LIGHT POLLUTION

ENVIRONMENTAL EFFECTS OF ROADWAY LIGHTING

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ABSTRACT

Environmental impacts resulting from transportation infrastructures have been the subject of research for many years. One environmental aspect of transportation facilities largely ignored is that of light pollution. In many areas light pollution has become an important aspect of both planning and design. Neighborhoods are becoming more sensitive to the stray light that is being directed towards their property and windows. Astronomers and observatories are becoming more concerned with the increase in the sky glow around urban areas.

It has been estimated by some researchers that up to 50% of all light pollution may be the result of roadway lighting. This firmly puts light pollution in the hands of traffic engineers and it will become their responsibility to find adequate and economic solutions.

We will see that by employing some simple solutions, using today's technology, the effects of light pollution can be brought under control. All that is required, and this may be the most difficult part, is the political will to act.

INTRODUCTION

The environmental effects of transportation systems are becoming of increasing importance to traffic engineers and designers. While engineers are well aware of the problems associated with air and noise pollution a widely neglected area associated with transportation systems is that of light pollution. Although some may feel that lighting is not the area usually associated with traffic engineering, it has been estimated that 35% to 50% of light pollution is caused by roadway lighting. This, coupled with the fact that roadway lighting design and construction is handled by the traffic engineering sections of municipal and provincial engineering departments makes it the responsibility of traffic engineers.

Light pollution is a broad term associated with three major areas of potential concern. These include light trespass, glare, and urban sky glow. A few of the more minor, but related problems consist of confusion caused by light sources, adverse aesthetic effects caused by clutter, energy waste, and general annoyance. All of these problems can have adverse effects not only on the general public but also can affect the safety of the driving motorist.

In this paper the three major effects of poor or improperly designed roadway lighting will be explored. The minor effects will be briefly considered. General remedies and mitigation procedures have been researched over the past several years by various associations, many of which have been reviewed and reported on in following sections.

Besides light pollution the installation of roadway lighting has several other negative side effects which can be loosely associated with environmental impacts. These include color of the lighting sources used, visual intrusion associated with the lighting structures, and the roadside hazards the structures impose on the highways. These items will not be looked at in depth but should be further researched by engineers responsible for the design of roadway lighting systems.

BASIC ROADWAY LIGHTING THEORY

To properly understand the adverse effects of roadway lighting one must have a basic understanding of the theory of lighting and the design of roadway lighting. The following section will outline some very basic theory and design principles. Those wishing to gain a fuller understanding should consult the Illuminating Engineering Society of North America *American National Standard Practice for Roadway Lighting ANSI/IES RP-8.*

DEFFINITIONS

- *Candela:* The luminous intensity of a lighting source is measured in candelas. This is the basic unit of photometric quantity. The historical basis of the candela was associated with the amount of light emitted from the flame of a candle and was formerly known as one candlepower. The SI definition of the candela is 'the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 X 10^{12} Hz and that has a radiant intensity in that direction of 1/683 watts per steradian.

- *Lumen:* The lumen is the unit of luminous flux produced by the source and is directly related to the candela. A point source of one candela intensity will produce a luminous flux of one lumen through a solid angle of one steradian. (A sphere has a total area of 4π steradians. Therefore a point source of one candela has a total luminous flux of 4π or 12.57 lumens). The lumen can be loosely interpreted as the amount of light emitted from a source with a certain intensity.

- *Illuminance:* Illuminance (or illumination level) is defined as the amount of light being transmitted upon a certain area. The SI unit for illuminance is the lux which is equal to one lumen per square meter. The Imperial unit for illuminance is the footcandel which is equal to one lumen per square foot. Illuminance is governed by the inverse square law. The illuminance of an area or object diminishes as the square of the distance.

- *Luminance:* Luminance is the brightness of an object which has been illuminated by a source. The luminance of an object depends on its material characteristics and reflectance. For example, under the same illuminance conditions a dark object will look less bright that a light object. Since luminance refers to the amount of light reflected back by an object this object in effect acts as a new source. There is a direct relationship between the luminance of a viewed object and the resulting illuminance of the image on the retina of the eye. The unit of luminance is the candela per square meter.

