In other situations, visibility is defined in terms of the contrast or size of a standard test object, observed under standardized viewing conditions, having the same threshold as the given object. Factors that directly influence visibility for drivers include:

- the luminance of objects on or near the roadway
- the luminance of the roadway and other backgrounds against which objects are viewed
- the size of an object and the identifying details of the object
- the contrast between an object, or the roadway, and its surroundings
- the time available for detection and recognition of objects
- the presence of glare from on- and off-roadway light sources (including other vehicular lighting)
- the driver's physical and mental condition (including visual ability)
- the condition and cleanliness of a vehicle's windshield.

## Visual Acuity

There are three components to visual acuity in any seeing task: the task, the lighting conditions, and the observer. Each of these acuity components has primary and secondary variables associated with it (Stein, et al, 1986), as shown in the following table.

**TABLE B-1. Variables Associated with the Components of Visual Acuity**

Component	Primary Variables	Secondary Variables
Task	<ul style="list-style-type: none"> <li>• size</li> <li>• luminance</li> <li>• contrast</li> <li>• exposure time</li> </ul>	<ul style="list-style-type: none"> <li>• type of object</li> <li>• degree of accuracy required</li> <li>• moving or stationary target</li> <li>• peripheral patterns</li> </ul>
Lighting Conditions	<ul style="list-style-type: none"> <li>• illumination level</li> <li>• disability glare</li> <li>• discomfort glare</li> </ul>	<ul style="list-style-type: none"> <li>• luminance ratios</li> <li>• brightness patterns</li> <li>• chromaticity</li> </ul>
Observer	<ul style="list-style-type: none"> <li>• illumination level</li> <li>• disability glare</li> <li>• discomfort glare</li> </ul>	<ul style="list-style-type: none"> <li>• subjective impressions</li> <li>• psychological reactions</li> </ul>

## Visual Size

The visual size of any detail that needs to be seen is a function of its physical size and its distance from the point of observation. By combining these two dimensions, one can express the size as a visual angle, which usually is measured in minutes of arc. Thus, the farther a given object is from the eyes, the smaller its visual size becomes. Various types of test objects, three of which are shown in Figure B-7, have been used for evaluating the size discrimination ability of the eye. In each case, the critical detail that must be discriminated is indicated by the dimension  $d$ . So for a constant viewing distance, the visual angle subtended at the eye by  $d$  is the same for the three objects, even though the maximum dimensions are different.

Another often-used way of expressing the size threshold of the eye is in terms of visual acuity. Quantitatively, this is the reciprocal of the visual angle. It often is defined as the ability of the eyes to resolve small detail. In driving, two types of visual acuity are of concern: static and dynamic visual acuity (explanations follow).

**Static Visual Acuity.** Static visual acuity occurs when both the driver and the object being viewed are stationary. Static visual acuity is a function of background brightness, contrast, and time. With increasing illumination, visual acuity increases up to a background luminance of about  $32 \text{ cd/m}^2$ , and then remains constant despite further increases in illumination. Static visual acuity also increases with increasing contrast of the object. Optimal exposure time for a static visual acuity task is 0.5 to 1.0 second when other visual factors are held constant at some acceptable level.

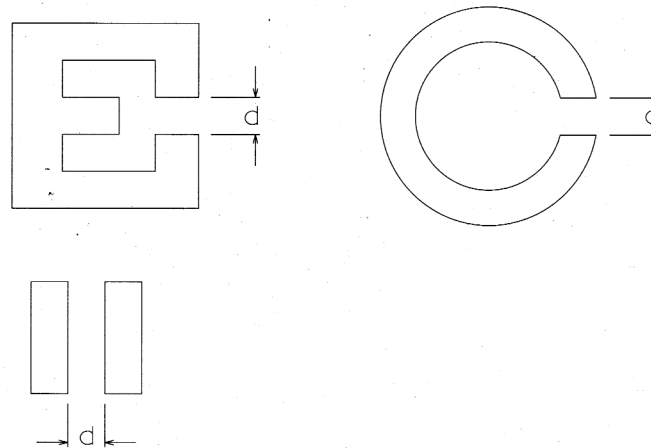


Figure B-7. Commonly used test objects for determining size discretion and visual acuity.

