Light Trespass Research

Technical Report

Light Trespass Research

TR-114914

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REPORT SUMMARY

Concern for problems created by unwanted lights in the nighttime environment is increasing. This light assumes numerous forms and creates various problems. With increasing awareness of environmental issues, it is important that local governing bodies and lighting designers recognize the need to control problems related to “light trespass.” This report provides basic data for defining general light trespass controls.

Background

In the 1980’s, it became apparent that control of light trespass and development of meaningful ordinances would not be an easy task. “Light trespass,” in fact, had not been defined. It was recognized that many factors were involved, but these were not categorized and no numerical information was available to provide the basis for light trespass controls. To define problem parameters and produce meaningful information for addressing the situation, a research program was needed. This project, cosponsored by the Lighting Research Institute, is a first critical step in that direction.

Objectives

- To define the nature of light trespass problems.
- To rank the various sources of light trespass according to their seriousness.
- To identify environmental zones where control of light trespass is considered necessary or desirable.
- To propose general, non-locale specific ordinances for these environmental zones.

Approach

The project's initial step was to organize a seminar on the subject, held in conjunction with the Edison Electric Institute Street and Area Lighting Conference in Alexandria, Virginia, March 19th and 20th, 1991. This meeting focused on defining the nature of light trespass problems and ranking the various sources of light trespass according to their seriousness. Based on the results of a questionnaire completed by all participants, members of the IES Roadway Lighting Committee, and power company representatives, a program was developed to investigate light source characteristics that produce light trespass. Using the results of this research and data from several other resources, the team developed basic recommendations for controlling light trespass.

Results

Based on the extent to which control of light trespass is considered necessary or desirable, the project proposed four environmental zones. For each zone, the report provides general recommendations for lighting ordinances (including pre- and post-curfew light trespass levels).

EPRI Perspective

This report provides guidelines to assist in ordinance development based on a flexible framework (it is not the report's intention to develop a widely adoptable model ordinance). Local conditions and viewpoints must always be considered. In this regard, the Illuminating Engineering Society of North America (IESNA), which serves as the prime authority for lighting matters, may wish to develop a model ordinance or several ordinances based on differing community needs. In such an effort, EPRI hopes that this current research will be of value.

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Keywords

Light trespass
Outdoor lighting
Street lighting
Glare

FOREWORD

Lighting Sciences Inc. wishes to express appreciation to the Lighting Research Institute, LRI, for developing and sponsoring this work. Thanks also are expressed to the various organizations which provided funding through LRI, including the Roadway Lighting Committee of IESNA.

Specific thanks are also due to Wisconsin Electric Power Co., Pennsylvania Power and Light and San Diego Gas and Electric Co. for providing major funding for the effort.

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1
INTRODUCTION

There is increasing concern for the problems created by unwanted lights in the nighttime environment. This light may take numerous forms and result in various problems. Particularly with increasing awareness of environmental problems of all types, it is important that lighting designers recognize the need to control problems related to the general subject of “Light Trespass”, or “Obtrusive Light” as it is sometimes called.

Numerous local communities, cities, countries, and states have developed ordinances to control unwanted light. These ordinances vary greatly, from simple to complex. They vary also in the aspects of lighting which they seek to control. There is no coordinated effort to create uniformity among such ordinances as no central authority has developed guidelines to assist in the writing of these ordinances. This problem will be compounded with time as the number and diversity of ordinances increases.

In the 1970’s, a particular form of unwanted light was identified, that of sky glow caused chiefly in urban areas. This resulted from light emitted above the horizontal from outdoor lighting devices and from light reflected from surfaces. The rapidly increasing problem had a major effect on the ability of astronomers to use ground-based telescopes in proximity to urban areas. The term used to describe these effects is “Light Pollution.”

Astronomers and others active in the effort to control the spread of light pollution lobbied for the development of light pollution ordinances. These are now in place in many areas, Arizona and California in particular. Twenty years later, these ordinances have been seen to be successful in reducing the spread of light pollution. As a result also of environmental awareness, lighting design techniques and luminaires have changed in a manner generally believed to be better for all.

Sky glow, however, is just one aspect of unwanted nighttime light. Just as widespread are problems associated with spill light encroaching onto properties adjacent to the lighted area, and the objectionable nature of the direct viewing of bright light sources. While the need and value of outdoor lighting is widely appreciated, it is also recognized that poorly designed lighting will produce problems which must be addressed.

In the 1980’s, it became apparent that the control of light trespass and development of meaningful ordinances would not be an easy task. “Light trespass,” in fact, had not been defined. There existed simply a feeling that many factors were involved, but these were not categorized and no numerical information was available to provide the basis for light trespass controls. A program of research was needed to define the parameters of the problem and produce meaningful information so that the situation could be addressed.

The Lighting Research Institute, LRI, of New York developed a problem statement and invited bids for the conducting of a research program. Lighting Sciences Inc., LSI, of Scottsdale, Arizona was the successful bidder. LRI provided funding from its sponsors to commence the work. Additional funding was donated by the Roadway Lighting Committee, RLC, of the Illuminating Engineering Society of North America, IESNA. Major funding which allowed the research to continue past its initial stage was donated by Wisconsin Electric Power Co.

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LIGHT TRESPASS: THE BASICS

While the nature and causes of astronomical light pollution were well known, the preliminary work effort required fundamental definition of "light trespass" and its various causes.

Definition of Light Trespass:

> *Unwanted light which, because of quantitative, directional or spectral attributes in a given context, gives rise to annoyance, discomfort, distraction, or a reduction in the ability to see essential information.* (Taken from the CIE definition for the term "obtrusive light.")

From this definition it can be seen that light trespass can be caused by several characteristics of nighttime lighting. These include:

- Spill Light. The presence of lighted area(s) beyond the primary area which the source is intended to light. Illuminance is produced outside of the property line containing the luminaire.
- Brightness. The presence of bright source(s) within the observer's field of view which are objectionable.
- Glare. The direct viewing of luminaires which may cause discomfort (discomfort glare), and/or a reduction in the visibility of significant visual tasks (disability glare).

These characteristics are in addition to light pollution effects noted earlier which are of primary concern to astronomers.

Light trespass will affect several classes of observers, which are primarily:

- Neighborhood residents. Encroachment of light over a residential property line, "or spill light", may be found objectionable. Entry of unwanted light into a residence, for example a bedroom window, is a commonly mentioned problem. Direct viewing of bright light sources also is frequently objectionable, particularly in neighborhoods where a low level of ambient light is considered desirable.
- Drivers. Bright light sources may seriously affect a driver's visibility because of disability glare. In addition, visual confusion created by extraneous light sources can effect the ability to locate and recognize signal lights.

It is apparent therefore that research in the field of light trespass must recognize the diversity of the effects. Such effects, however, can be broadly grouped, firstly into spill light in residential areas, and secondly, the presence of bright sources over a wide range of conditions.

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THE SEMINAR AND SURVEYS

The initial step in the project was to organize a seminar on the subject, held in conjunction with the Edison Electric Institute Street and Area Lighting Conference in Alexandria, VA, March 19th and 20th, 1991. This meeting focused on defining the nature of light trespass problems and ranking the various sources of light trespass in accordance with their seriousness. The following questions were directed to the participants:

1. What constitutes light trespass? Your comments are solicited to develop an in-depth definition of the problem. Spill light from street lighting? Ball field lighting? Residential lights? Sky glow?
2. Who is affected? What is the nature of the complaints?
3. Esthetics and safety. Does light trespass constitute a safety problem or is it chiefly aesthetically offensive?
4. What is the visual nature of light trespass? Is the problem the glare of bright offensive lights, or is it the illumination of areas which are preferred to be dark?
5. How can we numerically define the problem? What measurable quantities should be considered?
6. How can acceptable levels of light trespass be specified and ordinances developed? What regulations are now in effect? Have they been successful?
7. Looking to the future, can some form of simple meter be developed to check light trespass levels against ordinance specifications?