Roadway luminaires are classified by the way they transmit and distribute light. The use of various different types of reflectors and refractors permits the lighting designer to produce an efficient and aesthetic design. Luminaire classifications are defined in terms of vertical light distribution, lateral light distribution, and the control of distribution above maximum candlepower, known as cutoff. Vertical and lateral light distributions apply primarily to the shape of the roadway area to be illuminated. Both of these distributions can be important when determining the amount of light trespass from a source. Figure 1 illustrates four basic distributions of roadway lighting fixtures.

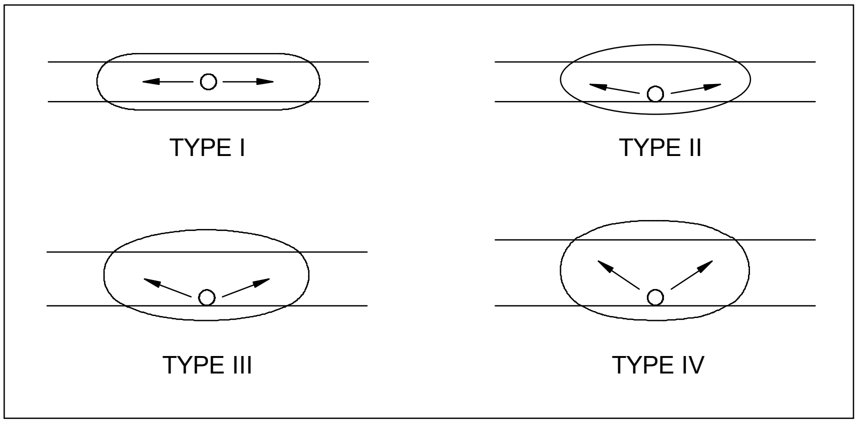

Figure 1. - Roadway Lighting Fixture Distributions

The control of the distribution above the maximum candlepower, known as the cutoff, is important for determining the amount of glare emitted by a fixture. A non-cutoff fixture typically has a dropped lens or refractor. This allows the light to be more easily distributed from the fixture and permits the illumination design to be less precise, however it produces more undesirable glare. A full cut-off fixture typically has the dropped refractor replaced with a flat-glass lens. This provides much better glare control, however the illumination design must be much more precise to maintain lighting uniformity. Examples of both non-cutoff (sometimes also referred to as semi-cutoff) and cut-off (sometimes also referred to as full-cutoff) luminaires are shown in Appendix A. Figure 2 illustrates the effect of non-cutoff and full cut-off luminaires.