**Dynamic Visual Acuity.** When there is relative motion between the observer and an object, such as occurs in driving, the resolving ability of the eye is termed dynamic visual acuity. Dynamic visual acuity is more difficult than static visual acuity because eye movements are not generally capable of holding a steady image of the target on the retina. The image is blurred, and therefore, its contrast decreases. The conditions favorable for dynamic visual acuity are slow movement, long tracking time, and good illumination. These are rarely found in the nighttime driving environment, but are very important for sign reading, distance judgment, object discrimination, and other dynamic visual acuity tasks.

## Contrast and Visibility Level

The *contrast* between an object and its surroundings is one of the key determinates of visual acuity. The contrast ( $C$ ) of an object to its background is defined as

$$C = \frac{L_o - L_b}{L_b} \quad (\text{B-3})$$

where  $L_o$  and  $L_b$  are the luminances of the object and the background, respectively. Recognition of an object is most often based on a discrimination of the luminance differences. For nighttime conditions, an obstacle may appear as a dark area against a bright background (negative contrast), or it may appear as a bright area against a dark background (positive contrast). *Contrast threshold*,  $C/\bar{C}$ , is the level of contrast required for an object to be discernable, usually with a probability of detection of 50%, for a specified condition. The ratio of the actual contrast to the contrast threshold is designated the *visibility level* (VL):

$$VL = \frac{C}{\bar{C}} \quad (\text{B-4})$$

A VL of less than one indicates that there is a low probability that an object will be detected. As VL increases above a value of one, the probability of detection also increases. Note that even with a high value of VL, there is no certainty of detection, rather only an increasing probability. Detection relies on several factors other than contrast, including the amount of time available to make an observation, the physical and mental state of the observer, and the presence of glare.

### Illuminance and Luminance Evaluations

The calculation of the illuminance at a point, whether on a horizontal, vertical or inclined plane, consists of two parts: the direct component and the reflected component. The total of these two components is the illuminance at the point in question. Of the methods for determining the direct component of the illuminance, two methods—inverse square and illumination charts and tables—can be used for evaluating the effect of inclination.

***Inverse-square Method for Calculating Illuminance.*** Variations in the formula for the inverse-square law are used to determine the illuminance at definite points, where the distance from the source is at least five times the maximum dimension of the source. In such situations the illuminance is proportional to the square of the distance from the source.

The illuminance on a horizontal plane ( $E_h$ ), as measured at a point defined by a set of angles from a given light source ( $\phi, \gamma$ ), illustrated in Figure A-4, is expressed as:

$$E_h = \frac{I(\phi, \gamma) \cos \gamma}{D^2} \quad (\text{B-5})$$

where:

- $I(\phi, \gamma)$  = luminous intensity of the source in the direction of the point in question;
- $D$  = actual distance from the light source to the point in question;
- $H$  = vertical mounting height of the light source above the horizontal plane;
- $\phi$  = the angle from the light source reference axis to the point in question; and
- $\gamma$  = the angle from the nadir of the light source to the point in question.

For a horizontal plane,  $\cos \gamma = H/D$ . Therefore:

$$E_h = \frac{I(\phi, \gamma) \cos^3 \gamma}{H^2} \quad (\text{B-6})$$

## Pavement Surface Luminance

The luminance of a surface ( $L$ ) is defined as the luminous flux per steradians emitted (reflected) by a unit area of surface in the direction of the observer. When the unit of flux per steradians is candela and the area is measured in square meters, the unit of luminance is candela per square meter ( $\text{cd}/\text{m}^2$ ). The surface luminance at a point can be calculated if the reflectance coefficient at the point, based on the incidence angles,  $q(\beta, \gamma)$ , and the illuminance value are known:

$$L = \frac{1}{\pi} E_h q(\beta, \gamma) \quad (\text{B-7})$$

where:

$E_h$  = illuminance at the point in question, as defined in Equation (B-6); and  
 $q(\beta, \gamma)$  = the directional reflectance coefficient for angles of incidence  $\beta$  and  $\gamma$ .