A questionnaire was developed which was completed by all participants, see appendix C. The questionnaire also was sent out to members of the IES Roadway Lighting Committee and power company representatives. Approximately 50 responses were received.

Respondents were asked to rate the seriousness, in their opinion, of various forms of light trespass within their geographical area or jurisdiction, with results as follows:

Most serious:	Glare from ball fields
Moderate:	Spill light from roadways and parking areas Spill light from ball fields Roadway or other light sources entering residence through windows Glare from roadway lighting Glare from advertising signs Glare from building floodlights Glare from retail operations

In addition, light pollution affecting astronomers was ranked from not serious to very serious, presumably depending upon geographical area.

Other sources of light trespass mentioned in the comments were as follows, in decreasing order of importance:

Residential spill light
Signage
Sports lighting
Car sales facilities
Commercial floodlighting
Improperly aimed security lighting
Incandescent sources in downtown areas
Shopping center lighting
Roadside markets

It is apparent that there can be some overlap in the categories, e.g., car sales facilities may have been categorized by some respondents as commercial floodlighting.

Respondents also were queried about the nature of light trespass, and what creates the offending conditions. Greatest offense was caused by directly viewed glare sources, although spill light from adjacent properties onto their surroundings also was rated as highly offensive.

A solution to the problem of glare sources was felt to be essential by most respondents. A solution to spill light was felt to be desirable.

Respondents indicated that they receive anywhere from 3 to 100 complaints per year concerning light trespass.

The questionnaire requested information regarding the types of lighting equipment and lighting practice which create light trespass problems. This is a similar question to that in paragraph 1 above, but requested more details. Problems were outlined as follows:

Very important:	Dusk-to-dawn lights Street lights with inadequate optical control Ball field lighting/sports Commercial lighting
Moderately important:	Use of lamps of excessively and unnecessarily high lumen output Incandescent floodlights Not extinguishing lights when not in use
Low importance:	Searchlights for advertising Landscaping lighting Light reflected off surfaces close to the luminaire

In general, the opinions provided in answer to the questions match those presented earlier.

Respondents were asked what items should be included in ordinances. The suggestions were as follows:

Very important:	Specification of some form of shielding Applying a limit to the amount of glare
Moderately important:	Place a limitation on the amount of allowable spill light over the property line Restriction on the time of day (i.e.; mandatory switch-off time)

Respondents felt that ordinances should be written so as to specify acceptable lighting practices which could be verified by plan check, but that compliance verification by the use of a field meter also should be possible. As expected, a low cost meter is preferred.

In terms of developing ordinances, most felt that the project should develop guidelines for ordinances rather than the development of a model ordinance.

4
SUBJECTIVE TESTING

A program was developed to investigate the characteristics of light sources which produce light trespass. Source brightness had been generally identified as being the principle characteristic to which persons object. Spill light was seen as a less significant effect. It was decided therefore to design experimentation to identify quantitatively the relationship between source brightness and the degree to which the light source was found objectionable.

Brightness is a difficult characteristic to investigate. It is the observed effect of the source's physical luminance, and as such is related to the intensity of the retinal image. This in turn will be affected by characteristics of the observer's eyes. The measurement of subjective brightness is not practical under the conditions of the experimentation, nor could brightness be used to realistically limit the luminaire appearance in a practical ordinance.

It is thus logical to base the research on source luminance, or physical brightness. The relationship between luminance and subjective brightness is affected primarily by the level of ambient light. Meaningful research therefore can be conducted to relate source luminance to the observer's reaction, if conducted under different ambient levels. Recommendations then must be developed for these different ambient levels, and in doing so, source luminance will be a realistic indicator of source brightness.

The Experimental Design

Observational experiments were planned where human subjects would be presented with several different situations and tasks, in the presence of a test fixture. This test fixture would consist of a controlled source of light of known photometric characteristics. By varying the location, size, and luminance of the test fixture, subjects would determine the degree to which the source was objectionable while conducting the various tasks.

The Test Fixture

A simple test fixture was developed which provided the necessary variability for the experiments. The fixture consisted of a plywood box, 2 x 2 ft. square and 1.5 ft. deep. Figure 4-1. Inside the box, nine medium base sockets were installed, all connected in parallel. A 150 watt reflector incandescent lamp having a flood-light distribution was placed in each socket, aimed towards the front aperture. The inside of the fixture was painted white.

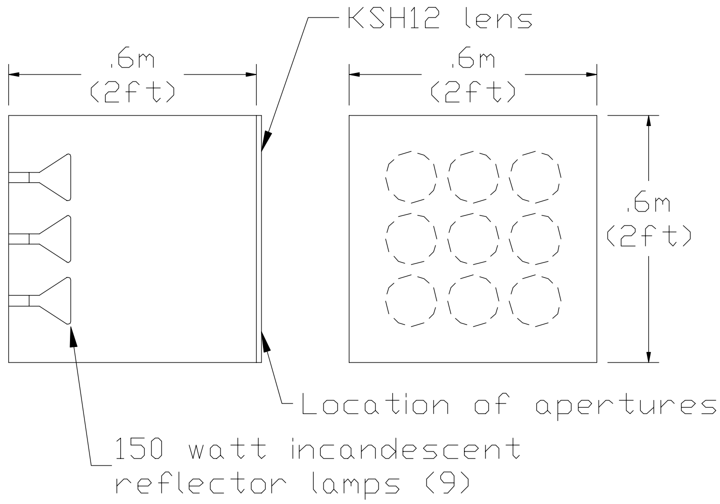

Figure 4-1
Test Fixture

Initial experiments were run to determine the transmitting material to be placed in the aperture to provide diffusion of the light and to create good uniformity of appearance. The material found satisfactory was KSH12 lens material as commonly used in fluorescent luminaires. This lens also has the advantage of high transmittance.

Voltage supplied to the test fixture was via a variable transformer. A Valhalla power analyzer was coupled to the test fixture to monitor voltage, current and wattage.

Removable front apertures were constructed which could be used over the diffuser panel. Two sizes were made to provide apertures of .3 x .3m (1 x 1 ft.) and .46 x .46m (1.5 x 1.5 ft.), while the use of no aperture allowed exposure of the full .6 x .6m (2 x 2 ft.) area.

Photometric testing was conducted to establish the relationship between source voltage and luminance for a direction of view normal to the test fixture front surface, for the three aperture sizes.

The Observers

Preliminary experiments were run with employees of Lighting Sciences Inc. to identify any procedural problems. The data so derived were not included in the final results.

A total of 30 observers were used in the actual experiments. Age ranged from 20 to 60 years. 14 male and 16 female observers were used.

The Experimental Procedure

Prior to the experiments, each subject was provided with simple written instructions. See Appendix D.

A reporting form was developed for subjects to record the degree to which they found the test fixture objectionable under the particular conditions. No attempt was made to describe to the subjects how they should interpret the meaning of each of the adjectives in order not to influence the data by the opinions of the person organizing the experiments.

Lighting Conditions and Tasks

Numerous situations were considered for conducting the experiments. Due to the number of possible permutations of visual task type, ambient lighting and task fixture condition and location, only a few carefully selected conditions could be tested. The selected conditions were:

1. Observers in a room watching television. The test fixture was located outside of a window to simulate a street light or floodlight. The interior lighting level was low, averaging 5.0 lux. The distance from the observers to the light source was approximately 10m (32 ft.).