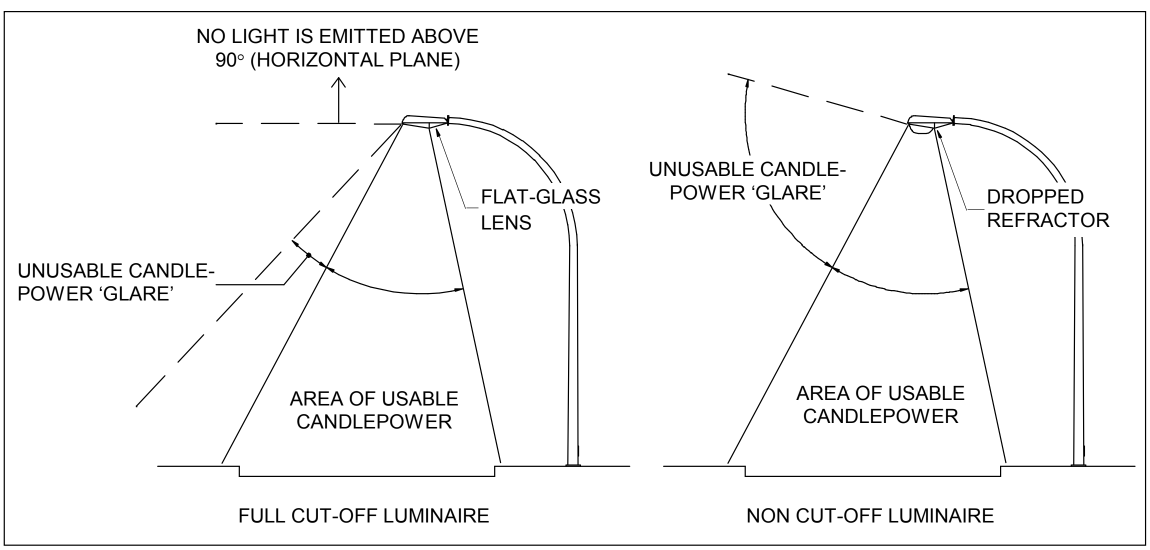

Figure 2. - Effects of Full Cut-off and Non Cut-off Luminaires

The Illuminating Engineering Society is the recognized authority for the setting of various illumination standards including roadway lighting. These standards, as listed in ANSI/IES PR-8, have been well researched and established as the minimum requirements for the safety of roadways. Several studies have been undertaken in recent years involving test targets placed on roadways (Ref 10). The IES standards have been confirmed during these studies as the minimum requirements for proper illumination with respect to stopping sight distances. To give some idea of the scale of illuminance required for various roadways refer to Table 1 below.

ROAD TYPE	ILLUMINACE IN LUX
Urban Freeway	10
Freeway Interchange	14
Commercial Arterial	20
Residential Collector	8
Local	6

Table 1 - Illuminance for Various Roadway Types

source: ANSI/IES RP-8

Roadway lighting is generally designed as the illuminance of the area in question. Basic calculations for roadway illuminance is as follows:

$$E_{ave} = \frac{(L \times CU \times LLF)}{S \times W}$$

where:

E_{ave} = average illuminance of the area in lux

L = luminous flux of the source in lumens

CU = coefficient of utilization of the luminaire (this value is obtained from a photometric data chart supplied by the manufacturer and is dependent on the width of the road and the spacing of the streetlight poles - examples of photometric data charts are contained in the Appendix)

LLF = light loss factor (this is the amount of light that will be lost over time due to dirt accumulation on the luminaire and lamp depreciation - typically 0.7 + 0.8)

S = spacing of the streetlight poles

W = width of pavement to be illuminated

For example, a roadway with a pavement width of 10m and a streetlight pole spacing of 50m utilizing a luminaire which has an output of 25000 lumens, a coefficient of utilization of 45%, and a light loss factor of 70% will have an average illuminance of:

$$I = \frac{(25000 \times 0.45 \times 0.7)}{50 \times 10} = 15.75 \text{ lux}$$

Roadway lighting may also be designed by calculating the luminance of the roadway surface. This involves determining the reflective properties of the pavement which can vary dramatically depending if the surface is concrete or asphalt. Although considered superior to the illuminance method the luminance method is very complex and properly undertaken by several different computer programs commercially available and will not be described in detail here.

A important component of the lighting design is the determination of the glare that is produced by the lighting source. The calculations for the predicted glare are dependent on the luminaire type, the mounting height, and the observers position. The basic empirically derived formula for roadway glare (veiling luminance) is as follows:

$$L_v = \sum_{i=1}^{n} \frac{10E_{vi}}{\theta^2 + 1.5\theta}$$

where:

L_v = glare (veiling luminance) at the observer location in cd/m^2

E_v = vertical illuminance on the plane of pupil of the observer's eye

θ = angle between the line of sight and luminaire in degrees

n = number of luminaires in sight

Glare calculations again are very complex and best handled by the commercially available computer programs. The importance of glare as a component of light pollution will be further explored in following sections of this report.

LIGHT POLLUTION

Light pollution has increasingly become a major concern as an environmental impact of transportation facilities. It has been estimated that between 35% to 50% of all light pollution is produced by roadway lighting (Ref 13). Misdirected or misapplied outdoor lighting has prompted many jurisdictions in the United States and Canada to enact control bylaws to alleviate the problems associated with the poor or improper designs.

Roadway lighting, as a supplement to vehicular headlights, is considered essential in all our cities and towns. When the lighting design principles are properly applied the increased visibility provided on the roadways can provide social and economic benefits to the public, including:

- Reduction of nighttime accidents
- Aid to police protection
- Facilitation of traffic flow
- Promotion of businesses
- Inspiration of community growth
- Safety for pedestrians

Light pollution is a generic term that encompasses many different aspects of improper lighting. Each aspect will be discusses separately below. The three major components of light pollution are light trespass, glare, and urban sky glow.

