EVALUATION OF ROADWAY LIGHTING SYSTEMS DESIGNED BY STV METHODS

A Review of the Design of Roadway Lighting by Small Target Visibility (STV) Methods.

by

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Report Number: TX-97/0-1704-3R
Project Number 0-1704

Research Sponsor:
Texas Department of Transportation

Texas Tech University
Departments of Engineering Technology
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Technical Report Documentation

1. Report No. TX -97/0-1704-3R	2. PB99-113375	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of Roadway Lighting Systems Designed by STV Methods-A Review of the Design of Roadway Lighting by Small Target Visibility (STV) Methods		5. Report Date June 1997
		6. Performing Organization Code TECH
7. Author(s) Douglas D. Gransberg, Sanjaya Senadheera, Olkan Culvalci, Bobby Green, and Alexandr Gilman		8. Performing Organization Report N Interim Research Report 1704-3R
9. Performing Organization Name and Address Texas Tech University Departments of Engineering Technology, Mechanical Engineering, and Civil Engineering Box 43107 Lubbock, Texas 79409-3107		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project 0-1704-3
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology P. O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Cov Interim Research September 1996-February 1997
		14. Sponsoring Agency Code

15. Supplementary Notes
Study conducted in cooperation with the Texas Department of Transportation.
Research Project Title: "Evaluation of Roadway Lighting Systems Designed by STV Methods"

16. Abstract
The project's objective is to evaluate the design of roadway lighting systems by the Small Target Visibility (S method and determine if it is indeed practical, worthwhile design methodology and should be adopted by the Department. This evaluation will compare STV to current design methods and asses the potential liability associated with making the change. The project consists of seven tasks. The first is to conduct a comprehens international literature review to identify roadway lighting issues and their relationship to accident reduction potential. The review will also include a search for risk management and tort liability issues that relate to the subject. Tasks 2, 3, and 4 involve the development of experiments to establish a benchmark of empirical data which to evaluate STV and compare it with current design methods. Task 5 is the synthesis of the first four t into a formal plan of experiments and the conduct of those experiments directed by the Project Director. Tas consists of further experimental work as well as detailed analysis of the impact of STV on the Department's lighting design program, and a recommendation of STV standards language and design and construction tolerances. Task 7 is a comprehensive final report.

17. Key Words Small Target Visibility, Roadway Lighting, Luminaire		18. Distribution Statement No restrictions. This document is available to public through the National Technical Information Service, Springfield, Virginia 221	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 58	22. Price

Form DOT F 1700.7 (8-72)

IMPLEMENTATION STATEMENT

At this point in time, experimental work has not been completed to validate the inferences made in this report. If the experimental work does indeed support the conclusions, a recommendation will be made that the Texas Department of Transportation choose not to implement Small Target Visibility (STV) design methodology even if it is adopted as a National standard for roadway lighting design.

Dissemination of this information will best be accomplished through the Traffic Operations Division. A letter clearly stating the policy for roadway lighting design should be published and disseminated to all districts.

DISCLAIMER

ACKNOWLEDGEMENTS

The authors would like to take this opportunity to acknowledge the valuable contributions of the following people.

Karl Burkett, P.E., Project Director, Traffic Operations Division, TxDOT
Dr. Werner Adrian, McGill University, Waterloo, Ontario

Without their help, professional guidance, and direction, the work to date would have been much more difficult and time consuming.

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PROJECT ABSTRACT

The project's objective is to evaluate the design of roadway lighting systems by the Small Target Visibility (STV) method and determine if it is indeed practical, worthwhile design methodology and should be adopted by the Department. This evaluation will compare STV to current design methods and asses the potential liability associated with making the change. The project consists of seven tasks. The first is to conduct a comprehensive, international literature review to identify roadway lighting issues and their relationship to accident reduction potential. The review will also include a search for risk management and tort liability issues that relate to the subject. Tasks 2, 3, and 4 involve the development of experiments to establish a benchmark of empirical data from which to evaluate STV and compare it with current design methods. Task 5 is the synthesis of the first four tasks into a formal plan of experiments and the conduct of those experiments directed by the Project Director. Task 6 consists of further experimental work as well as detailed analysis of the impact of STV on the Department's lighting design program, and a recommendation of STV standards language and design and construction tolerances. Task 7 is a comprehensive final report.

BACKGROUND

"With the advent of computer design systems and computer modeling of lighting systems, it is feasible to calculate Small Target Visibilities (STV). STV is being proposed as the recommended design practice of the Illuminating Engineering Society of North America (IESNA) as well as the American National Standards Institute (ANSI)."

> "Small target visibility concepts, basis and assumptions need to be verified. Technical problems associated with the design procedures need to be investigated to determine the extent such problems affect the design. The impact on departments of transportation, city street & road departments, utility companies, and construction & maintenance contractors needs to be investigated. The design method needs to be examined to determine if it is practical and worthwhile."

The Small Target Visibility (STV) concept, as defined in the proposed ANSI/IES RP-8-1990 (IESNA, 1990), is a calculated measure of the visibility of an arbitrary two-dimensional (2-D) target. The Visibility Level (VL) is a metric used to combine effects of factors listed in RP-8-1990 on a 2-D sample target 18 cm square with a diffuse reflectivity of 20% (ANSI, 1990). The target is perpendicular to the road surface and 83 meters from an observer. STV is then calculated based on surface reflectivities and orientations with respect to an observer. The result of the calculation is a contrast picture of the small target with respect to the background surrounding the target. The calculations follow a typical ray tracing model-summing reflectance from various light sources around the target. Following the generation of the STV model, data has been collected to compare the STV with frequency of vehicular accidents. The outcome of the data is that high contrast targets are easy to see and avoid. Proposed ANSI/IES RP-8-1990 has a disclaimer recognizing that the standard target does not characterize real visual driving tasks or real characteristics of a driving individual (ANSI, 1990). The STV model is a static or steady state model and does not take into account the dynamics of change in contrast due to the relative motion of a small fixed target, background reflectivities and a dynamic observer.

Contrast (luminance ratio) (Stein, et al, 1986) is a dimensionless number, defined as the following.

$$C = |(L_t - L_b)/L_b| \qquad (1)$$

Where: C = Contrast
L_t = luminance of task (lumens)
L_b = luminance of the background (lumens)

Contrast taken as an absolute value of the above ratio will vary from no contrast (0.00) to maximum contrast (1.00). Illumination of the task and the background may be the same. But, since luminance is the product of illuminance and reflectance plus the direction of the light source (Stein, et. al, 1986), contrast may also be expressed as:

$$C = |(R_t - R_b)/R_b| \qquad (2)$$

Where: R_t = Reflectance of task (lumens)
R_b = Reflectance of background (lumens)

So, neglecting specularity, contrast is generally independent of illumination (Stein, et. al, 1986). Typically a flat plate will exhibit some specularity in its reflection pattern, even if a flat plate is very diffuse it usually does not exhibit a lambertian reflection pattern (Green, et, al, 1987). The plate will have a specula component plus a lambertian reflection component.

Both the Illuminance and Luminance design methods are determined by source lighting intensity at a point in space not by a measure of reflectivity. Illuminance, a light flux, is usually measured in lux or lumens-per-square meter, and luminance is measured by combining the brightness of an object and the conditions at the observer's eye and is reported in candela-per square meter. Illuminance and Luminance methods are combined in this report and will be referred to as Illuminance/Luminance (ILL/L). Brightness and luminance are different measures (O'Hair and Green, 1990). Luminance is an engineering measure where brightness is a subjective impression of an object. Brightness is also known as subjective brightness or apparent brightness. Luminance is in terms of luminous flux from a surface. The surface may be reflecting, transmitting, or emitting one candela per square meter. In a luminance measure, much like an STV measure, the source of radiation is not an issue. However, in the ILL/L measure, the incident radiation intensity is measured and taken into account.
The STV design method is a measure of the reflection of a target placed in a background. STV attempts to characterize the light sink rather than the light source as a measure of effective lighting. If reflectivities of the target and background are similar, then a static target will have very low contrast and will not be viewable to a static observer regardless of available illumination. The ILL/L design method does not neglect the reflectivity of a target but places emphasis on the light sources not the light sinks. Thus, ILL/L concentrates the salient elements of design around those environmental parameters over which the designer has control. Thus, it is

extremely important to evaluate STV within the environanometerent in which it must produce output to ensure that a change to the design method does not incur additional tort liability as a result of adopting a new design methodology.