By combining Equations (B-6) and (B-7), the luminance of the pavement surface can be calculated as:

$$L = \frac{q(\beta, \gamma) I(\phi, \gamma) \cos^3 \gamma}{\pi H^2} \quad (\text{B-8}).$$

Although a simple concept of the quantity of light reflected by a surface is assessed from the reflectance coefficient,  $q(\beta, \gamma)$ , the distribution pattern depends on the surface characteristics and the angular relationship between the light source, the point in question, and the observer position. In principle, two types of reflectance are identified: diffuse and specular (mirror). New fallen, dry snow is an example of a diffuse surface, whereas a smooth, wet road is a good example of a specular surface. Most road surfaces provide a mixture of diffuse and specular reflectance.

In practice,  $q(\beta, \gamma) \cos^3 \gamma$  is expressed as a *reduced coefficient of reflectance*,  $R$ , and is given in a table for each road surface classification (see IESNA RP-8-00, Tables A1-A4). Additional discussion of the Coefficient of Pavement Reflectance, and the reduced coefficient of reflection, is found later in this Appendix.

Accuracy of calculations of pavement luminance depends on the following factors:

- whether the photometric data used to determine the candlepower intensity at a particular angle correctly represent the output of the lamp and luminaire
- whether the directional reflectance table accurately represents the reflectance of the actual surface
- atmospheric attenuation factors, such as mist or fog.

## Field Evaluation of Installed Systems

The difference between predicted and calculated point luminance values can be substantial. One study (Janoff, 1993) found “almost no consistent relationship between measured and predicted point-wise luminances at 84 m (275 ft.) distances.” And, “for luminances the differences between measured and predicted can be attributed to a number of well known, but not easily quantifiable conditions. For background luminances the differences result from the nonuniformity of the road surface—caused by wear, dirt, and other surface contaminants; seasonal variations in moisture content; aggregate polishing, etc.—and difference between the actual road surface and the CIE ideal road surface defined by an  $r$ -table.”

## Methods of Evaluation

The evaluation of pavement luminance and veiling luminance (explained later) of an installed system can be done in three ways:

- direct measurement with luminance instruments
- measurement of incident light
- calculation from photometered luminaires.

Discussions of each of these methods follow.

***Direct Measurement with Luminance Instruments.*** Luminance of the pavement can be measured with a special telephotometer. The instrument should be set up at the observer's position and a measurement made at the desired point. If the moving observer method (IES) method of calculation has been used to predict the luminance at the same point, then a different instrument location is required for each point measured. In addition it is very difficult to determine if the difference between calculated and measured values is due to the lighting system or the pavement. While it is necessary to use this method in research investigations it is not recommended as a method to determine if an installation is performing as specified.

***Measurement of Incident Light.*** Measurement of incident light can be used as a method of determining if an installation is performing as specified. In this method a computer printout of the predicted initial incident light level (Footcandles or Lux) is made at the same time as the printout of the luminance. After the installation is completed and operating, the incident light level can be measured at each grid point in the customary manner. This method eliminates the pavement as a variable and will reveal incorrect installation procedures such as leveling, tilt, or rotation. These are difficult to separate from the effects of other variables such as dirt, light source output, luminaire and ballast variability, and voltage variations.

***Calculation From Photometered Luminaires.*** Calculation from photometered samples is an excellent way to evaluate the performance of an installation. Several random samples of luminaires (with ballast) and lamps are selected and sent to a competent laboratory to be photometered. The resultant photometric data can be averaged (or analyzed independently) and the luminance calculated by a computer run. If desired, the light sources (lamps) can be photometered separately, dirt can be removed from the submitted luminaires, or they can be photometered twice, once dirty and once clean, to determine its effects. This technique has many variations and is the preferred way to write specifications to permit field evaluation of the performance of an installed system. Random sampling at the rate of one per hundred luminaires installed with a minimum of three per installation is a good practice.

