Roadway Visibility Using Minimum Energy

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The basic requirements for nighttime roadway visibility are reviewed, and a table of recommended values for roadway lighting of city streets is presented. The values are based on five classifications of streets and a separate category for intersections. The primary standard of measurement is roadway luminance, but illumination and glare values are shown as parallel requirements. The recommended values for roadway lighting are less than the current American Standard Practice (RP-8, 1978) values but have more stringent quality specifications. Thus, it is shown that vision on roadways can be equal to or better than current practice and energy use can be appreciably reduced, by as much as 50-60 percent in some cases. Data for a study project in Portland, Oregon, are reviewed to demonstrate that the recommendations are achievable and that energy and cost reductions are practical.

Roadway lighting systems have evolved over the years from gas lamps to arc lamps to incandescent lamps to mercury lamps and now to other types of gaseous discharge lamps. The available alternatives raise many questions and cause engineering and administrative dilemmas in selecting the most cost-effective system for new or retrofit projects. This paper attempts to identify some of the factors to be considered and to quantify some of the parameters that are necessary to achieve satisfactory roadway visibility with minimum energy consumption.

The cost of energy is paramount in the minds of most administrators of roadway lighting systems because of the escalations that have occurred in recent years and the projections for further increases in the future. When the life-cycle costs (the total annual costs) are analyzed, it is invariably found that energy costs are far greater than all other costs. The multiplier may be 4-10 times the capital and maintenance costs combined, depending on the type of system and the energy rate. So it is important to consider minimum energy systems.

This paper emphasizes city-street lighting systems rather than limited-access roadways such as freeways, thruways, and parkways. City-street lighting systems are frequently installed, maintained, and operated by public utility companies on a contract basis. The lighting is determined by a set of policy guidelines that prescribe the lighting on a design manual or recipe basis. Systems that are city owned and operated are usually established on similar bases. Reasonably satisfactory visual conditions are assumed to result when the guidelines are followed. The procedure is straightforward and simple, but the results are not always adequate in terms of either visibility or costs.

Many cities are faced with problems of future growth in both population and the provision of services, including vehicle and pedestrian traffic. Since the basic street pattern cannot be changed, it will be necessary to improve the operating efficiency of the present streets. This does not mean just "more of the same" but rather improved quality with less energy plus other visual aids and control devices that can increase traffic flow with safety.

City streets have different visibility requirements based on their use and functional demands. The following six categories apply to most city streets except those in the downtown central district:

1. Regional trafficway--Four or more lanes, without parking, 40-45 mph, mixed traffic with trucks, commercial vehicles, and passenger cars;
2. Major traffic, major transit--Four lanes, with parking, 30-35 mph, mixed traffic plus buses and pedestrians;
3. Neighborhood collector, major transit--Two lanes, with parking, 30-35 mph, mixed traffic plus buses and pedestrians;
4. Neighborhood collector, minor transit--Two lanes, with parking, 30-35 mph, few buses;
5. Local service--Two lanes, with parking, residential or local collector; and
6. Intersections.

These classifications are approximately parallel with the types of roadways used by the American Standard Practice for Roadway Lighting (RP-8, 1977). A new American Standard is to be issued in the near future in which there may be new names for the types of streets but the functions will remain the same.

The existing American Standard Practice (RP-8) does not address the problem of energy use in any way. No mention is made of the use of high-efficacy sources or the visual aspects of the roadway. The new proposed standard will attempt to remedy these omissions but, since it is not yet available, some of the important factors are reviewed here.

TECHNIQUES TO PROVIDE GOOD VISIBILITY

Lighting codes or standards vary from one locality to another, depending on the local conditions and the requirements for critical seeing. Nevertheless, there are basic concepts and principles that are common to all nighttime traffic situations. The basic visual parameters that must be covered are (a) road surface luminance, (b) roadway illumination (required to produce luminance), (c) glare restrictions, and (d) optical guidance information.