PURPOSE OF THE STUDY

Small Target Visibility (STV) is being proposed by members of the Illuminating Engineers Society of North America Roadway Lighting Committee as a design methodology to replace the current accepted practice of designing these systems by illuminance /luminance methods (IESNA, 1990). This professional group is proposing to promulgate this method through the publication of ANSI/IES RP-8, "American National Standard Practice for Roadway Lighting" (hereafter referred to as RP-8). This study was commissioned by the Texas Department of Transportation (TxDOT) to investigate STV and provide an authoritative recommendation on whether TxDOT should adopt this new standard when it is offered by IES. As such, the purpose of this report is to present a review of the literature regarding this subject. The review has been conducted with an eye to identify those aspects of past research and study that may cause the conclusions to be questioned. This paper will catalog those aspects of past work which require further study and analysis before a definitive change in design methodology in Texas is warranted. It must be noted that this paper is not meant to criticize or question the professionalism of previous researchers in this field, but rather to open up to analysis to aspects of the collection of past work which may require additional study and verification before a wholesale change in design methodology is justified. As such, the focus of this literature review is on the fundamental assumptions used by past researchers to simplify the analytical process and attempt to quantify the possible range of error potential introduced in the results. It is hoped that by doing this, TxDOT engineers and policy makers will be able to make a technically well informed decision on the future of STV design in this state.

METHODOLOGY

A worldwide, comprehensive review of the literature of this subject was undertaken. This literature fell into the four general categories listed below.

- Visibility and lighting
- Accident correlation to roadway lighting improvement
- Pavement reflectance
- Tort and liability issues (to be addressed in a later report).

The bibliography of RP-8 was used as the starting point to identify and analyze those studies on which the proposed STV standard was based. Additional articles, reports, and papers were obtained based on the bibliographies of those articles cited in RP-8. The study team then split up the articles based on each individual member's area of professional expertise for analysis. All members of the team read the first nine entries in the RP-8 bibliography as they were judged to be the primary body of work on which the STV standard was based.

Each article was first analyzed, to identify any 1) explicit assumptions made during the course of each researcher's work, and the second analysis was performed to identify those assumptions which were either 2) inherent to the type of work being done or 3) implicit in the conclusions of the study. Next a matrix of assumptions was developed, and each author's work was posted to that matrix to identify studies that shared common fundamental assumptions. Finally, an engineering analysis of each assumption was completed to estimate the possible range of error introduced by the assumption in much the same fashion as sensitivity analysis is conducted on an engineering algorithm. By this manner, a technical judgment can be made as to whether the work of a particular author can be reasonably accepted as written or whether additional research on that subject needs to be completed before the author's conclusions can be adopted. Thus, this review's output is actually a set of recommendations for future work rather than an authoritative judgment on the validity of past work. The general conclusion is that this subject is one of extreme complexity and seemingly infinite variability. Therefore, the work done to date is not yet to the point where STV has definitively been proven to be a large enough improvement over past practices to justify its implementation without further study.

THE CHALLENGES OF ROADWAY LIGHTING DESIGN

Before one can get to the specifics of this topic, one must first understand the environmental context of the design solution. Engineers tend to focus on the technology and as such, tend to ignore the salient features of the environanometerent in which the technology under design must operate. Roadway lighting is a good example of this mentality. First and foremost, engineers and scientists must remember that light is the fastest thing on earth. As a result, it is virtually impossible to predict the actual levels of lighting in a specific area under design. Intuitively, one can make the assumption that if ambient light is ignored in the design any light that is added to the area under design will merely increase the level of lumination and illumination and make the area brighter than it was designed to be. It would then follow that to ignore ambient light would constitute a conservative and hence desirable design methodology. This seems so logical, but it ignores one of the fundamental concepts of visibility and its effect on traffic safety. When the contrast of an object on the road goes to zero, it literally becomes invisible. The addition of light to a specific area can indeed decrease its safety if the amount of light creates a decrease in contrast. Therefore, the assumption that ambient light can be neglected could have a potentially deleterious impact on the operation and function of roadway lighting system. To make things even more complicated, the presence of transportation facilities tends to encourage development. As development occurs the quantity and quality of ambient light changes in a specific area. For instance, if a freeway interchange lighting system was designed assuming an undeveloped lot abutting the ramps and if at a later date a shopping center is built in that area because the presence of the interchange has enhanced the commercial attractiveness of surrounding properties, the addition of parking lot lighting and advertising lighting to the ambient light load on the roadway lighting system could materially change visibilities on the interchange.

Man-made ambient lighting is not the only potential culprit. The natural change in nighttime lighting due to phases of the moon and weather conditions also creates a dynamic that ultimately impacts the operation of a roadway lighting system. The ability of the pavement to reflect light is also a dynamic function. Not only does pavement change its reflective characteristics as it ages, but it also changes dramatically when it is wet from rain, snow, or ice. Additionally, the introduction of recycled materials such as shredded rubber tires and glass cullet introduces an entirely new set of potential reflectances. Finally, there is the contribution to the lighting in a specific area due to headlights of vehicles both moving and stopped. These vary randomly with traffic. Thus it is difficult to predict or even assume a value for this contribution because of the variation in the population of vehicles with respect to output, head lamp height, direction, and number of lights at any given point in time. When one considers that the effects of both ambient lighting and headlights are amplified in areas of reduced lighting, the problem's difficulty grows some more. Thus it must be concluded that the roadway lighting design model and methodology is an extremely complex, highly dynamic one. As a result, those who have chosen to study this problem have been forced to simplify their analysis by make certain basic assumptions. This is typical and considered good practice when the limitations and constraints on the interpretation of output is taken into consideration and the range of possible error due to variation in the assumption is understood and taken in to account in the final design.

With all of the above in mind, the problem faced by roadway lighting designers is really a break-even problem. At some point, the addition of more precise analysis and computation does not justify the additional level of engineering effort required to apply that form of analysis. Simply put, one can frame the problem in the following manner. Intuitively and confirmed by research, adding light to a stretch of road increases visibility and that enhances safe operation. However, determining exactly how much light should be provided and the design effort required to determine that amount is a point of diminishing returns problem. Is a design produced by a three-dimensional computer model requiring forty hours of design effort that much safer than a standard design that requires merely a geometric adaptation of standard dimensions and can be done in four hours? Therein lies the crux of the problem and is the philosophical basis of this literature review as well as the justification for this project.

REVIEW OF LITERATURE ON LIGHTING AND VISIBILITY

To make the literature review coherent and to standardize the terms used by the various contributors to this report, the first document to be reviewed is *Mechanical and Electrical Equipment for Buildings, Seventh Edition* by Stein, Reynolds, and McGuinness. Chapter 18 of this handbook provides a very clear encapsulation of all the salient principles that must be understood by both the researchers and the readers of this and subsequent research reports. Thus it is felt that the next section will create a common foundation of knowledge on which to interpret the remaining information.

Light as Radiant Energy

The Illumination Engineering Society (IES) defines light as a form of energy that permits us to see. Light is considered to have a dual nature, the nature of a particle (photon) and the nature of a wave. The wavelengths of visible light are from 380 x 10^{-9} meters to 780 x 10^{-9} meters. A wavelength of 10^{-9} meters is usually referred to as a nanometer. So, the wavelengths are from 380 to 780 nanometer. Violet light is the shorter wavelength, higher energy 380 nanometer light, and the 780 nanometer wavelengths are the lower energy red lights. Green light falls between

500 and 600 nanometers. The previous measure of light wavelength was in Angstroms (10^{-10} meters), so violet light would be 3800 angstroms.

Light Incidence, Transmittance, Reflectance and Absorption

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

- Transmittance
- Transmission factor
- Coefficient of transmission
- Transmission coefficient.

These 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.

The ratio of reflected light to incident light is called one of the three names listed below.

- 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 reflection of a beam of light takes place on 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 surface is called diffuse.

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.

$v_m = c_o/n$.

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

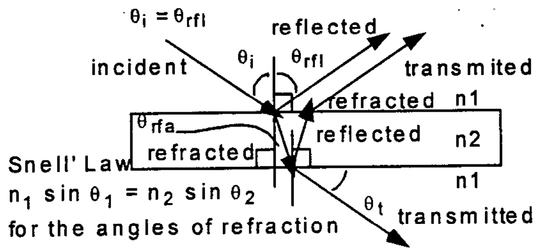


Figure 1. Specular Ray Tracing Model

Incidence radiation, I_o, @ Incidence angle, θ_i,
Reflected radiation, I_{rfl}, @ Reflected angle, θ_{rfl},
Transmitted radiation, I_t, @ Refracted angle, θ_{rfa},

The angle of incidence is equal to the angle of reflection, $\theta_i = \theta_{rfl}$.