- LIGHT TRESPASS

Light trespass can be described as the effects of light or illuminance that strays from its intended purpose. On a roadway lighting system it is desirable to have all the light directed onto the roadway and not on the adjacent area. Poor quality lighting fixtures, which are generally of a non-cutoff type, will allow some of the light to fall on areas away from the road such a lawns and houses. A poor lighting design, which has employed the wrong luminaire distribution can also lead to unwanted light trespass. Some people are upset by the stray light that enters there property or windows. Related problems also involve the operators of motor vehicles and aircraft.

Light trespass is easily quantifiable as a measure of illuminance and easily measured in the field by a standard light meter (similar to a meter purchased from a camera store). Some limits have been developed by San Diego County in California regarding light trespass. The county ordinance place the limit of stray light at 0.21 lux (equivalent to bright moonlight) on the horizontal and vertical planes at a point 1.5 m inside an owners property line. An ordinance from Skokie, Illinois classifies light falling on residences from a roadway lighting system in excess of 3 lux as a public nuisance. Although these limits cover a wide range of values they serve to illustrate that light trespass is being taken seriously as an environmental problem.

The solutions to minimizing the problems of light trespass are simple and inexpensive. First, the designers must take care to use luminaires with distributions suitable to the roadway. For example, the use of a Type 3 distribution is inappropriate for a narrow residential road where a Type 2 distribution is more applicable. Second, the designer must take care to carry out the calculations properly to ensure the most efficient placement and design. Design levels should correspond as closely as possible to the IES minimum requirements. It is not necessary to apply an arbitrary “safety factor” and overlight an area. And finally, the use of full-cutoff luminaires greatly increase the control of the stray light.

- GLARE

Probably the most annoying and safety related aspect of light pollution is glare. Glare, which can be described as unwanted source luminance, can be categorized into three areas, and is defined by the IES as the sensation produced by luminance in the visual field that is sufficiently greater than the luminance to which the eye has adapted to cause annoyance, discomfort, or loss of visual performance and visibility (Ref 8). The three categories are described as follows:

Blinding Glare: A glare that is so intense that for an appreciable time after the stimulus has been removed no object can be seen or easily distinguished. This is typical of the effect experienced when an oncoming driver forgets to dim the high beam headlights. Many psychologists have quantified this value for various age groups although this data will not be presented here.

Disability glare: Glare that causes reduced visual performance. Disability glare is also known as ‘veiling luminance’ and is cause by the effect of the luminance of a source illuminating the inside of the eye in which the light rays are scattered or reflected within the eye reducing the contrast of images on the retina. This is analogous to turning on the lights in a movie theater and washing out the image on the screen. Disability glare can have serious repercussions on a roadway system as it reduces the drivers ability to distinguish objects clearly. The empirical formula for veiling luminance is listed in the previous section of this report.

Discomfort Glare: Glare that produces discomfort or annoyance without necessarily interfering with visual performance. The IES although has reported that discomfort glare may cause fatigue which may result in driver error. This effect is very subjective and not easily quantifiable although several jurisdictions have applied some limits to the amount of discomfort glare permissible from a lighting system. The California Motor Vehicle Code limits the measured luminance of a light source, within 10 degrees of a driver’s line of sight to not more than 1000 times the minimum measured ambient luminance in the field of view. This ordinance refers not only to roadway lighting but also to commercial signs adjacent to the road. Source luminance can be measured by sophisticated equipment such as luminance meters.

Glare can be easily reduced, although not completely eliminated, by the proper use of cut-off luminaires. Even in the areas not directly related to driver safety, glare is reported as the most annoying aspect of roadway lighting (Ref 2).