## Glare

Glare is an especially disturbing influence when viewing a difficult task under low brightness conditions (such as night). Two types of glare have a critical influence on driver visual performance:

- disability glare (physiological glare), caused by stray light that reduces contrast sensitivity, and thus produces a loss of visual efficiency
- discomfort glare (psychological glare), ocular discomfort from a bright light source.

Discussions of these two types of glare follow.

***Disability Glare.*** The effect of disability glare is well understood, and relatively easy to quantify. The scattering of light within the eye produces a luminance that is superimposed on the retinal image, reducing the contrast level of the image and resulting in a loss of visual efficiency. The summation of the superimposed luminances due to all of the sources in the visual field is known as the *veiling luminance*. Note that the scattering of light within the eye occurs even at relatively low illuminance levels that do not

cause discomfort glare. However, the effect on visual efficiency of a glare source is directly proportional to the luminous intensity of the source, or luminance of an area, and is inversely proportional to the angle between the source and the viewing direction.

**Discomfort Glare.** Discomfort glare is a measure of the level of sensation experienced when a light source is within the field of view. It cannot be directly measured, and is defined in qualitative rather than quantitative terms. It is generally accepted that discomfort glare does not have a direct effect on visual efficiency. However, the long-term effect of discomfort glare is believed to result in fatigue, leading to potential driver error.

Glare is an especially disturbing influence when viewing a difficult task under conditions of low luminance, as is typically experienced during nighttime driving.

## Quality of Lighting

“Quality of lighting” refers to the relative ability of the available light to provide contrast in the visual scene in such a manner that people may recognize the cues required for the viewing task. Quality of lighting is intimately related to the task. That is, a system that provides high quality lighting for driving may be clearly inadequate to meet the needs of an office worker or a tennis player.

The factors involved in producing a high quality lighting system are interrelated. Care must be taken in balancing the various parameters of the lighting system to obtain maximum quality. In general, a reduction in disability glare will improve visibility, and reductions in discomfort glare should improve driver performance. Glare caused by reflections off the roadway may conceal contrast differences and should likewise be reduced. However, a change in pavement reflectance, which may reduce reflected glare, will also change the pavement luminance and may have an adverse effect on the contrast between the roadway and objects on the road. Each adjustment of a parameter of the lighting system must be evaluated to obtain the proper compromise.

## Light Loss Factor

In most cases, measured values are less than the calculated values of the new, clean lamp and luminaire. Any lighting parameter, including luminance and veiling luminance, can be calculated in terms of either an initial or maintained value. It is generally assumed (but not always true) that the highest light level in the life of the installation will be found when the system is first energized and that all effects of system aging will cause the light level to decrease. For this reason any compensation for system aging (formerly the “maintenance factor” or MF) is part of the “light loss factor” (LLF).

Light loss factor is the overall factor used to link calculated to measured levels. The lighting design must incorporate an LLF in all calculations. Light loss factors that change with time after installation may be combined into a single multiplying factor for inclusion in calculations. Note that a LLF is composed of still separate factors, each of which is controlled and evaluated separately. Many of these are controlled by the selection of equipment (equipment factor) and many others are controlled by planned maintenance operations (maintenance factor).

LLF is usually considered to be made up of the following:

- reduced output from the light source due to aging—lamp lumen depreciation (LLD).
- reduced output from the luminaire (2–7% per year) due to:
  - dirt accumulation on lamp
  - dirt accumulation on luminaire reflector, refractor, or lens, resulting in reduced transmissivity
  - changes in relative light intensity due to dirt accumulation altering the characteristics of lamp, reflector, and enclosure surfaces
- changes in relative light intensity due to changes in reflector and enclosure characteristics with time

- changes in ballast characteristics (percent regulation) with lamp burn or line voltage time (this factor is improved with electronic or other more expensive ballast types)
- changes in lamp characteristics with burn time or installation position.