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, θ_t,

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

$I(x) = I_o e^{-kx}$,
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.

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

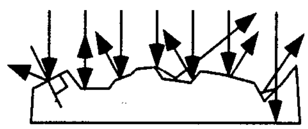


Figure 2. First Surface Diffuse Reflections

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

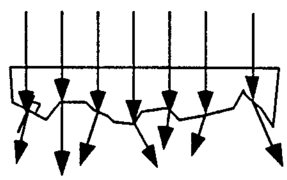


Figure 3. Second Surface Diffuse Refraction/Transmissions

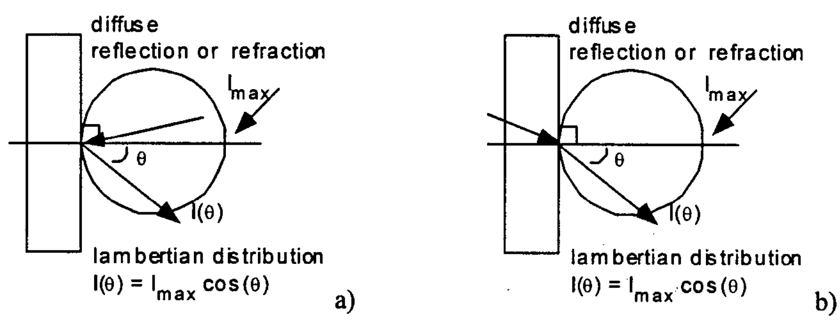


Figure 4. Lambertian Reflection or Refraction/Transmission Distribution

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 5.

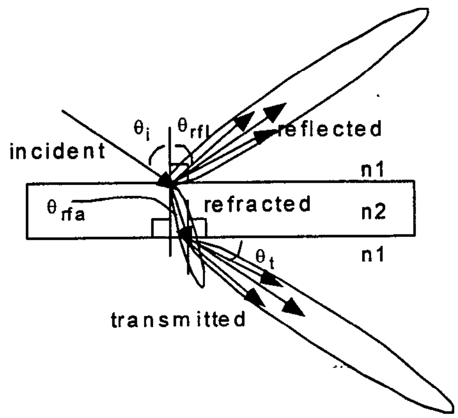


Figure 5. Reflection and Transmission Distributions

Most surfaces are somewhat smooth and somewhat rough so we get 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.

Definitions

There are two basic systems of units used in lighting, American Standard (AS) and International System (SI) metric units. The IES uses SI units in their handbook and publications with AS units in brackets [AS].

Luminous Intensity: The AS unit for Luminous intensity is the candlepower (cp), and the SI unit is the candela (cd) and normally represented by the letter "I". A wax candle has a luminous intensity horizontally of approximately one candela (cp). A candela and a candlepower have the same magnitude. Luminous intensity is characteristic of the source only and independent of the visual sense of the eye.

Luminous Flux: The unit of luminous flux in both SI and AS units is the lumen [lm]. An isotropic radiator of one candela emanating from a sphere of one meter radius then one square meter of surface on the sphere has one lumen of flux passing across the boundary.

The human eye response to visible radiation is roughly a gaussian or normal bell curve with the center of the maximum visible sensitivity near 555 nanometer and 0.7 of the maximum visible range at approximately 505 nanometer and 595 nanometer. The relative sensitivity response of the eye is multiplied by the spectral output of a light source to determine the visibility of the light source with respect to a human eye. The output of the light source is measured in watts, the total power output of the light. The lumen is a measure of photometric power as perceived by the human eye, is frequency dependent, and a function of human physiology. A 500 watts (w) incandescent lamp amounts to approximately 45 watts measured radiometrically and about 10,000 lumens, so we have about 20 lm/w.

Illuminance: One lumen of luminous flux on one square foot produces one foot-candle (fc) of illuminance in AS units or one lumen of flux on one square meter produces one lux (lx) in SI units. Illuminance is normally represented with the letter "E." It is readily seen that one square foot is about an order of magnitude smaller than a square meter, so a lux is roughly an order of magnitude smaller than a foot-candle (10.764 lx =1 fc).

Illuminance Measurements: Due to the frequency response of the human eye, it takes roughly 10 times as much brightness of 400 nanometer blue light in the photopic region, to give a brightness of 1.00 at the 555 nanometer, yellow-green, wavelength. If an illuminance meter is to be useful, its response must be color corrected to the response of a human eye. Cadmium sulfide photo-cells roughly approximate the visible spectrum of a human eye and can be color corrected to match the spectral response of a human eye. The meter must also be correct for light incident at oblique angles to the glass surface shielding the photo cell; the oblique angle correction is known as cosine correction. A good illuminance meter will plainly indicate its color and cosine correction.

Luminance and Brightness: Light entering the eye gives us the sensation of brightness; however, brightness is a subjective measure because it depends on the object luminance (L) and on the state of adaptation of the eye. Brightness is referred to a subjective brightness, apparent brightness or brightness. The measurable, reproducible state of objective luminosity is its luminance of photometric brightness. Luminance is the luminous intensity per unit projected area of a primary (emitting) or secondary (reflecting) light source. The SI unit is candela/square meter or a nit (cd/m^2 =nit); the AS unit is the foot-lambent (3.14 fL = 1 cd/f^2).

Luminance Measurement: Illuminance measurements (lux) are the most common measure of lighting levels; however, luminance (cd/m^2), a measure of brightness, is a measure of what we see. Luminance is a directional measure of light passing through a surface. A luminance meter is basically an illuminance meter with a hooded cell to block oblique light and calibrated in units of luminance.

The Eye as an Instrument/Photometric Sensor

Light entering the eye through the pupil is focused on the retina on the back surface of the eye. The retina contains light-sensitive cells called "cones," due to the shape of the cells, and light sensitive cells called "rods," also due to the cell shape. The cones are near the *fovea* in the center of the back of the eye with the rods being further out from the center. The cones respond rapidly to changes in lighting levels during day lighting and are responsible for color and detail vision. Rods are extremely light sensitive and responded to light levels 1/10,000 as bright a cone cell;

however, rods lack color sensitivity and detail discrimination. Therefore, night vision (rod vision) is very coarse and all colors appear as shades of gray.

In central (*foveal*) vision, we have great detail and color sensitivity, central vision subtends about a 2 degree angle in the center of our visual field, from 2 to 30 degrees we have near field vision, from 30 to 60 degrees we have far field vision, and beyond 60 degrees we have peripheral vision. Near field vision has color and some detail, far field, and peripheral vision detects motion and has a high concentration of rod cells for low light conditions.

Visual Acuity

There are three components to visual acuity in any seeing task: the task, the lighting conditions, and the observer, and there are variables associated with each of the acuity component. Each of the visual acuity components have primary variables and secondary variables (Stein, et al, 1986)

1. Task: Primary Factors
    a. Size
    b. Luminance
    c. Contrast
    d. Exposure time

2. Task: Secondary Factors
    a. Type of object
    b. Degree of accuracy required
    c. Moving or stationary target
    d. Peripheral patterns

3. Lighting Conditions: Primary Factors
    a. Illumination level
    b. Disability glare
    c. Discomfort glare

4. Lighting Conditions: Secondary Factors
    a. Luminance ratios
    b. Brightness patterns
    c. Chromaticity

5. Observer: Primary Factors
    a. Condition of eyes
    b. Adaptation level
    c. Fatigue level

6. Observer: Secondary Factors
    a. Subjective impressions
    b. Psychological reactions

Contrast

Contrast (C) is a dimensionless ratio of luminance defined previous in equation 3. High contrast is critical in recognizing outline, silhouette, and size (Stein, et. al, 1986). It can be further described as follows.

$$C = (L_T - L_B)/L_B \tag{3}$$

Where: L_T = luminance of the task
L_B = luminance of the background, or as

$$C = (L_F - L_B)/L_B \tag{4}$$

Where: L_F = luminance of the foreground
L_B = luminance of the background.