2. Observers mingling in an exterior area with a low level of ambient lighting of just under 2 lux (0.2 fc). The sources of this light were building perimeter light and distant street lighting. The test fixture was located peripheral to the area at a height of 3m (10 ft.). The distance from the observers to the light source was approximately 15 meters (49 ft.)

3. As 2 but with an ambient illumination of approximately 20 lux (2 fc).

In the exterior experiments, the test subjects were not instructed to perform any particular task but to judge conditions on the basis of being located on a residential property.

The Experiments

A total of 36 test box conditions were used for each experiment, consisting of 12 different luminance levels for 3 aperture sizes. Using three experimental locations and 30 observers, the total number of observations was 30 x 3 x 36 = 3240.

For each experiment, the luminance and aperture sizes to which the subjects were exposed were chosen by the Latin squares method to ensure randomness. While the luminance and apertures were being changed, the test fixture was screened from view.

Luminance levels were controlled by means of voltage to the test source. Voltages were set to various levels to create luminance levels as predetermined by photometric testing. The preliminary subjective testing had indicated the general range of luminances required as being from 2000 to 7500 cd/sqm. Accordingly all testing was run between these two limits, in steps of 500 cd/sqm, but in random order.

Test Results

Results were converted to a numerical measure by assigning the following points to each response:

5. Extremely objectionable
4. Very objectionable
3. Quite objectionable
2. Slightly objectionable
1. Not objectionable

Points were analyzed for each experimental condition, both as the average for all observers and individually.

For each individual test condition, there was a wide range of ratings assigned by the individual observers, as expected. In general, however, responses showed a range of 2 to 3 points on the objectionable scale. It was rare, for instance, to find one observer judging a test condition to be "slightly objectionable" while another judged the condition to be "extremely objectionable."

In order to handle the spread of results for a given test condition, an average score was calculated using the responses of all observers. This is termed "Objectionable Rating" or OR. This rating, in theory, can vary from 1 to 5, although in practice OR values tend to be concentrated between 2 and 5.

Figure 4-2 presents the results of the indoor testing and provides a plot of these data. OR data are provided for all 12 luminance levels and the three aperture sizes.

Figure 4-3 presents equivalent data for the outdoor test conducted under low ambient conditions and provides plotted data.

Figure 4-4 gives the data and plots for the outdoor test for medium ambient conditions.

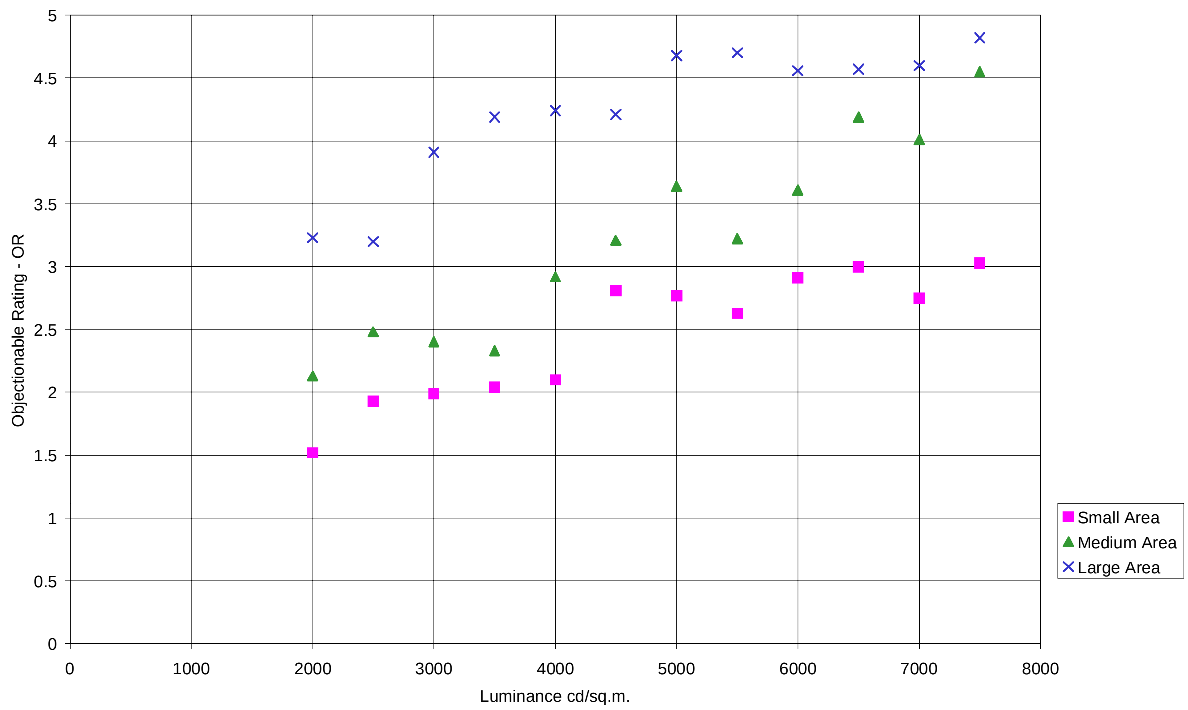

Figure 4-2
Results of Indoor Testing

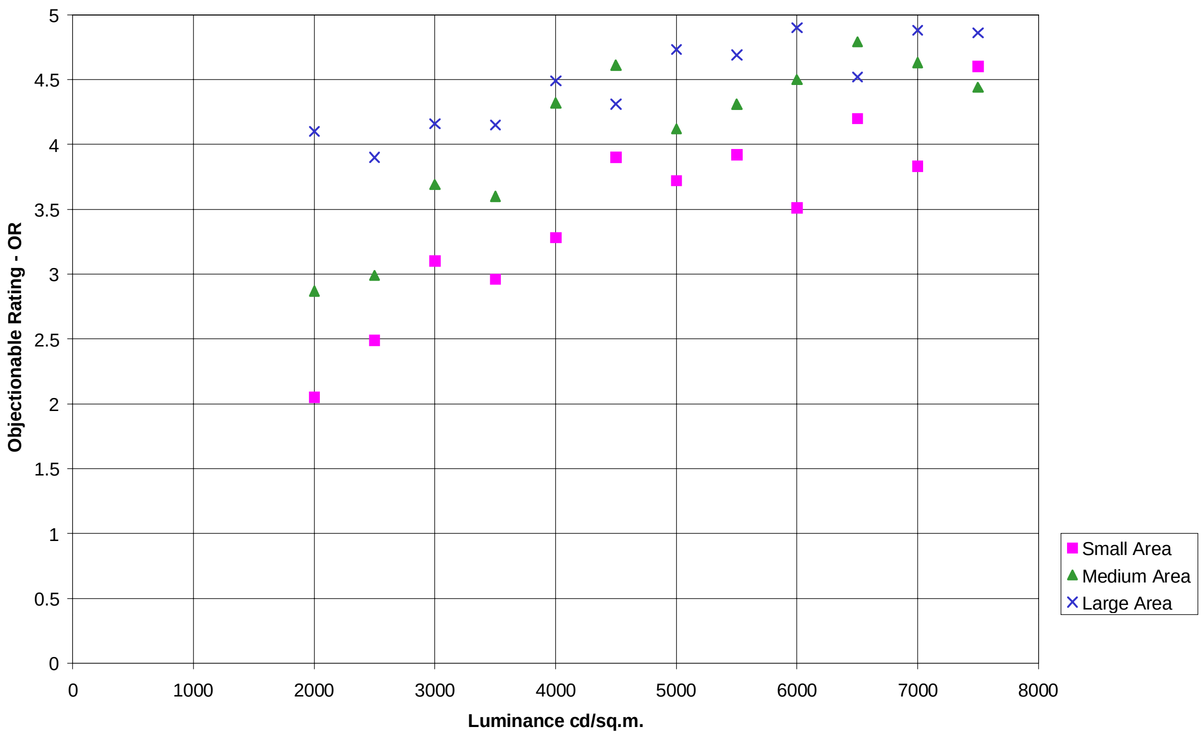

Figure 4-3
Equivalent Data for the Outdoor Test Conducted Under Low Ambient Conditions