- URBAN SKY GLOW

Urban sky glow is the result of stray light being scattered in the atmosphere brightening the natural sky background level. This effect is extremely detrimental to astronomers as well as annoying to many people in the general public. It is sometimes difficult to comprehend the effect of sky glow and the sensitivity of astronomical instruments. Human eyes can barely discern a star of the 6^{th} magnitude which is about 15 million times brighter than a 24^{th} magnitude star that astronomers observe. A candle flame (luminous intensity of approximately one candela) observed at a distance of about one kilometer is as bright as a 1^{st} magnitude star and easily seen by the naked eye. This candle is about 1.5 billion times brighter than the limits of astronomical instruments.

Street lighting has been blamed for up to 50% of the urban sky glow due to 95% of the light directed down toward the pavement being reflected upward at reflectance rates ranging from 6% for asphalt to 25% for concrete (Ref 1). Urban sky glow has been reported to be increasing around 30% annually in some American cities (Ref 5).

An empirical formula has been developed in California by Merle Walker known as Walker's Law (Ref. 5) which is used to estimate the sky glow at an observing site, looking at a zenith angle of 45 degrees toward an urban source r kilometers away.

$$I = 0.01 \times P \times r^{-2.5}$$

where:

I	=	the increase in sky glow level above the ambient background
P	=	the population of the urban center
r	=	distance in kilometers from the urban center

For a city with a population of 300,000 (Greater Victoria) and an observing site 25 km away (Sannich Observatory):

$$I = 0.01 \times 300{,}000 \times 25^{-2.5} = 0.96$$

The increase in sky brightness, at a 45 degree angle, over the natural background is approximately 96%, half of which may be caused by roadway lighting.

Another source of sky glow, possibly of greater consequence (although studies to date are scarce) is the direct luminance from the luminaires above the horizontal plane. Many of the poor non-cutoff luminaires emit up to 10% of their light above the vertical angle of 90 degrees, with up to 30% of their light above a vertical angle of 80 degrees. Full-cutoff luminaires on the other hand emit no light above 90 degrees and considerably reduce the contribution to sky glow.

Other problems related to sky glow comes from the radiation outside the visual spectrum emitted by roadway luminaires. The traffic engineering profession has been mostly concerned with visible light, however astronomers observe the sky in many wavelengths. The use of full spectrum lights such as mercury vapor and metal halide emit high degrees of ultraviolet radiation. The use of high pressure sodium lights emit a more monochromatic light which can be easily filtered out by astronomical equipment.

Although urban sky glow has been difficult to quantify, some jurisdictions, particularly those around observatories such as Tucson, Arizona, have enacted ordinances requiring the use of full-cutoff luminaires and glare shields for roadway lighting.

Some of the more minor aspects of light pollution involve confusion, clutter, energy waste, and general annoyance.

- CONFUSION

Confusion or visual distraction is caused by a large number of lighting sources with noticeable source luminance, such as unevenly spaced roadway lights, which may cause distraction instead of guidance. This can also include lighting sources from commercial establishments such as illuminated signs and flashing lights. Many cities have enacted bylaws restricting or limiting the use of such signs and devices.

An interesting example of confusion caused by roadway lighting is illustrated by the admonition on the aeronautical charts for approaches to Miami Airport, warning pilots to avoid landing on the brightly lit highway adjacent to the airport.

- CLUTTER

The adverse aesthetic effect caused by considerable wasted light is characterized as clutter. The lighting design should be used to enhance the aesthetics of the area not destroy it.

- ENERGY WASTE

Energy wasted by the misdirection of roadway light is a direct side effect of light trespass. Light trespass can be correctly equated to wasted energy. It has been estimated by research undertaken by the International Dark Sky Association (Ref. 5) that up to 30% of all roadway lighting is lost or misdirected from the intended source. IDA has translated this energy loss in the United States to over $1 billion per year as well as the corresponding increases in air pollution resulting from this wasted energy.

- GENERAL ANNOYANCE

For some people any amount of obtrusive lighting is considered an annoyance. Although this is a completely subjective matter it is the duty of engineers and designers to be aware of any and all effects there designs may have on the public. Some researchers are working on developing an average Visual Comfort Probability Index in order to try to quantify this matter (Ref. 3).

As seen above many jurisdictions have been developing light control standards on an ad-hoc basis for the various areas of light pollution. To date the two main lighting organizations the IES and the CIE (Commission Illumination d'Eclairage) have not produced any definite guidelaines or standards. Both organizations, however, are actively working on the subject and have produced many working papers, many of which have been researched for this paper.