Contrast is may be positive or negative and varies from $-1<C<0$ and $0<C<1$ and is generally independent of illumination, neglecting specularity (Stein, et. al, 1986). Note that in the second part, we demonstrated these equations (equations 3 and 5) as an absolute value of the ratio and defined contrast as a relative value. Reflectance is also a measure of candela per square meter, so contrast may also be represented in terms of reflectance as shown in equation 5 as:

$$C = (R_T - R_B)/R_B \tag{5}$$

or

$$C = (R_F - R_B)/R_B \tag{6}$$

Where: R_T = Reflectance of the task
R_B = Reflectance of the background
R_F = Reflectance of the foreground.

Now that we have created a common framework for the technical thrust of this study, we can move on to the specifics of the study itself and how the literature lends itself to the objectives cited in the project abstract.

Luminance Evaluations

The calculation of the illuminance at a point, whether on a horizontal, a vertical or an inclined plane consists of two parts: the direct component and the reflected component (Lighting Design Practice Committee, 1974). The total of these two components is the illuminance at the point in question. Of the methods of determining the direct illumination component at a point, two methods: Inverse Square and Illumination Charts and Tables can be utilized for evaluating inclination effect. Variations in the formula involving 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.

Illuminance on horizontal plane (E_h) is expressed as the following equation.

$$E_h = \frac{I\cos\gamma}{D^2} = \frac{I\cos^3\gamma}{H^2} \tag{7}$$

Where: I = Candlepower of the source in the direction of the point
D = Actual distance from the light source to the point
H = Vertical mounting height of the light source above the plane of measurement
γ = Angle between the light ray and a perpendicular to the plane at that point.

For horizontal plane: $\cos\gamma = H/D$

The surface luminance (L) is defined as the luminous flux per steradian emitted (reflected by a unit area of surface) in the direction of an observer. When the unit of flux per steradian is candela and the area is measured in square meters, the unit of luminance is candela per square meter . The surface luminance in general terms can be calculated if the reflectance coefficient $q(\beta,\gamma)$ and the illuminance value are known:

$$L = \frac{1}{\pi} E_h q(\beta,\gamma) \tag{8}$$

Where: $q(\beta,\gamma)$ = directional reflectance coefficient for angles of incidence of β and γ.

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 will depend upon the surface characteristics and the angular relationship between the light source, the observation point, and the observation position. In principle, two types of reflectance are identified: diffuse and specular (or mirror). Snow is an example of diffuse surface, whereas a smooth, wet road is a good example of a specular surface. Most road surfaces are a mixture of both diffuse and specular reflectance.

The horizontal illuminance can be expressed as the following equation.

$$E_h = \frac{I(\phi,\gamma)\cos\gamma}{H^2} \tag{9}$$

Combining (6-3) and (6-4) the luminance can be written as the following equation.

$$L = \frac{q(\beta,\gamma)I(\phi,\gamma)\cos^3\gamma}{\pi H^2} \tag{10}$$

In practice, $q(\beta,\gamma)\cos^3\gamma$ can be expressed as a reduced luminance coefficient r and is given in a table for each road classification (see tables B1...B4 of National Standard Practice, 1990).

Target Luminance is a function of the vertical illuminance from each luminaire in the layout detected toward the target times the directional reflectance of the target toward the oncoming driver. The reflectance is 0.18 (IES, 1983). This yields the following equation.

$$L_t = 0.18 \frac{L \sin\gamma \sin\phi \cos^2\gamma}{DZ^2} \qquad (11)$$

Luminaire light distribution developed over the past fifteen years reflects the desire of the luminaire manufacturers to produce an optimal level of horizontal lux with acceptable uniformity in accordance with past versions of the Standard Practice. Such luminaire light distributions yield reasonably good patterns of pavement luminance if used carefully (American National Standard Practice (1990). Accuracy of calculations of pavement luminance depends on two factors.

- If the photometric data used to determine the candlepower intensity at a particular angle correctly represents the output of the lamp and luminaire

- If the directional reflectance table represents accurately the reflectance of the actual surface

Since, in most cases, differences result in measured values less than the calculated values of the new, clean lamp and luminaire, the overall factor used to link calculated to measured levels is called the "Light Loss Factor" or LLF. The lighting design must incorporate a 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. It must be realized 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). A few factors, such as voltage regulation and weather, are beyond the control of the lighting system owner/operator and depend upon the actions of others.

REVIEW OF LITERATURE ON ACCIDENT CORRELATION TO ROADWAY LIGHTING IMPROVEMENT

The hypothesis that lighting a section of road must intuitively make it safer seems so logical that it almost begs to be accepted without evaluation. The question that really must be answered in this study is not whether roadway lighting enhances safety, but rather does the use of STV design methodology yield a safer nighttime driving environanometerent than the accepted illuminance/luminance (ILL/L) methods of design.

To understand the correlation between lighting and accidents, one must first identify those parameters that impact a driver's ability to avoid accidents. This is normally expressed through the components of stopping. In order 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 data that generates 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) which 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 ability of the driver 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 environanometerent of enhanced visibility.

Safety Lighting

The Texas Department of Transportation Highway Illumination Manual (TxDOT, 1995) speaks to warrants for both continuous and safety lighting. In both cases, a ratio of night to day accident rates is used to identify cases where lighting of some form is justified. For continuous lighting (Case CL-4), a night to day accident ratio greater than 2.0 justifies the installation of this type of lighting. For safety lighting, the ratio is predictably less. A ratio greater than 1.25 justifies the installation of partial interchange/intersection safety lighting (Case SL-3), and a ratio greater than 1.5 justifies the installation of complete interchange/intersection safety lighting (Case SL-7). Thus Texas has created a warrant to light particular portions of the roadway when accident rates exceed a particular level. This contains the implicit assumption that adding light to a roadway will enhance nighttime traffic safety. This tracks well with the literature. Other authors have used a ratio of accident occurrence at night versus the accident rate during the day as an objective yardstick to both identify lighting requirements and to measure the efficacy of lighting upgrades after installation.

The Norwegian Institute of Transportation Economics conducted a study to validate the hypothesis that adding light enhanced 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:

$$\text{CS effect} = \frac{\text{No. of night accidents after lighting/No. of night accidents before lighting}}{\text{No. of day accidents after lighting/ No. of day accidents before lighting}} \quad (12)$$

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, the argument that adding light to an area could conceivably make the contrast very small and essentially render objects invisible which would, in turn, cause the potential for accidents to increase. Elvik's system can be used to test this argument as well. This 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 "are 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 which did not satisfy warrants. It should be noted that he found, in some cases, nighttime accident rates went up after public lighting was installed.

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 12 to determine the effect of adding lighting.

$$\text{Safety ratio unlighted} = \text{No. of night accidents/No. of day accidents} \quad (13)$$

$$\text{Safety ratio lighted} = \text{No. of night accidents/No. of day accidents} \quad (14)$$

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 not possible to determine an optimum level of illumination. He also concludes that those areas with the lowest illumination range had the best night/day accident ratios. This would lend 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). A great variation in luminaire output was found in the field. Data was analyzed for over 800 mercury lamps, and wide variations were found 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 twenty-five percent 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 that the target height should exceed 150 millimeters by Kahl and Fambro of Texas A&M University (Kahl and Fambro, 1994).

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).

$$r = \frac{\text{No. of night accidents after lighting/No. of day accidents after lighting}}{\text{No. of night accidents before lighting/No. of day accidents before lighting}} \qquad (15)$$

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 importantly 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, and its results are felt to be significant with regard to the basis of our own study. 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:

$$U = \frac{\text{Lower hemisphere flux per unit area after upgrading}}{\text{Lower hemisphere flux per unit area before upgrading}} \qquad (16)$$

He compared that to a cost function (SOC) which was the savings in accident costs over increased lighting costs due to the upgrade. Figure 6 is a copy of the graph from Fisher's paper and clearly shows 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 the following.

> "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."

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.

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% that 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.

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. This paper cites 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 and 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.