With regard to pavement luminance, the effects of wear, patching, moisture, and repaving must be added to the above list.

Many of the above factors are complex in nature and are interrelated. Additional information can be found in other chapters of this guide and in publications of the IESNA, CIE, and others. A few important points are discussed.

***Effect of Lamp Voltage Changes.*** The high-pressure sodium lamp is the most common light source used in new roadway lighting installations in the United States, and the relationship between the lamp and ballast is very complex. It is not usually recognized that these lamps, when used on the most common types of ballast, produce less light when first installed than after several thousand hours of operation. This is not the fault of the ballast or lamp but is due to the fact that the lamp voltage rises during life of the lamp and typical low-cost ballasts do not compensate for this voltage change. This means that for luminaires operating in clean conditions, the light level is likely to increase for some time after initial installation.

***Deterioration of Surface Reflectance.*** The surface finish of metal reflectors, plastic reflectors, and plastic enclosures can be scratched and dulled by some maintenance techniques. Sandstorms and exposure to ultraviolet light can also affect the transmission of some plastics. This damage is permanent and not reversible.

## Maintaining Light Levels

In general two approaches can be taken to the question of how to maintain light levels. One is to anticipate the normal maintenance practices and schedules and select an LLF based on estimates of the effects of those schedules and practices. The other is to select an LLF and then monitor the light level and tailor the maintenance schedule and practices to what is occurring at the installation. Typical LLF values for High Intensity Discharge lighting on highways is 0.6 to 0.65 for High Pressure Sodium lamps and 0.45 to 0.5 for Metal Halide lamps. Designing branch circuits with low voltage drop, the use of electronic ballasts, and improvements in lamp manufacturing can mitigate LLF.

## Coefficient of Pavement Reflectance

In understanding the calculation and use of pavement luminance, it is useful to understand the significance of the coefficient of reflectance ( $R$ ) as used in the  $r$ -tables. The following explanation is as simple and non-technical as possible. This is not a derivation of  $R$ .

As a single ray of light striking a surface does so, a portion of the energy is absorbed by the surface, and the remainder is reflected at a variety of angles. We are interested only in one reflected ray: that which will reach the eye of the observer. A coefficient of reflectance ( $R$ ) can be the multiplying factor to be used in calculating the intensity of the reflected ray as compared to the incident ray. If this concept had been used in the  $r$ -tables, then the numbers would have been very small and would have varied greatly as the angle of incident light ( $\gamma$ ) and as the angle to the line of sight ( $\beta$ ) change. Such a relationship can be represented as

$$\text{Luminance} = \text{Light Intensity } (I) \times \text{Reflectance Coefficient } (R). \quad (0-5)$$

The concept used in the “reduced coefficient”  $R$  first calculates the incident ray of light as a horizontal illuminance value ( $E_h$ ):

$$Lux = \frac{I(\phi, \gamma \times \cos^3 \gamma)}{H^2} \quad (B-9)$$

and then relates the value of the horizontal illumination at a point on the pavement to the intensity of the reflected ray directed toward the observer’s eye. By mathematically placing the “cosine cubed gamma” into the *r* value ( $r \times \cos^3 \gamma \times R$ ), it is possible to greatly reduce the spread of the size of the numbers in the *r*-table. The numbers are still very small, so they are multiplied by 10,000 before the table is compiled. “Remember from page C-13 that the “reduced coefficient of reflection” *R* is equal to the directional reflectance coefficient times  $\cos^3 \gamma$ . Thus the calculation of the pavement luminance, *L*, may be written as:

$$L = \frac{I(\phi, \gamma \times r)}{H^2 \times 10,000} \cdot (\text{in cd/m}^2)$$

It is a very useful concept to present the coefficient of reflectance in this manner. The correct terminology is “reduced coefficient of reflectance.”