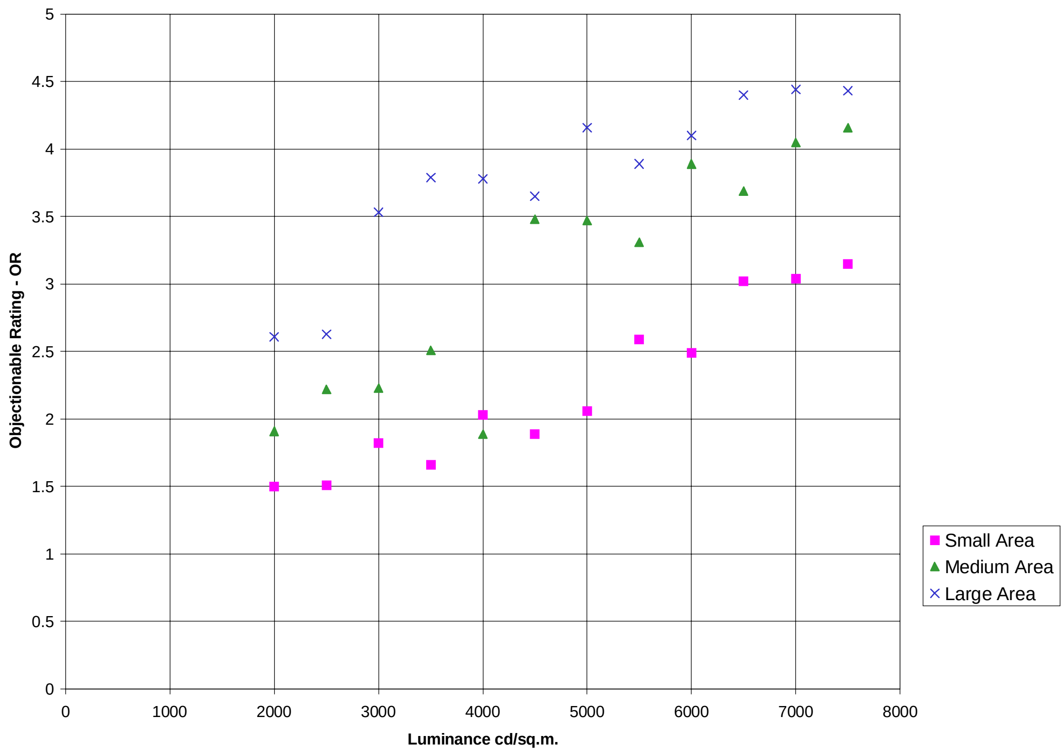

Figure 4-4
Equivalent Data for the Outdoor Test Conducted Under Medium Ambient Conditions

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ANALYSIS OF RESULTS

There is substantial diversity between the reactions of individual subjects, as is normal in all evaluations of this type.

Data analysis can most readily be seen by viewing the plots, figures 2, 3, and 4. Each of the three experiments indicates the same general trends, all of which appear to be logical.

Close examination of the data reveals significant insight into the relationship between the characteristics of the light source and the degree to which it is objectionable.

As a broad summary, the data indicate the following:

1. For a given size of test fixture aperture, increasing luminance causes an increase in the OR, under otherwise identical test conditions.

2. For a constant luminance level, increasing the aperture size increases the OR, other factors being constant.

3. The ambient lighting level has a significant effect upon the OR.

Due to the wide number of possible variables in testing of this type, and the enormity of the task of evaluation of all possible variables, each test was conducted at a fixed distance between the subjects and test light source.

However, while not a part of the full experiment, subjects were asked to move away from the source to distances of up to 150 m (480 ft). They were then asked whether their rating of the source had changed. In virtually all cases, subjects indicated that the degree to which the light source was objectionable decreased as distance increased. This again is logical: a source which may be offensive at 10 m may not be a problem at 1 km.

This leads to a further conclusion: Test distance from the test fixture to the subject affects OR, with decreasing OR for increased distance.

All of these general conclusions appear to be reasonable and unsurprising. It may almost be assumed from cursory examination that such results would be obtained. When we perform a detailed analysis, however, it becomes apparent that important information is provided which allows us to derive a clear indication of what causes negative reaction to unwanted sources of light. This in turn leads to the derivation of a quantitative basis by which such light trespass effects can be evaluated.

Regarding variability between observers, such is normal in any subjective testing program. Furthermore, another important factor must be considered in this research, that being the involvement of emotional or personality factors. Most subjective evaluations involve judgments where physical conditions are presented to observers. These observers may be asked to respond when they see a light source, or perhaps judge when two sets of visual conditions appear similar. In the testing involved here, however, subjects can vary greatly in emotional response. A particular source of light trespass under given conditions may be highly objectionable to one observer, who may feel strongly that extraneous light sources should not encroach upon their environment. Another observer may be relatively oblivious to such light trespass.

Considerable variation in observer reaction therefore does not indicate lack of proper controls in the test conditions or a reduced validity of the data. Rather it is exactly as would be expected when human reactions are being documented which are strongly dependent on individual attitudes and personality.

Even given the wide spread of results for any particular test condition, the trends are strong and significant.

As is fundamental to the form of experiment, the OR rises as the degree of light trespass increases. With increasing trespass, the OR becomes constant. This is due to the rating system: No condition can be rated higher than “very objectionable” and the associated point score cannot exceed 5. Thus when light trespass conditions are so severe that most or all observers rate the situation as very objectionable, no further increase in the OR is possible.

Considering the relationship between luminance and OR, the anticipated connection is found: Changing luminance is a major controlling factor in the observer reactions. Such a conclusion is obvious; but what the results provide is a quantifiable basis for the derivation of limits and recommendations for light trespass control. Other factors beside luminance, however, must be considered.

The area of the aperture which exposes the test fixture luminance to the subjects is found to be important. This is not unnatural: An observer presented with a very large area of high luminance can be expected to find it more objectionable than a very small area of a similar luminance, which may not be objectionable at all. This result, however, has considerable significance: It teaches us that the observers do not simply react to the level of luminance but to a combination of luminance and source area. Considering this further, our assumption might be that the observers are reacting in fact to intensity, intensity being the product of luminance and area.

Applying additional analysis will cause modification of this possible conclusion. It has been noted that test distance has a significant effect upon the rating assigned by the subjects. Again, this is a reasonable result. Consider a source of a given luminance and a given size. If such a source is within a few meters of the subject, this may be highly objectionable. If this same source is hundreds of meters away, the degree to which it is objectionable is likely to be substantially reduced.

The effect of test distance tells us that subjects react not simply to intensity, but a combination of intensity and distance. A quantity which combines these two factors is illuminance at the eye.

Increasing intensity increases the OR, while increasing distance reduces the OR. OR therefore behaves in a manner similar to the illuminance at the eye.