The primary function of the lighting on roadways is to facilitate the movement of traffic, both vehicle and pedestrian. The lighting is considered to be of good quality if it ensures ease of perception, develops adequate adaptation luminance, is comfortable, and provides guidance information.

The driver's visual task is extremely complex and has not been synthesized or modeled completely. But several aspects of the task can be identified: (a) The driver must use advance planning for the run of the road ahead and must therefore have visual information on the alignment of the road, curves, dips, rises, intersections, and so on; (b) the driver must make short-term decisions on rate of closure with other vehicles, objects, and pedestrians on the roadway ahead; and (c) the driver must use short-term memory and mental data processing to keep track of his or her position, the position of other vehicles, and objects in the immediate surroundings.

Good visual conditions must hold over the whole of the roadway for some distance ahead and within the driver's immediate environment. Perception should be quick, reliable, and easy so that the visual tasks can be continued over a period of time without excessive strain and fatigue. Thus, ease and comfort in seeing are not luxuries that can be dispensed with.

The perception of relevant objects leads to action by a driver. The action may involve (a) proceeding with caution or no action, (b) decelerating or stopping, or (c) changing lateral position and turning. Among the relevant visual objects are (a) information objects, such as road markings, traffic lights, direction signs, and destination signs; (b) hazard objects, such as pedestrians, animals, parked cars, boxes, rocks, road damage, and so on; and (c) other moving vehicles on the roadway in the traffic stream.

Visual perception depends on (a) the luminances in the visual field; (b) the state of adaptation of the observer; (c) the size, shape, color, and pattern of objects; (d) motion; (e) time available; (f) the physiology of the observer's visual, neural, and mental systems; (g) age; and (h) many psychological factors, such as attention, familiarity, diversions, and so on. From the engineering point of view, one can prescribe the physical parameters for a design level of perception for a normal, attentive observer in a given age group. However, even though such a physical array will provide the environment for adequate visual perception, it will not ensure the perception of critical relevant objects due to the vagaries of human responses.

Luminance is the physical parameter that must be prescribed as the basic quantity in the visual field. Luminance is the luminous flux within a small solid angle that is incident on the observer's eye from a specific direction. The physical quantity, luminance, may cause a reaction within the observer's visual system that results in a subjective response termed "brightness". The brightness sensation is related to the external luminance, but it is not directly proportional since there are many nonlinear links in the perception system.

We have, therefore, a man-machine-environment system with both objective (physical) and subjective (human-factors) attributes. Only the objective specifications that relate to roadway lighting on city streets are developed in this paper.

Both quality and quantity considerations are needed in specifications for roadway lighting. Quality is measured by the uniformity of roadway luminance and illumination and by the relative freedom from glare. Quantity is measured by the average roadway luminance (L_{ave}) and illumination (E_{ave}). The primary measurement should be roadway luminance, since this is the parameter that directly affects visual perception. However, it is not enough to specify only luminance, since there may be unique situations in which the design procedure for luminance indicates a satisfactory pattern but the actual installation may not result in a satisfactory job. This may happen because of the limitations of the luminance calculation procedure, which assumes the observer to be at a fixed location and the roadway to be represented by one of the standardized reflection factor tables, neither of which is true.

Hence, in addition to luminance values, a set of illumination values should be prescribed. The rationale for this is that the collective experience of street-lighting designers in the United States relates to horizontal illumination values (footcandles) and thus the practitioners will be comfortable with a specification that requires known quantities. In addition, in order to develop roadway luminance patterns, it is necessary to have incident illumination on the street. There is not a one-to-one relation between luminance and illumination, but experience indicates that, for asphaltic road surfaces with twin-beam luminaires on about 25- to 40-ft mounting heights, there is an approximate correlation between L_{ave} and E_{ave} in which $L_{ave} \approx k \times E_{ave}$, where $0.25 \geq k \geq 0.15$ (1-4), when L is in footlamberts and E is in footcandles. Therefore, a given level of average luminance will have a requirement for average horizontal illumination.