Since the *r* value is sometimes loosely defined as converting horizontal incident light into luminance, the erroneous conclusion may be reached that the *r* value can be used to convert the sum of all horizontal incident light from several luminaires into luminance at a point defined by the angles of the table. This is not the case. The conversion is limited to the horizontal incident light coming from a single direction defined by the angles in the table. The position of the point on the pavement is defined and specified by the observer’s location and angular direction of sight.

## Light Sources

The light source (the lamp) is the device that actually converts electrical energy to visible light.

Light sources of interest in highway illumination design fall into two groups—incandescent lamps and electric discharge lamps. This section covers the various types of incandescent and electric discharge lamps.

## Incandescent Lamps

The following table describes of two types of incandescent lamps along with usage notes for each.

**TABLE B-2. Types of Incandescent Lamps**

Lamp Type	Description	Usage
Common Incandescent	Consists of a tungsten filament enclosed in a glass envelope (the bulb) attached to a metal base. The bulb is evacuated and an inert gas (argon or nitrogen) is introduced into the bulb for longer life and better efficiency. For wattages less than 40, the filament usually operates in a vacuum, without the inert gas. A voltage applied to the filament through the base causes a current to flow through the filament which causes it to incandesce.	Low initial cost, but low efficacy (less than 22 lumens per watt) and short lamp life. Typically used in traffic signals.
Tungsten Halogen (quartz iodide)	Has a halogen, such as iodine, introduced into the lamp envelope. This lengthens lamp life and improves efficiency.	Tungsten halogen lamps are not normally used in highway lighting. Low efficiency (30 lm/watt)

## Electric Discharge Lamps

Electric discharge lamps produce light by the passage of an electric current through a vapor or gas instead of through a tungsten wire. The application of an electrical potential ionizes the gas, and permits current to flow between two electrodes located at opposite ends of the lamp. The electrons which comprise the current stream, or “arc discharge,” collide with the atoms of the gas or vapor, causing light to be emitted. Electric discharge sources have a negative resistance characteristic, and a transformer or ballast must be provided to limit the current.

### Electric Discharge Lamp Types

Electric discharge lamps come in five common types. The following table provides descriptions of each type along with usage notes.

**TABLE B-3. Types of Electric Discharge Lamps**

Lamp Type	Description	Usage Notes
Fluorescent	Tubular bulb containing mercury. The mercury arc operating at a low vapor pressure produces ultraviolet light. The inside of the bulb is coated with a phosphor, and the ultraviolet light striking the phosphor causes visible light to be emitted.	Medium initial cost, long life, high efficacy (30–70 lm/w), but light varies with ambient temperature. Linear light source more difficult to control.
Induction Fluorescent	Same as fluorescent, except not tubular.	High efficiency (75 lm/w). Extremely long 100,000 hour life.
Mercury Vapor (MV)	Mercury arc in quartz arc tube. Operates at higher pressure and temperature than fluorescent. Arc produces visible light and some ultraviolet light. Far-ultraviolet filtered out by glass envelope. Clear lamps and phosphor-coated lamps available.	Phosphor-coated lamp used for sign lighting. High initial cost, long life, high efficacy (30–65 lm/w). Smaller light source than fluorescent.
High Pressure Sodium (HPS)	Arc in ceramic tube containing sodium and other elements. Provides light primarily in yellow spectrum but other elements provide light in blue, green, orange and red to improve color rendition. Requires a starting aid to provide pulse to start arc stream.	High initial cost, long life, high efficacy (45–150 lm/w), small light source.
Low Pressure Sodium (LPS)	Arc in long tubular glass envelope containing sodium only. Light is mono-chromatic yellow with poor color rendering.	High initial cost, moderately long life, high efficacy (145–185 lm/w). Light source hard to control photometrically.
Metal Halide (MH)	Similar to mercury lamp but contains various metal halides in addition to mercury. Excellent color rendering.	High initial cost, moderately long life, high efficacy (75–125 lm/w).

Note: The theoretical maximum efficacy is 683 lm/w. (lm/w = lumens per watt.)