It cannot be concluded with certainty that OR is related to intensity and distance in precisely the same way as illuminance. Because of the wide spread in the subjective ratings for a given condition, precise relationships should not and cannot be derived. We do not know whether there is a linear relationship between OR and intensity, nor whether OR follows the inverse square law as does illuminance. However, it can be argued that this is irrelevant, as OR is an arbitrary scale without absolute meaning. OR is derived and should be analyzed broadly, as a means of showing trends to be used to develop general conclusions. Such a conclusion, which appears reasonable from the data, is that illuminance at the eye is a useful measure of the degree of light trespass.

We must further consider what form of illuminance is most reasonable to use as a measure of light trespass for a bright light source. Illuminance may be calculated and measured on a horizontal plane, a vertical plane, or any slope plane between the two. Further, a vertical or slope plane may be oriented to face in any horizontal direction.

The most logical plane upon which to evaluate illuminance appears to be the plane perpendicular to the line of sight. This is one measure of light entering the eye, which, of course, is the source of the light trespass problem. It is also well established that a prime factor in the evaluation of disability glare is the vertical illuminance at the eye. We cannot assume that light trespass and disability glare are quantitatively identical. There are separate variables which affect each of these. It appears quite reasonable, however, to assert that illuminance perpendicular to the line of sight is a significant factor which affects both.

One further point requires consideration: Observers tend to view sources of light trespass by looking directly at them. Even when attention is away from the offending sources, the eyes look in a variety of different directions under most practical situations. Thus there is an additional variable which is uncontrolled: The angle between the line of sight and the offending source. There is no definite basis for using any particular such angle in our analysis. The worst, and quite normal, situation is for the observer to view the offending source directly. It is therefore logical to use the illuminance at the eye on a plane perpendicular to the line of sight as a quantitative indicator of the amount of light trespass caused by the appearance of an offending source. This conclusion is seen as a significant result of the research project. It will be used in later sections as the basis for developing criteria for light trespass control.

Relationship to Other Research

An important document covering this subject is the CIE document titled "Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations". Reference 1. The CIE committee has developed conclusions which fall into two broad categories: light trespass control firstly requires adherence to certain limits on spill light, or illuminance of the ground (or other horizontal surfaces) beyond the property area of the property being lighted. Secondly, limits are provided for the control of intensity of offending sources. This first set of limits, applying to horizontal illuminance, will be evaluated later. The second conclusion, that light trespass can be evaluated on the basis of intensity, requires closer scrutiny.

The CIE committee states that the luminance of the offending luminaire(s) is a proper measure by which to control light trespass. Due to the difficulty of measuring luminance, however, this conclusion is modified to recommend the use of intensity as the controlling factor, on the basis of the two quantities being directly related. No basis is quoted for the assumption that luminance is the proper factor to address for the control of bright light sources. As indicated by previous rationale in this report, effects of luminaire size and distance between the observer and the source are significant. Our conclusion of illuminance on a plane perpendicular to the line of sight therefore is different from the CIE report, but we believe there is ample justification for our conclusion.

The CIE provides a very worthwhile basis for categorizing areas based upon environmental impact. It also contains much useful information regarding the development of a framework for a recommended practice. It further provides numerical limits, although as noted these are based on spill light levels and luminaire intensities. Where logical and applicable, the principles of the CIE system have been incorporated in this report so that any approach developed from this work for North America is unified with CIE practice to the extent possible.

Multiple Luminaires

A further factor which must be addressed is the presence in the field of view of multiple luminaires. Are light trespass limitations to be derived to apply to all luminaires, to each luminaire singly, or to particular groups of luminaires?

The entire field of view may contain a very large number of luminaires; for example, an urban area may have street lights, parking lots, signage and other neighborhood property lights. The aim of an ordinance is to control a particular lighting installation or luminaire on a specific property. It is not usually practical under normal circumstances to control the entire night-time scene. Thus an ordinance cannot reasonably apply to the entire array of all luminaires on all properties. In fact, numerous extraneous sources will create a general increase in nighttime brightness which may mitigate the effect of a lighting installation on one particular property. This effect can be addressed under area classifications in an ordinance.

The aim of an ordinance is to control excessive brightness from particular luminaires. If a single luminaire is judged to be objectionable, then the lighting system as a whole must be objectionable. To provide proper control, therefore, an ordinance must logically be applied to individual luminaires. The recommendations in this report have been developed on this basis.

This conclusion is entirely consistent with methods used for establishing disability glare limitations, which as noted earlier, appear to bear some relationship to light trespass effects.

As a further point, the illumination at the eye on a plane perpendicular to the line of sight was stated earlier to apply to the viewer directing the line of sight to the luminaire. If this is now to be applied to a system, we have multiple lines of sight. How is the illuminance level to be calculated and measured?

A difficulty in applying limitations to the light level produced from a single luminaire is that frequently there is more than one luminaire on a pole. If there are two luminaires on a pole, for instance, they are usually so close together that the eye is essentially aimed at both luminaires together. Thus our limitations should logically be applied to a group of luminaires on a pole. This approach has a further advantage: measurement of the light from such a group of luminaires is relatively simple, while measurement of individual luminaires contained in a group may not be.

In any case if a particular luminaire, or set of luminaires on a pole, appears to be the cause of a light trespass problem, this could be checked by calculation or measurement, as well as the entire system.

Spill Light

The foregoing has discussed the problem of direct viewing of bright light sources. As stated, a further factor to be considered is the encroachment of light on surfaces outside of the property intended to be lighted. A reasonable measure of such spill light is the horizontal illuminance on the ground in the adjacent areas. Several ordinances have been developed using this as the factor to be evaluated in the control of light trespass. Other ordinances have used illuminance at certain heights above the ground. A further variation is the points at which the illuminance limitations apply: At the property boundary itself or a certain distance within the area onto which light spills.

It should be remembered that this form of spill light is generally considered to be of much less significance than the direct viewing of bright luminaires.

If we examine the geometry of typical lighting systems, an assessment can be made of the relative effects of spill light versus offensive brightness (as measured by illuminance at the eye).

Lighting geometries were evaluated which cover common situations. On the basis of given intensities, calculations were performed for horizontal illuminance values at ground level, Eh, and illuminance levels at the eye perpendicular to the line of sight, Ee. As the distance from the luminaire to the eye increases, Ee falls in accordance with the inverse square law only, as the angle between the line of sight and the direction of the light ray is zero degrees. In the case of Eh, the illuminance falls much more rapidly due to the influence of the cosine of the angle of incidence. For normal nighttime intensities, the illuminance at the eye remains a significant value at distances far from the source, while the horizontal illuminance falls almost to zero. Using some of the figures recommended in the CIE document in such calculations very strongly suggests that when conditions are satisfactory for controlling source brightness, any reasonable limitations of horizontal illuminance will easily be met. For this reason and because spill light is generally regarded as being a minor contributor to light trespass problems, it appears reasonable to exclude limitations on ground illuminance from recommendations. Eye illuminance limits should be sufficient to satisfy both concerns in almost all situations.

We can conclude, therefore that it is unnecessary to complicate an ordinance by requiring adherence to two sets of specifications, spill light and source brightness evaluated by eye illuminance.

Development of Recommendations

Data are available from the research work undertaken in this project, and from several other sources (see References 1-9). Development of recommendations has been undertaken using these various sources in order to obtain as broad a perspective as possible.

Task 1 is to develop area categories. It is apparent that the nature of the area, and the sensitivity to light trespass which exists, will strongly influence the light trespass control requirements. Task 2 then is to develop meaningful quantitative recommendations for the various area categories.

Area Classifications

The principles of area classification which are to be recommended for incorporation into an ordinance must be logical, both to lighting personnel and others. The classification system must be simple so that there is minimum difficulty in determining into which area category a particular property falls. In addition, the system must be flexible enough to accommodate the opinions and wishes of widely diversified communities.