The average roadway luminance and the nearby surroundings determine the visual adaptation level of the observer's eyes, which is related to visual performance criteria (e.g., the higher the adaptation level, the better the visual performance) (6).

In terms of seeing details on the roadway, the uniformity of luminance is very important. For example, a small object in an area of minimum luminance may not be visible, whereas the same object in another area of higher luminance may be easily perceptible. Three measures of uniformity are needed: (a) a measure of the minimum value on the roadway compared with the adaptation luminance (L_{min}/L_{adapt}), (b) a measure of the total luminance variation along the projected path of the vehicle [the latter given by the ratio of L_{max}/L_{min} (longitudinal) along a line ahead of the observer], and (c) the ratio of L_{max}/L_{min} (overall).

Another factor that must be specified in a roadway lighting system is the degree of glare that will be permitted. This is a subjective parameter that has been dealt with in different ways by different researchers and regulatory bodies. The effect is caused by high-brightness sources in the field of view that cause a reduction in the ability to see objects and cause discomfort, fatigue, and annoying responses. The current state of the art tries to isolate the disabling aspect from the discomfort aspect without complete success. Research studies have established the physical parameters that are significant in glare evaluation. They are (a) luminance of the source, (b) location in the field of view, (c) size of the source, (d) adaptation luminance, and (e) age of the observer. The combination of multiple sources is reported to be nonlinear insofar as comfort is concerned and approximately linear insofar as disability is concerned.

With the above brief description of the parameters required for good roadway visibility and by reference to selected research (1-3, 6-12), it is possible to establish recommended values for illumination, luminance, and glare. The recommended values are given in Table 1. The values for illumination are slightly lower than in the current American Standard Practice, but they are fully justified on the basis of the improved quality provided by the luminance and glare requirements, which provide for adequate visibility. Their application can provide energy-efficient systems. Present connected loads can be reduced as much as 50 percent in many areas where these recommendations are applied by using high-efficacy sources and luminaires.

RECOMMENDED LIGHTING STANDARDS

Explanation of Values

Before the bases of the recommended standards are discussed, specifications for the use of the measurements given in Table 1 are explained.

Horizontal Illumination

The value of average horizontal illumination [$E_{h(ave)}$], in footcandles, is calculated as the average over the area of the traffic lanes including the center median and bicycle lanes, if any. The area for $E_{h(ave)}$ does not include parking lanes, sidewalks, berms, or other areas outside of the traffic lanes. A parking lane is assigned 7 ft of width, to be subtracted from the curb-to-curb width. For design calculations, the end-of-life lamp lumens are used together with an appropriate luminaire maintenance factor. Areas out to 15 ft to each side of the outside traffic lane shall be lighted to ≥ 0.2 footcandles (average) if such areas are used for parking or pedestrian traffic.

Luminance

L_{ave}, measured in footlamberts, is the average luminance within the traffic lanes from a transverse

Table 1. Recommended street lighting standard.

	Horizontal Illumination (footcandles)			Luminance (footlamberts)				Glare		
Street Classification	$E_{h(ave)}$	Ave/min	Max/min	L_{ave}	Ave/min (overall)	Max/min (overall)	Longitudinal	GM	TI	L_v
Regional trafficway	≥ 1.2	≤ 3	≤ 9	≥ 0.30	≤ 2.5	≤ 5	≤ 2.5	≥ 6	≤ 20	≤ 0.05
Major traffic, major transit	≥ 1.0	≤ 3	≤ 9	≥ 0.24	≤ 2.5	≤ 5	≤ 2.5	≥ 6	≤ 20	≤ 0.04
Neighborhood collector										
Major transit	≥ 0.7	≤ 3	≤ 9	≥ 0.18	≤ 2.5	≤ 5	≤ 2.5	≥ 6	≤ 20	≤ 0.03
Minor transit	≥ 0.5	≤ 3	≤ 9	≥ 0.12	≤ 2.5	≤ 5	≤ 2.5	≥ 6	≤ 20	≤ 0.02
Local service	≥ 0.2	≤ 6	≤ 20	≥ 0.06	≤ 5	≤ 10	None	≥ 4	≤ 25	≤ 0.05
Intersections				$L_{ave(i)} \geq 1.5\, L_{ave(r)}$ Unif. $[L_{ave(i)}/L_{min(i)}] \leq 2.5$				≥ 7	≤ 10	≤ 0.05