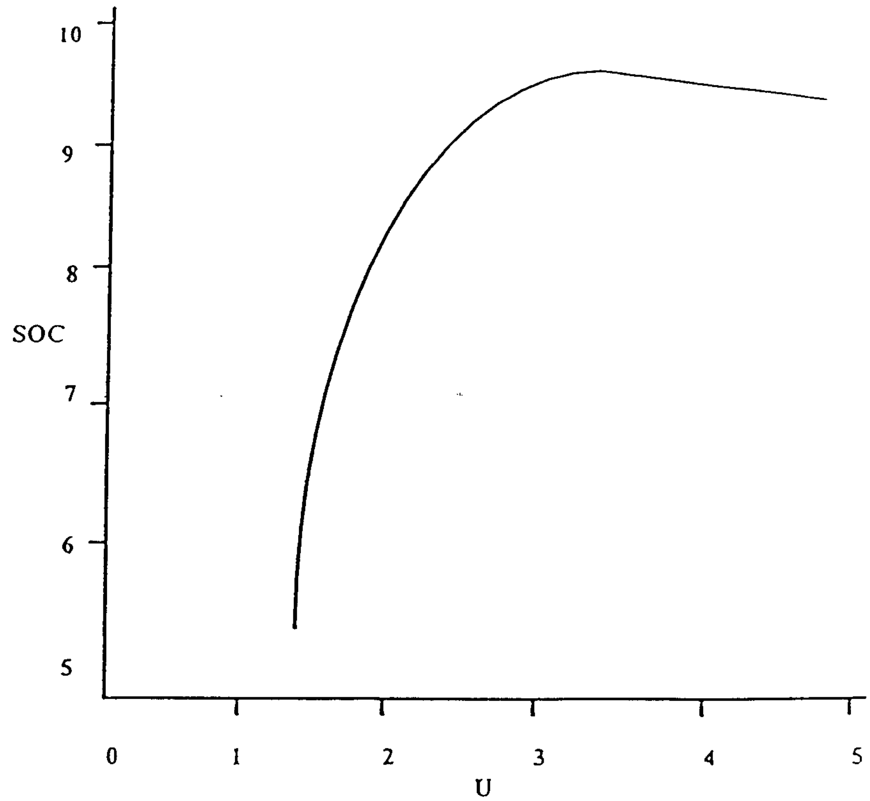


Figure 6. Fisher's Optimum Lighting Upgrade Analysis (Fisher, 1977).

This dilemma was addressed after a fashion by Jung and Titishov (1987). They used a standard 20 x 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 (1978) examined the design of roadway lighting system 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 x 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 to formally question the introduction of a contrast based visibility metric because of the difficulty of understanding the impact of inherent simplifications to the output of the design methodology.

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.

Driver Parameters

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 accident rates relative to day and night conditions. 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.

In order 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. day time) 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 will increase.

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

Most night time positional information is gathered from lane lines, edge lines, curb lies and 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

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 tasks.

Navigational Information

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. Road way lighting increases the positional information supply by increasing the visibility distance. Decreasing speed also increases visibility distance.

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 the light levels decrease the spectral sensitivity of the eye changes, the sensitivity curve remains approximately the same shape. However, the peak of the curve shifts away from 550 nanometer, to a slightly bluer 520 to 530 nanometer. Low light level contrast sensitivity is shifted into the blue with higher contrast sensitivity in blue than in red.

Target Size and Composition

RP-8 (IES, 1990) specifies that size and composition of the "Small Target" to be 18 centimeters square and of 20% diffuse reflectance. This reference is silent as to the reasons why this particular target is chosen as the standard. Obviously, 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 regard to 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 drivers 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 in these papers to relate to some other parameter of visibility, recognition, or other such factor). Roper (1953) used targets which were 40.64 centimeters square and which had a reflectance of 7.5%. Haber (1955) used a much larger target with a mean linear dimension of 91.4 centimeters 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-centimeter square target which had a reflectance of 18%. Zwahlen and Schnell (1994) used targets of varying reflectances that were 60.96 centimeters square and installed 30.48 centimeters 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 percent power, 50 percent power, every other luminaire extinguished, one side extinguished and no lighting and measured photometric data for each conditions. Subjects were required to drive the vehicle at the 55 miles per hour (88 kph) constant speed limit. The controlled field experiments results show that drivers tended to dislike reduced lighting on ramps or interchanges as opposed to reduced lighting on straight mainline roadway sections. They obtained a linear relationship between detection distance and horizontal illumination, pavement luminance and visibility index by using the six conditions.

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^2) 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 a 3-degree 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 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 which is 150 millimeters 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 millimeter target. They found that only 0.07 percent 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-millimeter object height in the critical Stopping Sight Distance model. In fact, they found that only two percent of all accidents involved objects or animals in the roadway. In urban areas, 10.4 percent of the objects struck were less than 150 mm in height, and on rural roads only 1.8 percent were 150 mm or less in height. They also found that "more than 95 percent 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 that are of interest to 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 millimeters) is probably a good measure for the height of a typical hazard.

This would track well with the results of Zwahlen and Schnell (1994) who found that a 60.96 centimeter square target with 15.5% reflectance placed at 30.48 centimeters above the pavement could be spotted by subjects at an average distance of 104 meters with a standard deviation of 16.6 meters through the filter of a windshield. When this is compared to the STV model of the 18 centimeter target visible at 83 meters, 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 equate to those hazard visibilities 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 which 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.

REVIEW OF THE LITERATURE ON PAVEMENT RELFECTANCE

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, cannot 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)* 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 percent of the pedestrian clothing had a reflectance of less than 5 percent and 80 percent of the clothing had a reflectance below 15 percent. Based on these results, it was possible to show that a 10 percent 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 that is 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.

1. "Quality" of a lighting system is always higher when average pavement luminance is high.
2. "Quality" of a lighting system is always higher when "empty street" pavement luminance uniformity is excellent.
3. Glare needs to be considered in the design.

It was interesting to note that contrast was not considered as design criteria. 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.

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. The ideally specular surface reflects all the luminous flux received by a point at an angle of reflection equal to the angle of incidence. 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.

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 appear to approximate closely with the perfectly diffuse surface. However, these surfaces behave as diffuse only if the angle of incidence is close to zero.

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 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 7.

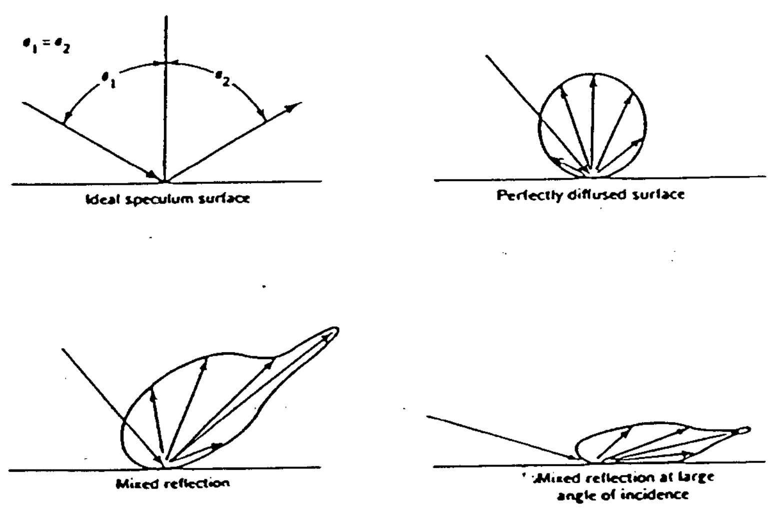


Figure 7. Luminous Intensity Distribution Curves for Different Types of Reflection (King 1976)

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

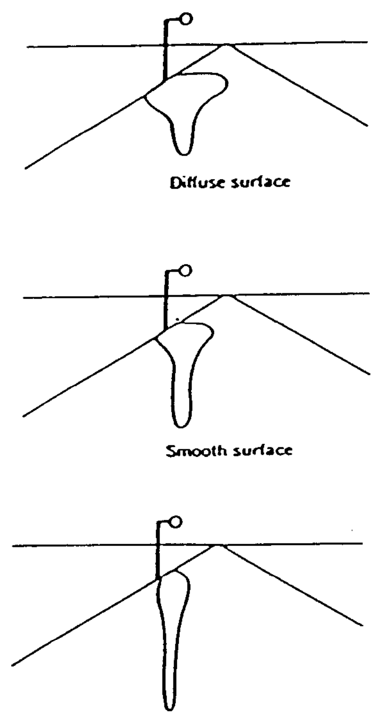


Figure 8. Luminous Patch Produced on Different Roadway Surfaces (King 1976)

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 within an accuracy level of 15 percent. Christie adopted the point of 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 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 one hour to take one set of reflection data corresponding to a set of angles. If measurements were taken at 5-degree 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 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 1970's, 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, 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. The proposed IES RP-8 Lighting Standard (1990) adopts the R-Series classification for its pavements and its features are indicated in Table 1.