In examining the CIE system, it is apparent that considerable thought has been given to this subject. A framework has been developed which appears to fulfill the necessary objectives. Rather than developing a completely different set of area classifications, it appears logical to review the CIE system.

Areas may be classified into a series of environmental zones, based upon the extent to which control of light trespass is considered necessary or desirable. These are described as zones E1, E2, E3, and E4.

E1. Areas with intrinsically dark landscapes. Examples are national parks, areas of outstanding natural beauty, or residential areas where inhabitants have expressed a strong desire for strict limitation of light trespass.

E2. Areas of low ambient brightness. These may be outer urban and rural residential areas. Roadways may be lighted to typical residential standards.

E3. Areas of medium ambient brightness. This will generally be urban residential areas. Roadway lighting will normally be to traffic route standards.

E4. Areas of high ambient brightness. Normally this category will include urban areas with mixed residential and commercial use with a high level of nighttime activity.

Utilizing four categories is probably sufficient for ordinances. If a lesser number were used, the categories likely would be too broad to serve their intended purpose. A greater number will produce unnecessary further complications in the document.

Curfew

Numerous ordinances, and also Reference 1, refer to the use of curfews. As an example, floodlighting of neighborhood sports areas was found to be the most objectionable source of light trespass in our survey. Yet if such lighting is to be allowed at all, even when well designed, it is likely to cause a trespass problem. Many existing ordinances therefore require that lighting of certain types be extinguished at a particular hour.

Establishment of curfews is a logical method to provide partial control of light trespass. In fact, in many situations, this may be the only method to satisfy conflicting requirements. The very nature of outdoor lighting and the desire by residents to have no sources of high brightness may be incompatible. A curfew may be the only method of compromising the need and desire for outdoor lighting with its accompanying problematic effects.

Where a curfew is established, the local ordinance for pre-curfew hours can allow higher limitations of light trespass. During post-curfew hours, lighting which is non-essential such as that of sports facilities, building floodlighting and outdoor advertising, for example, will be extinguished and much stricter limits can be provided in the ordinance.

Recommended Limitations

It has been detailed above that an ordinance should incorporate a range of environmental areas and that four such categories have been proposed. Further, in each of the categories, pre-curfew and post-curfew light trespass levels can be set.

Given these eight categories, recommendations must be developed for each. It is strongly emphasized, however, that no set of values will be totally satisfactory. As discussed, light trespass by its very nature is subjective and is affected by the personalities and desires of the persons involved. We can only develop recommendations with the understanding that individual communities can change these to any extent required to fit local needs. At least, however, we can produce a framework for ordinances and suggested limitations based on this and other research.

An ordinance should not be developed with the intent of controlling every light source that is even slightly objectionable. This would result in virtually all outdoor lighting being disallowed. The realistic aim of an ordinance would seem to be to control lighting which is very objectionable, as even controlling light judged simply “objectionable” may prove to be unduly restrictive given the needs which outdoor lighting must fulfill.

It is therefore proposed in this report that the levels of eye illuminance to be recommended as a limitation be those which prevent light trespass in the “very objectionable” or “extremely objectionable” categories. Under curfew conditions, however the aim is to restrict lighting to the “not objectionable” or “slightly objectionable” categories.

It is re-emphasized, however, that the recommendations herein are just general guidelines. Actual ordinances should be developed by authorities who view and measure existing outdoor lighting, and who then may decide to relax or tighten the limitations.

Light trespass limitations, designated by letters representing illuminance values at the eye in a plane perpendicular to the line of sight, are given in Table 5-1 .

Table 5-1
Light Trespass Limitations

Environmental Zone	Pre-Curfew Limitations	Post-Curfew Limitations
E1	A1	C1
E2	A2	C2
E3	A3	C3
E4	A4	C4

Test data were collected during the earlier-described experiments for areas which could generally be described as:

Indoor tests:	E4
Outdoor tests, low ambient:	E2
Outdoor tests, medium ambient:	E3

No test data are available for E1 conditions, but this zoning represents a rather extreme condition. Also, it may be questioned whether the indoor tests are a truly reasonable measure of E4 conditions. In view of the level of interior lighting used, however, this is probably acceptable.

The data can be analyzed in terms of the illuminance level at the eye on a plane perpendicular to the line of sight for an observer viewing the source from:

$$\text{Eye illuminance} = \frac{\text{Source luminance x source area}}{\text{distance}^2}$$

Each set of conditions has been analyzed to determine levels of eye illuminance which cause OR values to exceed 4 (pre-curfew) and 2 (post-curfew).

Indoor Tests

Testing for the small area source indicates that the OR value does not exceed 4 even for the highest luminance level.

For the medium area source, a luminance level of around 7000 cd/sqm causes the OR value to exceed 4. For the large area source, a luminance of approximately 4000 cd/sqm creates OR values over 4.

For the medium area source:

$$\text{Eye illuminance} = \frac{7000 \times 0.46^2}{10^2} = 14.8 \text{ lux}$$

For the large area source:

$$\text{Eye illuminance} = \frac{4000 \times 0.6^2}{10^2} = 14.4 \text{ lux}$$

A limitation for this condition of approximately 15 lux therefore appears reasonable.

Examination of the data shows that to keep the OR value to less than 3, as is desirable for post-curfew conditions, the luminance levels need to be roughly in the range of 40% to 60% of those for pre-curfew conditions. If the value of 40% is used, the limitation for eye illuminance becomes 40% of 15 lux, or 6 lux.

Outdoor Tests, Low Ambient

Applying a similar rationale, for pre-curfew conditions, results for the three different source areas indicate the following.

Small area. A luminance of 7000 cd/sqm roughly corresponds to an OR = 4.

$$\text{Eye illuminance} = \frac{7000 \times 0.3^2}{15^2} = 2.8 \text{ lux}$$

Medium area. A similar calculation yields a value of 3.8 lux.

Large area. The value is 3.2 lux.

A pre-curfew recommended limit of 3 lux thus seems appropriate.

For post-curfew conditions, a level in the range of 40% to 60% of the pre-curfew level is needed. Conservatively, a limit of 1 lux appears reasonable.

Outdoor Tests, Medium Ambient

Similarly to above, the luminance limit to maintain an OR value of 4 or less for the medium area source is roughly 7000 cd/sqm. (This is identical to the indoor test result, but leads to different eye illuminance values as the distance is greater.) The small area source does not reach the OR = 4 condition, while the large source meets the OR limit at a luminance of about 5000 cd/sqm.

Medium area.

$$\text{Eye illuminance} = \frac{7000 \text{ x } .46^2}{15^2} = 6.6 \text{ lux}$$

Large area.

$$\text{Eye illuminance} = \frac{5000 \text{ x } .6^2}{15^2} = 8 \text{ lux}$$

An appropriate recommendation therefore appears to be 8 lux for pre-curfew conditions.

On the same basis as used earlier, the post-curfew condition should be in the order of 3 lux.

A general point of importance needs to be made: these recommendations are based on testing under a limited range of conditions. A test program to satisfactorily cover all of the widely ranging conditions present in light trespass would be an enormous task. It is therefore emphasized that these conclusions require review, and additional research is highly desirable. The importance of users viewing and measuring light trespass sources before adopting any particular values for ordinances is highly important. However, it should be noted the levels which are being recommended are in the same general order as those contained in the references.

Summary of Recommendations

The following recommendations are suggested, based on the foregoing and the analysis of other research.

Level A1. Intrinsically dark, pre-curfew
It is recommended that the value A1 be 1 lux, (0.1 fc).