line approximately 100 ft ahead to about 400 ft ahead of the observation point. The lateral boundaries shall include the area of the traffic lanes. At least 20 points shall be used to calculate L_{ave}, at least 5 points along the centerline of the lane ahead of the observation point. The individual luminance points shall be calculated or measured from a point 4.5 ft above the roadway located approximately in the center of the outside lane and at longitudinal points located to include the maximum longitudinal variations in road luminance. For roadways with two-way traffic, the luminances shall be determined for each direction of traffic if the luminance pattern is asymetric.

Field measurements will be made with a suitable telephotometer that uses an acceptance aperture with a 2-arc-minute vertical angle. At least 20 points will be measured on the roadway within the prescribed area at approximately equal angular increments. The L_{ave}/L_{min} ratios (longitudinal and overall) shall be calculated for each observer location and shall consider all of the luminances within the area. The L_{max}/L_{min} ratios shall be calculated overall and along the centerline of the outside lane for each direction of traffic and shall be met for observer locations.

Glare

Glare is evaluated by two criteria: (a) discomfort glare and (b) disability glare.

Discomfort Glare

The discomfort from glare is described by a glare control mark (GM) (4,8), which expresses on an ordinal scale the subjective appraisal of the degree of discomfort experienced. The value of GM is related to different glare sensations as follows:

GM	Glare Sensation
GM-1	Unbearable
GM-2	Disturbing
GM-5	Just admissible
GM-7	Satisfactory restriction
GM-9	Unnoticeable

These words are not intended to indicate an absolute level of glare. They are listed here as used in experiments of the International Commission on Illumination (CIE) (1,4,8). The subjective appraisal of the glare and the associated value of the GM depend on the photometric and geometric characteristics of the lighting installation, and the GM should be used as a relative index.

Disability Glare

The method of evaluating disability glare is based on the Holladay formula (7). According to the formula, the effect of glare is quantified by an equivalent uniform luminance that describes the effect of the stray light in the eye--lowering the contrast. The relative threshold increment (TI) is expressed as the difference between the threshold under glare conditions and its value without glare, expressed as the percentage of the value without glare. The veiling luminance (L_v) represents the illumination at the eye due to glare sources and is the equivalent uniform luminance, in footlamberts, superimposed over the entire visual field. To evaluate its effect, this value can be compared with the average luminance or the adaptation luminance.

Recommendations on Glare

The recommendations in Table 1 concerning the restriction of glare in road lighting installations have been given in terms of GM and TI. These values should be considered as minimum requirements. If higher values for GM and lower values for TI are economically feasible, preference should be given to such improvements.

Field measurements of glare should be made by using a telephotometer located at the luminance observation location. The photometer should use a 6-arc-minute aperture (a 2-in circle at 100 ft) and should have a mount that can give the vertical and horizontal angles of the photometer axis with respect to a reference line of sight. All sources within the normal field of view of a driver that are greater than 20 times the average road luminance should be measured for maximum luminance. The approximate field of view to be covered should be ±30° horizontal and +20° to -5° vertical. The location and magnitude of each glare source should be recorded. If the sources subtend a solid angle greater than 0.0002 steradians (2 ft^2 at 100 ft), separate measurements should be made to give the average luminance.

Intersections

The area used to determine L_{ave} is the roadway area within the traveled lanes extending from the approximate centroid of the intersection along each lane to a transverse line 10 ft beyond the point of entry. $L_{ave(i)}$ is the average luminance in the intersection, $L_{ave(r)}$ is the average luminance of the intersecting road with the highest value, and $L_{min(i)}$ is the minimum luminance within the intersection.