Table 1. Road Surface Classifications Description

Class	Q_o	Description	Mode of Reflectance
R1	0.10	Portland cement concrete road surface. Asphalt road surface with a minimum of 15% of the aggregates composed or artificial brightener aggregates (labrodorite, quarzite)	Mostly diffuse
R2	0.07	Asphalt road surface with an aggregate composed of a minimum 60% gravel (size greater than 10 millimeters)	Mixed (diffuse and specular)
		Asphalt road surface with 10 to 15% artificial brightener in aggregate percent artificial brightener in aggregate mix. (Not normally used in North America)	
R3	0.07	Asphalt road surface (regular and carpet seal) with dark aggregates (e.g. trap rock, blast furnace slag) rough structure after months in use (typical highway)	Slightly specular
R4	0.08	Asphalt road surface with a very smooth texture	Mostly specular

Theoretical Basis for "R-Series" Classification of Pavement Surfaces

The classification is based on specularity of the pavement as determined by a ratio, S1, and a scaling factor, Q_o, as determined by the overall "lightness" of the pavement. The normalized Q_o is given in table 1 for each of the pavements described. Greater accuracy in predicting pavement luminance can be achieved by evaluating specific pavements as to their S1 ratio and specific Q_o and then choosing the correct R-table.
The S1 ratio and specific Q_o for a pavement can be determined in one of two ways: (1) a core sample can be removed from the pavement and photometered by a qualified laboratory; (2) a field evaluation can be made.

The characteristics S1 and Q_o 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_o is given by the following equation as a measure of the lightness of a road sample.

$$Q_0 = \frac{1}{\Omega_0} \int_0^{\Omega_0} q(\gamma, \beta) d\Omega \tag{17}$$

In the formula 8-1, Ω_0 is the relevant solid angle of incident light at a specified point on the road. Ω_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 S1 given by:

$$S1 = \frac{r(\tan\gamma = 2, \beta = 0)}{r(\gamma = 0, \beta = 0)} \tag{18}$$

The angles γ and β are as shown in Figure 9.

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

$$r(\gamma, \beta) = q(\gamma, \beta) \cos^3 \gamma \tag{19}$$

It was found that Q_o is highly correlated with the average luminance $\overline{L}$ on the road.

$$\overline{L} = \frac{1}{A} \int_0^A L_p dA \tag{20}$$

Where L_p is the luminance at point P
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_o 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_o 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.

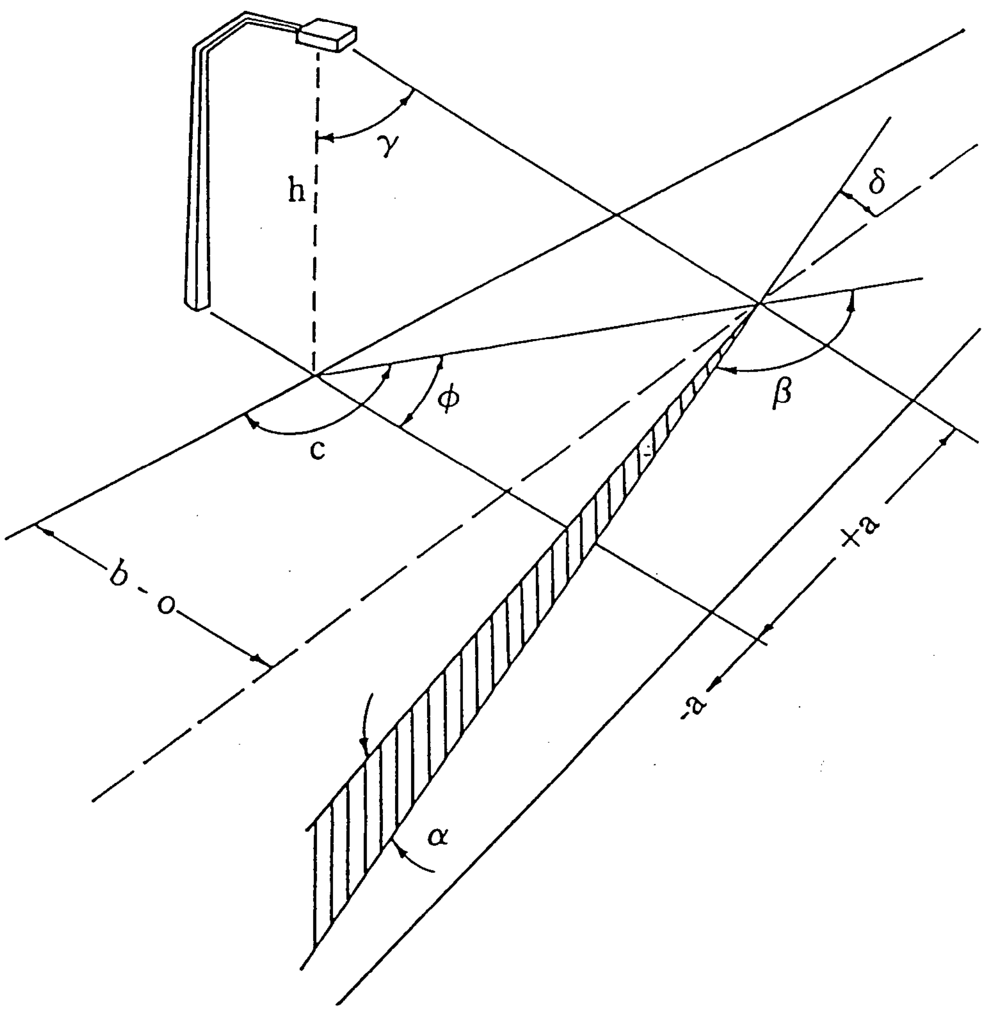


Figure 9. Schematic Diagram of Roadway Lighting

Table 2 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 (1 974). 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 2. 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

Results from this data quite clearly indicated a relationship between the S_1 ratio and the type of coarse aggregate used on the pavement surface. Table 3 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.

Table 3. 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 4 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 4. Relationship Between Coarse Aggregate on Pavement Surface and S_1 (Jung et al. 1984)

Coarse Aggregate	Range of Log (S_1)
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 of the 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 x 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 5.

Table 5. Summary of Observations by Nielsen et al. (1979)

Factor(s) Investigated	Conclusions/Observations
Parameter Relationships	Q_0 and S_1 are inversely correlated Retroreflection Q_R does not change significantly with the observation distan 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 tw 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 $(1 \pm 0.1)\overline{L}$ 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 factor to assist in the derivation of 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, and one placed upstream of the closest luminaire and one downstream (Janoff, 1993). The targets consisted of three different reflectances: 5, 30, 80 percent. 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 (Lv) was measured and predicted at 275 feet for each target. The results are shown in Table 6.

Table 6. Veiling Luminance

Variable	Target Reflectance	Target Position	Measured	Predicted	Result Ratio
Lv	-	1	2.10	0.16	13.1
Lv	-	2	2.86	0.22	13.0

The measured value at target position one 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 percent 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).

Pavement Luminance and STV

The visibility-based method of roadway lighting design proposed by IES RP-8 (1990) defines visibility using the parameter *Visibility Level* (VL) which is defined as the following equation.

$$VL = \frac{\Delta L_{actual}}{\Delta L_{th}} \tag{21}$$

Where ΔL_{actual} is the actual luminance difference of a target to its background (i.e. ΔL_{actual} = Target Luminance - Background Luminance)

ΔL_{th} is the threshold luminance difference that makes an object just perceivable from the background

This *Visibility Level* model is based on work done by Adrian (1989). To determine ΔL_{th}, the observer is assumed to be a young adult (23 years) with normal eyesight whose fixation time is 0.2 seconds. The standard target used for STV is a perfectly diffuse 18cm x 18cm square with 20 percent reflectivity that reflects light in a Lambertian manner. The target is placed on the pavement such that it is vertical and perpendicular to a line from observer to the grid point.