Level A2. Low ambient brightness, pre-curfew
The recommended level is 3 lux, (0.3 fc).

Level A3. Medium ambient brightness, pre-curfew
The recommended level is 8 lux, (0.8 fc).

Level A4. High ambient brightness, pre-curfew
The recommended level is 15 lux, (1.5 fc).

Level C1. Intrinsically dark, post-curfew.

For luminaires or systems which are not for public safety or security, this limit should be zero fc. This is based on the presumption that the environment of such dark areas should not be affected to any extent by artificial light sources after curfew hours.

Where safety and security are issues, nighttime lighting is needed. Such lighting should meet IESNA recommendations for the particular property being lighted. Lighting should be designed, however, to minimize light trespass, and it is suggested that under such conditions the light level, C1, should not exceed 1 lux, (0.1 fc). This is identical to the C2 level, see below.

Level C2. Low ambient brightness, post curfew

This category represents the most sensitive residential areas, that is, generally dark neighborhoods with the exception of those covered in area category E1. It is recommended that the subject lighting be restricted to a level, C2, of 1 lux.

Level C3. Medium ambient brightness, post curfew.

In areas of moderate ambient lighting, post curfew, the suggested recommendation is 3 lux, (0.3 fc).

Level C4. High ambient brightness, post curfew

In such areas, the recommended limitation is 6 lux, (0.6 fc).

These recommendations are developed on the basis of luminaires which are on constantly during the applicable period. Where luminaires are on for a short period only, these recommendations should not be applied. An example of this would be if a luminaire is on for a period of 2 minutes, perhaps while occupants of a car disembark and enter a dwelling.

These recommendations similarly would not be applicable if the light source is constantly on but is only viewed for a short period, perhaps while a viewer moves from one location to another. The principle behind the recommendations is to prevent the constant viewing of objectionable sources.

It is believed that when these recommendations are applied, they will serve as an effective measure for reduction of serious light trespass. For reasons stated earlier, however, they do not guarantee that no objections will occur, because of the nature of people and the problem.

Non-curfew Recommendations

The above levels are recommended where two time periods exist, pre and post curfew. If it is decided by a local authority that application of a curfew is undesirable, unnecessary or unenforceable, then any recommendations will apply throughout the nighttime. Under these conditions, it is necessary for the developers of the ordinance to decide upon recommended levels.

For non-curfew situations where light trespass is not seen as a significant problem, the pre-curfew limitations logically can be applied. Where light trespass is viewed as a critical local problem, the above post-curfew values can be applied. Under most circumstances, values between the pre-curfew and post-curfew levels are most logically applicable.

Exceptions

Certain situations may require lighting that cannot meet the above recommendations. Floodlighting of a ball-field, for example, produces large quantities of light trespass, even when luminaires are used which sharply reduce intensity above the beam. For such situations, the ordinances may include an exception. This may be based on limited use and time-of-day restrictions in addition to normal curfew hours.

Development of an Ordinance for Light Trespass

It is not the intention of this report to develop a model ordinance which then can be widely adopted. It is essential that local conditions and viewpoints be considered. Guidelines are provided below, however, to assist in ordinance development based on a flexible framework.

A possible layout of a light trespass ordinance is:

Purpose of outdoor lighting
The nature of light trespass
Definitions
Purpose of the ordinance
Classification of outdoor areas
Curfew
Recommended limitations
Designing to meet the limitations
Lighting calculations
Checking compliance

A brief description of these topics follows.

Purpose of outdoor lighting.

Provide a brief review of why outdoor lighting is necessary and desirable. Mention safety, security and amenity. Point out that there are well established benefits to outdoor lighting and elimination of such lighting usually is not a viable option for controlling problems.

The nature of light trespass.

Summarize the information provided in this report regarding what light trespass is and how it affects us: objectionable bright light sources in a dark environment, spill light, light entering homes through windows. State that light trespass is related to the amount of light (illuminance) striking the eye from the offending source.

Definitions.

Provide definitions of all lighting terminology used in the ordinance.

Purpose of the ordinance.

Provide the local viewpoint regarding problems of light trespass if possible. State that the intention of the ordinance is to promote good lighting design whereby safe and effective lighting can be provided without producing objectionable light trespass. Discuss the variability of opinions and indicate that no ordinance can provide total elimination of light trespass while allowing the use of lighting for legitimate needs.

Classification of outdoor areas.

Extract information from this report which classifies areas according to the limitations of light trespass which are applied.

Curfew

Discuss the application of the curfew for nighttime lighting, if such is to be applied.

Recommended limitations.

Provide this section only after a detailed examination of existing lighting in the area. First develop confidence that the values being recommended are realistic and meaningful for the intended purpose. Develop a set of recommendations, which may or may not be those values provided in this report.

It is important to clarify whether the limitations must be met at the property line of the lighted areas, (the most stringent and logical application of the recommendations), or at some greater distance away.

Designing to meet the limitations.

Provide a review of typically used outdoor lighting equipment. Compare different styles of lighting fixtures for particular purposes, indicating that some provide excellent control of light trespass while others provide little or no control. Illustrate and recommend techniques for selecting and using outdoor lighting fixtures.

Lighting calculations.

Provide a synopsis of the calculation method to be used to calculate the level of illuminance at the eye from a particular luminaire or group. See Appendix A of this report.

Checking compliance.

Describe the method to be used to determine whether a lighting system is in compliance with the ordinance. See Appendix B of this report.

6
CONCLUSIONS

A further recommendation is made to the Illuminating Engineering Society of North America, IESNA. This organization serves as the prime authority for matters concerning lighting. It has become apparent that the subject of light trespass is of great importance to many communities, as is well recognized by IESNA. The development of a report based on the findings of this research and other information available will provide significant benefits. The IESNA Roadway Lighting Committee may wish to carry the work further, possibly through the development of a model ordinance or several ordinances based upon differing needs of communities. In such an effort, it is hoped that this research will be of value.

7
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8. “Control of the Obtrusive Effects of Outdoor Lighting.” Interim Australian Standard. Standards Australia, Homebush, NSW, Australia.

9. “Outdoor Lighting Manual for Vermont Municipalities.” Chittenden County Regional Planning Commission. May 1996. Essex Junction, Vermont.

A
LIGHTING CALCULATIONS

Lighting calculations for the purpose of determining compliance of a design with recommendations of the type included in this report are quite simple. The recommendations are provided in terms of Ee, illuminance (lux or foot-candles) at the eye, on a plane which is perpendicular to the line of sight. See Figure A1.

The requisite formula is:

$$Ee = \frac{I}{D^2}$$

where I = the intensity or candlepower of the light ray from the luminaire to the eye
D = the distance from the luminaire to the eye

If D is in meters, Ee is in lux. If D is in feet, Ee is in footcandles.

Step 1. Calculate D^2.

Height of the luminaire above the eye, $H_{LE} = H_L - H_E$

Where H_L = height of luminaire
H_E = height of eye. Use 3.0m (5ft).