Bases for Recommended Standards

As discussed below, the recommended lighting standards are based on street characteristics, user requirements, and experience with comparable lighting applications.

Street Classifications

Regional Trafficways

The regional trafficways classification (class 1) represents the greatest demand for visibility because of the relatively high speed of the traffic (45 mph), the high volume (up to 25 000 vehicles/day), and the mixture of types of vehicles (trucks, commercial vehicles, buses, and passenger vehicles). Experience on such streets has shown that average illumination levels on the order of 1.2 footcandles and average luminance levels on the order of 0.3 footlambert are satisfactory when accident records and traffic flow are used as criteria (1,2,6,10-12). In similar traffic conditions in Europe and Japan, the average roadway luminance is specified as 1 cd/m^2 (0.29 footlambert) and in Canada as 1.2-0.8 cd/m^2 (0.35-0.23 footlambert) (1-3). The British use a combination of illumination and luminance specifications (13,14).

In a study (14) that covered a total of 38 installations, wet and dry, the range of L_{ave} was from 0.05 to 0.38 footlambert. The roads are described as ordinary traffic routes and motorways. These levels have been in use for some time and have been accepted as adequate. The Canadian values (3), which are approximately the same as those in Table 1, are being seriously considered as the basis for new U.S. values (i.e., American National Standards Institute/Illuminating Engineering Society) to be issued in the near future.

The recommended average illumination values in Table 1 are less than those currently recommended by IES for similar street classifications (RP-8). The lower values are suggested for several reasons: (a) Their extensive use in other countries has demonstrated their adequacy, (b) a ratio of maximum/minimum is specified to ensure better-quality lighting, and (c) luminance and glare restrictions are added in order to improve the quality and comfort aspects. Thus, it has been demonstrated in the reference articles that, with an improved quality of lighting, a reduced quantity of light can be adequate for safe operations and may improve the existing visual environment and will save energy.

Most authorities recognize the importance of roadway luminance and the deleterious effect of glare. In the past, the problems of their specification related to the methods by which the luminances were determined and the relative importance of the glare parameters. The problems are now solvable. The quantities, definitions, and techniques can now be described, measured, and calculated by use of currently available instruments and computer programs.

The luminance calculations for a roadway are based on the candlepower distribution of the luminaires and the R-3 classification of road surface reflection. R-3 is a CIE designation for asphaltic concrete with gravel sizes up to 10 mm but harsh texture (4). This may not truly represent all city streets, but in lieu of better data it is reasonably adequate. Luminance measurements on many city streets indicate an overall ratio of $L_{ave}/E_{ave} \approx 0.25$ to 0.15. The CIE data show a ratio of ≈ 0.17.

The glare calculations are based on CIE recommended techniques for evaluation of comfort and disability (8). These formulas have been criticized by several researchers as lacking correlation with subjective evaluations. The disagreements deal mostly with the details of the coefficients, the exponents used in the equations, the size of the visual field, and the adaptation luminance of the observer. Thus, while research continues and the techniques are being refined, the recommendations in this paper use the CIE recommended procedures and the established computer programs.

The fact that weather causes streets to be wet part of the time is another factor in establishing the suggested values of E, L, and glare. The values listed are for dry roadways, but the combination of ratios of E_{ave}/E_{min}, E_{max}/E_{min}, L_{ave}/L_{min}, and L_{max}/L_{min} ensure that under wet conditions the roadway luminance pattern will not deteriorate severely.

Local-Service Streets

At the other end of the lighting spectrum are the local-service roads (class 5). As used in this paper, a local street is a two-lane road with parking on one or more sides. The street has minor traffic and essentially serves as a collector. Daily traffic volume may vary from a few vehicles to approximately 2000. There is usually parking along at least one curb, and there may be pedestrians in crosswalks and on sidewalks. The block lengths vary from short (about 200 ft) to normal (about 400-500 ft). Many of the streets are in a rectangular grid pattern of blocks. Ideally, such streets should be lighted to minimum standards by use of a continuous lighting system. These streets are differentiated from purely residential streets where the intersections constitute the principal traffic-control and conflict areas.