A network of grid points is set up between adjacent luminaires, and for each lane of roadway there are 20 grid points for each lane between luminaires (Figure 10). The observer is positioned at a distance of 83.07 meters. The height of the observer is taken at 1.45 meters giving a downward direction of view of 1 degree at the location of the target. The following notable assumptions are made in the proposed STV design procedure:

- The pavement is a level surface
- The pavement surface is homogeneous
- The pavement surface is smooth, dry and its reflectance characteristics can be represented by one of four classes (R1 to R4) identified in the IES recommended practice (1990)
- Only the light from fixed luminaires is considered. No allowances are made for illumination from automobile headlights and from off-roadway sources

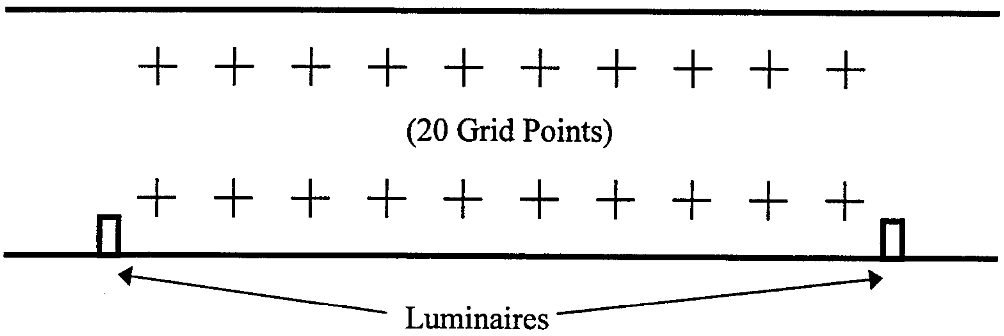


Figure 10. Network of Grid Points Between Luminaires Used to Calculate STV

The target luminance is calculated at the center of the target with only the light incident directly on the target from the luminaires being considered for its luminance calculation. The background luminance is considered as the average of the pavement luminance as viewed by the observer at a point adjacent to the center of the top of the target and at a point adjacent to the center of the bottom of the target. A simple calculation will show that the two points on the pavement whose luminances are averaged thus are approximately 12 meters (39 feet) apart.

Adrian et al. (Unpublished Data) recently 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 percent of the total target illuminance. This will significantly alter the *Visibility Level* (VL) required to see the target under positive contrast.

REVIEW OF PROPOSED STV STANDARD

Proposed RP-8-1990; "American National Standard Practice for Roadway Lighting."

Some of the fundamental assumptions in the proposed design method are by nature dynamic, not static as assumed. First, in Section 2.2, Area Classifications, the abutting land use is classified and used to define STV criteria presumably to provide some account for ambient light contributions to the lighted area from off-road light sources. Obviously, land use changes off the right-of-way are out of the Department's control. Research regarding the impact of transportation facilities shows that the proximity of transportation facilities, especially freeway interchanges and exits, increases the probability of commercial development and in this situation increases the probability that the Area Classification of a roadway lighting system will change after its installation and possibly invalidate the input design parameters. Next, Section 2.3, Pavement Classifications, also assumes a constant road surface classification. This neglects the effect of aging and polishing as well as the impact of surface treatments or overlays throughout the life of the pavement. The difference between the representative mean luminance coefficients is 30% (from 0.07 for R2 &R3 to 0.10 for R1). Presumably, an asphalt pavement could vary from a "slightly specular," R3 surface to a "mostly specular," R4 surface as it ages and polishes and back again when an overlay or surface coat is applied. This would constitute a dynamic variation of $\pm$ 10% across the design life of the lighting system for this factor alone. This system of classification also contains no factor for pavement distress. Cracking, pealing, debonding, and other typical types of distress will greatly effect the specularity of the surface.

Table 2 in Section 3 is a tabulation of STV and luminance criteria for various types of roadways. The statement is made that the values may be used regardless of speed limit. This seems to be an oversimplification of design methodology. Every major component of a highway's design is a function of design speed. Roadway lighting that is justified by potential accident reduction savings should probably be no different. The STV design algorithm is based on an 83-meter observer to target distance. At 56 kph, the distance traveled during the 2.5-second reaction time is 38.9 meters. Stopping distance at that speed is approximately 31.1 meters, making a sum of 70 meters to react and stop the car once a critical target is acquired. This leaves only 13 meters to correctly sample the driving environment, see and acquire the critical target. In terms of time, this is less than one full second. Thus, without regard to the myriad of other physical and physiological parameters that influence target visibility, if the target is perfectly visible, the average driver has only a split second to find the target and begin to initiate braking. This is at 56 kph, half the current freeway speed limit in Texas. This leads one to wonder how applicable this standard is to the wide range of lighting requirements that the standard is purported to cover. This brings us back to the question of target size and composition. A reasonable argument could be made that target size and composition should be a function of highway design speed and lighting criteria should be derived from the distance relationship established by the time required to sample, acquire, react, and stop the design vehicle traveling at the design speed.

Sections 3.4 and 6.2 discuss assumptions and standardized conditions for STV design. Besides the geometric constraints which will be discussed in subsequent paragraphs, it states that the "roadway is level, has no crown..." and "the pavement surface is assumed to be smooth, dry, and to have directional light reflectance characteristics..." The assumption that the pavement has no crown will be wrong in absolutely every situation and is an unnecessary simplification which introduces a calculable error into the methodology. All pavements are sloped and crowned for drainage. The typical crown is 2% or about 1E. While this may not seem like a large change, the superelevation on an exit ramp can get as high as 8% or 4E. This angle will measurably impact the actual reflecting angles of light on the road. The assumption that the pavement is relatively straight ignores the changes in angularity and superelevation that are inherent to horizontal circular curves used in highway geometric design. Additionally, there is no factor for change due to weather conditions. This system assumes that the pavement is dry at all times, but the most unsafe period for driving visibility is during times of adverse weather conditions. While it may not be possible to design an "all-weather" lighting system, some discussion regarding the changes in pavement luminance and reflectivity due to wetness is in order to at least give those who will attempt to apply this standard some idea of how to make engineering judgments. The addition of light to a foggy area can functionally decrease the effective sight distance by creating an optical condition that might be akin to glare. In the fog, lighting systems, regardless of their initial design purpose, change to navigational lighting. It would seem prudent to provide some guidance with regard to fog for those areas where this is a recurrent problem. Finally, the assumption that the pavement surface is uniform and homogenous is also questionable as previously discussed.

There appears to be a disconnect within the geometric description of the standard STV layout. Figure 7 to RP-8-1990 would indicate that the one degree downward angle of sight from the observer would fall across the top of the standard STV target. However, to get an 83.01-meter distance at a 1.45-meter observer eye height, the one degree angle must come from the base of the target. If one assumes the figure is correct, then the actual height of the observer's eye is 1.84 meters. This creates a potential error of 27%. We believe that there must be some editing error and have moved out with our study assuming that the STV computer programs that we have been provided are correct. If we are wrong, the points made earlier with regard to stopping distance at 56 kph is even more critical. In this case, the driver will hit the target before he can safely stop and the design speed limit relationship is for a speed slower than 56 kph that would make the design analysis functionally useless as very few lighted roadways have speed limits below this speed.

A comparison of RP-8-1990 to the current TxDOT lighting design policy as articulated in the Highway Illumination Manual (TxDOT, 1995) reveals that none of these simplifying assumptions are made. In fact, TxDOT uses an empirical design method that seeks to provide lighting with regard to specific warrants. In a nutshell, the TxDOT method is a geometry problem with regard to luminaire placement along the traveled way. While it would be difficult to provide a high degree of analytical justification for this design method, it does base itself on sound fundamentals and provides for a fair degree of variation in design to accommodate different design traffic volumes, speeds, and environments. The strength to this type of method is that it is very simple and does not require specialized technical knowledge to apply. Its major weakness is that it does not seek to optimize the lighting system's performance characteristics over time with respect to some rigorous visibility metric. Thus, the increased risk of substandard actual performance must be balanced by the reduced investment in design time. In light of all the previous discussion, it is hard to find fault with this design system. The greatly increased technical rigor provided by STV has not shown a commensurate increase in lighting system performance as measured by a verified reduction in nighttime accident rates.