Horizontal distance from the luminaire to the eye = A

If A is unknown, it may be calculated from the lateral and longitudinal separations B and C:

$$A = \sqrt{B^2 + C^2}$$

Calculate D^2:

$$D^2 = H_{LE}^{\ 2} + A^2$$

Step 2. Determine angle V

Angle V is the vertical angle of the light ray from the luminaire to the eye, measured from the downward vertical.

$$V = \arctan(A / H_{LE})$$

Step 3. Determine θ

Angle θ is the horizontal angle between the vertical plane containing the light ray and the primary (zero degrees) horizontal plane of the luminaire.

$$\theta = \arctan(C / B)$$

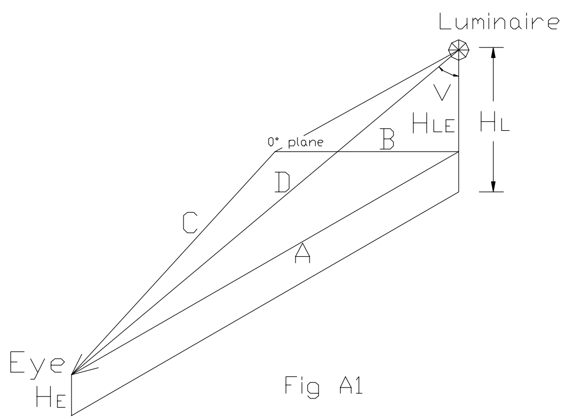

Fig A1

Knowing the vertical and horizontal angles, the intensity or candlepower, I, can be read from a photometric test report for the luminaire. Ee then can be determined.

Where multiple luminaires on a pole are being evaluated, the calculation is repeated and the Ee values are summed.

Calculations such as this can be conveniently carried using a suitable computer program.

B
MEASUREMENT OF LIGHT TRESPASS

To determine the light trespass created by a luminaire in terms of the recommendations in this report, it is necessary to measure the illuminance level at the eye on a plane perpendicular to the line of sight to the luminaire. Other light sources must be shielded from view.

A general purpose illuminance meter can be used for this application. Such meters are calibrated in lux or footcandles. All that is needed is the addition of a shielding device to block out unwanted light.

Figure B1 illustrates the use of a black cone with a conventional photocell. The inside of the cone should be painted flat black. Preferably black flocked paper can be adhered to the inner surface. (Available from Edmund Scientific Co., Barrington, New Jersey,

609-573-6250.)

To use the adapted light meter, the photocell and black cone are held at eye height and aimed at the light source to be measured.

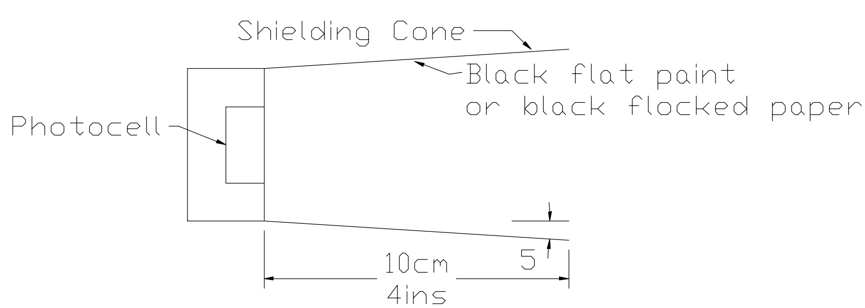

Fig B1

C
QUESTIONNAIRE

March 19-20, 1991
Alexandria, VA

PARTICIPANT'S QUESTIONNAIRE

Name ______________________________

Title ______________________________

Organization ______________________________

Address ______________________________

____

____

Telephone ______________________________

1. Within your geographical area of jurisdiction, please rank the importance of the following forms of light trespass. Please use the scale:

1 ---- Not important at all
2 ----
3 ----
4 ----
5 ---- Moderately important
6 ----
7 ----
8 ----
9 ----
10 ---- Extremely important

1.1 Light Pollution affecting astronomers ______

1.2 Light Trespass in urban and residential areas:

Spill light from roadways, parking lots ______

Glare from roadways, parking lots ______

Spill light from ball fields ______

Glare from ball fields ______

Spill light from other sources ______

Specify____

____

Glare from other sources ______

Specify____

____

Roadway or other light sources entering residence through windows ______

1.3 Light Trespass affecting drivers

Glare from roadway lighting ______

Glare/distraction from advertising signs ______

Glare/distraction from advertising floodlighting of buildings ______

Glare/distraction from retail operations ______

Explain nature of problem:

____

____

____

Other (please specify) ______

____

____

____

2. In urban and residential situations, objections to light trespass may relate to the viewing of glare sources, the illumination of an area from sources beyond the property line, or brightness of more distant areas where total darkness is preferred. Please rank these in order of importance (1,2,3).

	Rank
Glare sources	______
Illumination of surrounds	______
Distant brightness	______

3. Regarding your answers to question 2:

Do you feel a solution to the problem you ranked 1st is: (Check)

______ Essential ______ Desirable ______ Not important

Do you feel a solution to the problem you ranked 2nd is:

______ Essential ______ Desirable ______ Not important

Do you feel a solution to the problem you ranked 3rd is:

______ Essential ______ Desirable ______ Not important

4. Approximately how many complaints per year do you receive regarding light trespass problems? ______

5. Regarding the reasons that urban and residential light trespass occurs and causes complaints, please indicate the importance you attach to the following in terms of their contribution to the problems: (10 = extremely important, 1 = not important at all).

Dusk-to-dawn lights (inexpensive, open bottom refractor luminaires)	______
Incandescent floodlights (typically 150 watt Refractor-type lamps)	______
Searchlights for advertising	______
Street lights with inadequate optical control	______
Residential/club tennis court lights	______
High mounting height ball field lights (30 ft+)	______
Landscape lighting	______

Lack of extinguishing lights when not in use ______

Use of lights of excessively and unnecessarily high lumen output ______

Light reflecting off surfaces close to the luminaire (ground, vertical surfaces such as buildings, etc.) ______

Nearby lighting for commercial areas (advertising signs, parking lot lights) ______

6. In developing ordinances for control of urban and residential light trespass, please indicate the importance of including clauses related to the following: (10 = extremely important, 1 = not important at all).

Specification of some form of shielding for luminaires ______

Limitation of the level of glare from an offending light source ______

Limitation of the total glare from all visible light sources ______

Limitation of the illuminance (footcandle) level on horizontal surfaces outside the property line containing the light source. ______

Limitation of the illumination on vertical surfaces ______

Restrictions on the time of day, i.e., specifications of a mandatory switch-off time ______

7. Which form of ordinance enforcement do you think is preferable: (check)

   1. Ordinance contains rules regarding acceptable luminaire type placement and/or operating period, and compliance is judged by a plan inspector prior to installation. No field measurement involved.

   2. Ordinance relies on field measurement for verification of compliance. ______

8. If field measurement for compliance is necessary, an inexpensive easy-to-use meter is desirable. However, cheap meters may not offer the accuracy or capability of more expensive meters. What do you feel is a generally acceptable price range for such an instrument. (Check)

$ 500 - $1250 ______
$1250 - $1750 ______
$1750 - $2500 ______
$2500 - $5000 ______

9. Do you favor an attempt to develop a model ordinance regarding light trespass, or do you feel that due to the diversity of situations throughout the country, only a set of general guidelines should be produced. (Check)

    Develop model ordinance ______
    Develop guidelines only ______

D
INSTRUCTIONS FOR PARTICIPANTS

Generally, people do not like bright lights at nighttime, but lighting is very often important for safety, convenience and other reasons. The purpose of this test is to investigate whether or not certain sources of outdoor lighting are offensive and should lead to better control and use of lighting.

During the test, you will be asked to look at a target. While you are looking at the target, a light will be switched on which may be dim or bright. Keep looking at the target, not at the light.

We then want you to rate the light source from 1 to 5 as follows:

1. Not objectionable (acceptable)
2. Slightly objectionable
3. Quite objectionable
4. Very objectionable
5. Extremely objectionable

We will run lots of tests under different conditions. Try to be consistent with your answers.

Thank you for helping in our research.

Target:

Residential and Commercial Business Development

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