The basis for the minimum luminance specification is that at any point the minimum level on the roadway should be at least equivalent to full moonlight (approximately 0.01 footlambert). This is a consensus value that has been used for many years and is based on experience and public acceptance. This is the order of magnitude of the average roadway luminance produced by low-beam headlamps on an asphaltic roadway. The average should be 5 times the minimum--i.e., ≥ 0.05 footlambert--and the maximum 10 times the minimum--i.e., ≥ 0.10 footlambert. This corresponds to an average illumination of $E \approx 0.2$ footcandle, where the luminance is 0.05 L_{ave}. It is assumed that the lighting is continuous along the street, spacings are about 8 times the mounting height, and the intersections are lighted to ≈ 1.5 times the average roadway luminance between intersections. From a practical point of view, this means that for 400-ft blocks there should be at least one intermediate light but for 200-ft blocks there may be lights only at the intersections.

The 0.20-footcandle (0.05-footlambert) level should be the minimum average level acceptable for continuously lighted local-service streets. There may be (and probably are) other streets that are not eligible to be, or are not warranted to be, continuously lighted. If these streets have regions of potential traffic conflict that should be lighted, such areas should be considered as intersections and lighted accordingly.

In most instances, moving vehicles will be operating on local-service streets with low-beam headlights. For dry-road conditions on asphaltic surfaces, the maximum foreground luminance due to headlights on the roadway will be about 0.10 footlambert and the average will be about 0.05 (15). This means that the driver's adaptation level will remain about the same on both lighted and unlighted local-service streets. Glare considerations may have to be relaxed because of the long spacings. The prevalence of trees in such areas may alleviate some of the deleterious effects of glare. In any case, the vehicle speeds are usually low, which will to some extent compensate for the higher glare levels. Table 1 permits higher glare values for local-service streets.

The value of E_{ave} for local-service streets is the same as that recommended by the American Standard Practice of 1964 (16). Since that time, the recommended average value of 0.2 footcandle was doubled to 0.4. There is no rationale or apparent reason for this change. The American Standard Practice currently recommends 0.2 footcandle for alleys and sidewalks (most local-service streets have sidewalks). The suggested average illumination in Table 1 for local-service streets is also 0.2 footcandle.

Thus, it is logical to prescribe an average of 0.2 footcandle for the roadway, parking area, and sidewalk in a local-service area. Such a specification ensures some spill light that will provide additional guidance information, security, and visual enhancement of trees, yards, and house fronts.

Intermediate Types

The following street classifications represent intermediate types between regional trafficways and local-service streets and are based on traffic volume, speed, parking, mixes of vehicle types, loading and unloading of passengers and goods, pedestrian crossings, and sidewalk activities. Each needs varying amounts of light based on the user's visibility requirements. Values for class 2, 3, and 4 streets are logical intermediate steps between class 1 and 5 streets, based on driver, pedestrian, and other use demands.

1. Major traffic, major transit (class 2)--Class 2 streets have design speeds in the 35- to 40-mph range (many vehicles travel faster) and traffic volumes up to 20 000 vehicles/day. These streets should therefore have almost as much light as regional trafficways. There are usually businesses along these routes that contribute additional light to the roadway. Sidewalks, driveways, and loading zones are usually located around commercial establishments or near intersections where additional lighting is available.
2. Neighborhood collector, major transit (class 3)--Class 3 streets have somewhat fewer vehicles than class 2 streets (up to 10 000 vehicles/day) but have a large number of buses with loading and unloading requirements and with associated pedestrian traffic. Therefore, the lighting requirements during commuting hours will be fairly high. The suggested levels are lower than those for class 2 streets, but they are not absolute, since there are no clearly defined boundaries between the classifications. The lighting levels may be adjusted to the demand requirements (e.g., it may be desirable to reduce the lighting during hours when the traffic is light, such as from midnight to 5:00 a.m.).
3. Neighborhood collector, minor transit (class 4)--Class 4 streets generally have traffic volumes in the range of 2000-6000 vehicles/day, including some, but not many, buses. Such streets are relatively important traffic routes and have greater visibility requirements than local-service streets, though not as great as class 3 streets. Here, too, the level can be adjusted to meet the demand requirements and could be reduced between midnight and 5:00 a.m., if necessary, for energy conservation.