FINDINGS/CONCLUSIONS

The challenge to research in this subject area is to account for the highly dynamic, almost incalculable nature of the roadway environment. This is not a simple engineering problem that can be solved by the proper use of high level mathematics. We are faced with developing a design methodology that successfully integrates the fastest form of energy on earth, light, with a biological organism, the human being. The system contains an extraordinary degree of randomness and variation. Any attempt to simplify the problem to facilitate analysis introduces a potential error in the findings. Many of the finest engineers and scientists in the world have tackled this problem, and in every case, they have had to introduce simplifying assumptions. The potential for changes in the design parameters for a specific location is also high. Not only can adjacent land use change, but also the daily changes in weather can have a marked effect on the visibility at any given point on the road's surface. NCHRP Report 197 (1978) lays out the established relationships between various highway design elements and their corresponding cost and safety effectiveness. With regard to "surface visibility," the report states: "the term 'visibility' is too abstract and the term 'color' is not sufficient description of the surface's relatedness to driver visibility." In essence, the literature in 1978 showed no meaningful relationships between visibility factors controlled by actual pavement design elements and safety. This reaffirms the feeling that this problem may be entirely too complex to find a single, satisfactory analytical solution to the requirement to standardize roadway lighting design.

To put all the preceding discussion into perspective, one must return to the reason that roadway lighting is required in the first place. Public entities either wish to enhance nighttime driver performance by providing navigation aids or by making a particular area safer after dark. If we go back to the basics, it can be seen that the problem is one of identifying some method which will provide a driver with sufficient time to identify a critical target (i.e. one which will cause the driver to take some kind of evasive action) and maneuver the vehicle to a safe and appropriate point where an accident is avoided. Thus, if the worst possible case is assumed to be a situation which requires the driver to come to a complete stop before hitting the critical target, the physical functions can be broken down into the four Driving Tasks previously described in Section 7 and duplicated below.

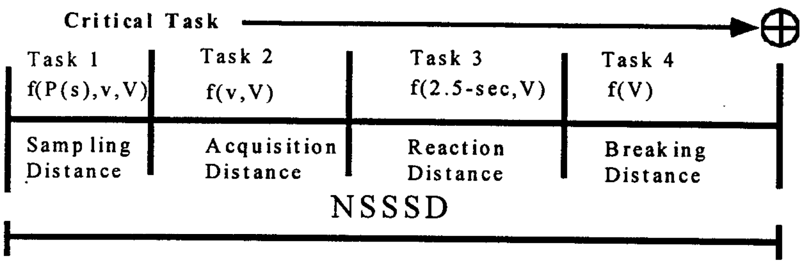
Task 1. The driver must sample the driving environment for data that generates adjustments in driving behavior such as changes in speed and direction. This can be called sampling rate and has a probabilistic function associated with it. If a piece of data is sampled which would require a change to zero, the next three items will occur. This can be called sampling time.

Task 2. The driver must see and acquire an image (for purposes of this discussion, the image will be called the target) which generates the thought that the vehicle should be stopped. This can be called target acquisition time.

Task 3. The driver must process that target thought and react by stepping on the brake. This will be called reaction time and is generally taken to be 2.5 seconds (AASHTO, 1990).

Task 4. The vehicle must rapidly decelerate from its initial speed to zero. This will be called stopping time.

Thus, the critical dimension in the whole problem is time. Obviously, to convert from time to the required dimensions needed to design roadway lighting, we must move from a dynamic to static measurement. To get there, we must first know the initial velocity at which the driver is traveling when this chain reaction occurs. RP-8 states that 56 kilometers per hour (35 mph) is the top speed at which standard headlights provide sufficient lighting to conform to safe stopping distance requirements. This seems to be somewhat at odds with nighttime speed limits on the average of 104 kilometers per hour (65 mph). Nevertheless, looking at the four tasks required for a driver to execute a safe stop, we can say that Task 4 is a function of initial velocity, the mass of the vehicle, and the coefficient of friction between the tires and the pavement. Calculating the braking distance is merely a physics problem that can easily be solved. Solving for the distance traveled during the reaction time in Task 3 is even simpler in that it is merely the velocity divided by 2.5 seconds. The problem becomes more complex when we try to solve for the distance traveled during target acquisition time. This is a function of velocity and visibility. Intuitively, the target's visibility is inversely proportional to the length of target acquisition time. The literature seems to indicate that the primary factor of nighttime visibility is contrast. However, we would argue that target size is also extremely important. The implied assumption with STV is that if a lighting system can be designed around a small target, then anything larger will be more visible. The work done by Zwahlen and Schnell (1994) and Kahl and Fambro (1994) would indicate that the STV target may be too small to be of effective use to designers. Work by Freedman et al. (1993) indicates that the probability of detecting a target strongly depends on its type. Finally, the most important factor in safe night driving is Task 1. The amount of environmental information available to a driver is greatly reduced in the hours of darkness. Thus, to assume that a target of any size can be acquired and reacted to begs the initial assumption that the driver is going to look at the point where the target rests at point in time where the subsequent three tasks can be safely executed.



Where P(s) = Probability of sampling target
v = visibility
V = velocity

Figure 11. Nighttime Safe Stopping Sight Distance (NSSSD)

The work by Walton and Messer (1974) shows that a driver must sample the environment for three primary types of information: positional, situational, and navigational, respectively. The identification of a critical target would be a situational piece of data. If we conservatively assume that the driver samples each type of information equally, then the probability that a driver would see the critical target is roughly 33%. That means that we would expect that, no matter how a roadway lighting system was designed, in only one instance out of three would the driver happen to see the critical target in time to execute a safe stop in the minimum time, assuming visibility down the road is 0. This is a somewhat depressing analysis, but it serves to vividly demonstrate the dynamics of this particular design situation. Thus, the problem becomes one of information theory rather than of physics or biology. The question becomes how does an engineer design a roadway lighting system in such a fashion as to increase the probability that any given driver will happen to be looking at the location of the critical target at a time which would permit him or her to execute a safe stop.

This conclusion is not meant in any way to denigrate the work done by others. The breadth of the work as shown in the literature has definitely impressed the authors of this report. The solution to this problem is terribly complex and as said many times before, highly dynamic. The work of previous researchers is outstanding and of the highest scientific quality. It has quantified many of the unknowns and should continue. However, the literature clearly shows that by adding lighting without regard to design methodology there is a documented reduction in accident rate.

It does not show that changing the design methodology or actual design input greatly improves the accident reduction rate. Thus, it is felt that while work must continue in this important field, there is no evidence to date that would recommend the STV design methodology over any other. In fact, the literature plainly demonstrates the complexity, variations, and dynamic quality of the problem. Australian researchers (Fisher and Hall, 1978) reached the same conclusion nearly twenty years ago. They cautioned against the premature introduction of additional complexity to the roadway lighting design process until it can be shown through research that a "lighting design based on a visibility metric gives significantly better results in terms of road user performance than present design methods and proof that specifications based on a visibility metric can easily be turned into optimum lighting installation requirements." Thus after nearly two decades of additional study, the problem can not be solved without inherent simplification and attendant error due to those simplifications. This leads us to believe that an empirical design methodology based on the experience of experts may be of more use than any attempt to develop a generic analytical methodology. To focus on visibility or contrast or other physical parameters may, in fact, be a suboptimization of the system parameters because it fails to address the parameter with greatest potential variation: the sampling rate.

Given the Figure 11 model and the discussion of information theory, the task of the experimental portion of this study is to evaluate the contribution of visibility to the nighttime safe stopping distance equation. If visibility's contribution is found to be minimal, then the use of STV will clearly not be justified. However, if the opposite is true and an analytical solution to roadway lighting design is required, then a thorough analysis of fundamental assumptions and standards must be made with respect to incorporating design of this vital safety apparatus into the roadway system as a whole. Physical factors such as design speed and physiological factors like target acquisition time must be optimized with visibility to achieve a final safe design solution to roadway lighting.

Requirements for Further Study

Further study is required in the following areas.

- Correlation between computed STV values and actual measured values must be attempted. If a good correlation can be found, then much of the above discussion with regard to cumulative error due to simplifying assumptions will be proved wrong. The opposite is also true and justifies the work associated with this approach.

- The contribution of pavement reflectance should be quantified and a set of design input values developed for a wide range of possible pavement types and ages including those pavements that contain a component of recycled material. As the pavement comprises the majority component of background luminance, its function must be well understood if one is to derive a consistent visibility metric for design purposes.

- Work to develop a computer simulation to assist in evaluating potential deviations due to variability in manufacturing and construction needs to be completed to permit the development of cogent specifications for roadway lighting installation based on allowable tolerances.

- The concept of NSSSD and its relationship to information theory must be expanded and to provide a possible alternative design methodology for roadway lighting if no correlation is found to exist in the STV model. In fact, it may be found that it is impossible to develop a NSSSD model and that would be a significant finding which would support a recommendation of not changing from current design based on illumination and lumination standards.

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