RELATED ENVIRONMENTAL ASPECTS

Besides light pollution the installation of roadway lighting has several other negative side effects which can be loosely associated with environmental impacts. These include color of the lighting sources used, visual intrusion associated with the lighting structures, and the roadside hazards the structures impose on the highways. Although not dealt with in depth by this report it is beneficial to be aware of these items when designing a roadway lighting system.

- COLOR

  Various different light sources for roadway lighting exhibit different color characteristics. Mercury vapor luminaires produce a white, full spectrum light, which is pleasing to designers, architects, and town planners. The problem with mercury vapor luminaires is that they are very energy inefficient compared to some of the other sources. Full spectrum light is also disliked by astronomers. High pressure sodium luminaires produce the familiar yellow light used by most roadway lighting installations today. This light is more monochromatic than mercury vapor and has poor color rendition. For this reason it is not well liked by planners, architects, and much of the general public. It is, however, liked by astronomers who can more easily filter out monochromatic light. The HPS luminaires are about twice as energy efficient for the same lumen output as mercury vapor. Metal halide luminaires produce a full spectrum light similar to mercury vapor and give good color rendition. Their energy consumption per lumen is about half way between that of HPS and MV. The lamp life for metal halide is shorter than either of the others and they fall out of favor with maintenance personnel. Many jurisdictions have compromised by using mercury vapor or metal halide in downtown and people oriented areas and high pressure sodium along arterial routes and highways.

- VISUAL INTRUSION

Lighting structures add to the visual intrusion and negatively impact the aesthetics of an area. This is a very subjective matter and difficult to quantify. As streetlight poles are tall but very narrow they do not fit easily into the standard visual intrusion prediction formulas using the solid angle predictor. Designers should however be aware that complaints may arise from using particularly large lighting structures, such as high-mast lighting poles near residential areas.

- ROADSIDE HAZARDS

The large number of lighting poles along roadways significantly adds to the hazards for the driver. From a safety aspect it is preferable to use fewer taller poles with higher wattage lighting sources. A trade off is made, however, with visual intrusion, light trespass, and glare. A properly designed lighting system should be able to minimize the light pollution aspects.

CONCLUSIONS

Light pollution is becoming an increasing problem in our modern urbanized society and must be dealt with. For many years it has been generally overlooked by engineers, possibly because items such as air and water pollution have attracted much more attention from the public. As 35% to 50% of all light pollution is caused by roadway lighting it now becomes the responsibly of the traffic engineer to face the problem and find solutions. The solutions to the problem are quite simple any only the require the political will to act.

First, all roadway lighting systems should be required to use efficient, full-cutoff luminaires to control the light output. This will not only reduce the level of light pollution but will also save energy and produce a more aesthetic and pleasing environment. Secondly, all lighting designers must be encouraged to undertake their designs using the latest design principles and design programs available. This will ensure efficient designs which will not result in unnecessary overlighting of roadways.

Many individuals may say it is already too late. There are already an estimated 20 million roadway luminaires in service in the United States and Canada, the majority of which are the inefficient non-cutoff type. The service life of a roadway luminaire, however, is only a maximum of 25 years. If all new lighting designs are undertaken using light pollution reducing luminaires and all existing designs were retrofitted with these luminaires as their service life comes due the entire system throughout the continent would be done within 25 years.

Research in this subject is ongoing in many areas but there is still much to be done. All traffic and lighting engineers should be encouraged to support research and development in this area as it will benefit everyone for years to come.

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Much of the information and literature gathered for this study was obtained from the Internet. The following World Wide Web sites provide excellent technical and general information regarding light pollution and lighting design.

Illuminating Engineering Society of North America

URL: http://www.aecnet.com/IES/ieshome.html

International Dark-Sky Association

URL: http://www.darksky.org

Commission Internationale d'Eclairage (CIE)

URL: http://www.hike.te.chiba-v.ac.jp/ikeda/CIE/home.html

New England Light Pollution Advisory Group

URL: http://www.harvard.edu/cfa/ps/nelpaq

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