Additional Bases for Recommendations

In an extensive review of street lighting in relation to road safety, Fisher (6) makes the following points that are relevant to our recommendations:

1. There is a good deal of agreement among countries on street lighting requirements. Most countries have a multilevel requirement related to the importance of the roadway (and presumably the difficulty of the visual task) and recommend an average roadway luminance of 1-2 cd/m² (0.3-0.6 footlambert) for the most important roads. Australia has a single minimum standard for ordinary urban traffic routes that is equivalent to a roadway luminance of about 0.75 cd/m² (0.22 footlambert). With these levels, the reduction in night accidents should be about the maximum that can be obtained through lighting alone.
2. For the case of a lighted road with an absence of vehicle lights, there is maximum probability of detecting pedestrianlike objects at a luminance level of 1 cd/m² (0.3 footlambert) (17).
3. Data obtained by Blackwell suggest that modest lighting levels of around 1 cd/m² result in relatively high levels of visual performance (18).
4. As shown by Narisada (9), visual performance, in terms of the probability of detecting a small standard object seen against the roadway, is related to both the light level and its uniformity. The light level can be lowered without adverse effect, provided uniformity is upgraded at the same time.
5. A comparison of the lighting codes of 16 nations (10) (excluding Australia) showed a common feature--i.e., a multilevel lighting requirement covering various classes of roads. The more heavily trafficked the road, the higher was the requirement. In addition, the requirements for the most important traffic routes were found to be similar: Most values were between 1 and 2 cd/m² (0.3-0.6 footlambert).
6. The material reviewed provides good evidence to suggest that the minimum luminance level to be used on urban traffic routes that have a mixed road-user population should be similar to the Australian minimum standard of 0.75 cd/m² (0.22 footlambert).

Impact of Recommended Standards

Energy Savings

The recommended standards can be met by using several types, sizes, and spectral distributions of light sources [e.g., Mercury (Hg), metal-halide (MH), high-pressure sodium (HPS), or low-pressure sodium (LPS)] in various types of luminaires made by a number of different manufacturers.

On roadways now using 1000-W Hg sources, the requirements can be met by using 400-W HPS lamps and core-coil ballasts or 310-W HPS lamps and solid-state ballasts. The energy savings are not directly proportional to lamp wattage, but it is reasonable to estimate that the power used can be on the order of half the present load. Similarly, on the other classes of roads that now use 400-, 250-, or 175-W Hg lamps, the power can be reduced by 50-60 percent. Then, if switching circuits are used on some of the roads to turn off or reduce the output of part of the system during off-peak hours (e.g., from midnight to 5:00 a.m.), an additional fraction (approximately 23 percent) of the power used on the road can be saved. This calculation is based on the assumption that the street lights are now on for 4000 h/year or about 11 h/day.

Thus, the energy consumption for a major road, such as Sandy Boulevard in Portland, Oregon (19), could be reduced from the present ≈95 700 kW•h/mile/year to 59 300 kW•h/mile/year, which at the low Portland rate of \$0.03/kW•h would be a saving of about \$1092/mile/year. Other streets in Portland (19) could have about the same percentage reduction; this yields an average cost reduction of about \$700/

mile/year. Thus, if the estimated 1500 miles of Portland city streets were brought to the recommended quantity and quality levels by using modern efficient light sources, there would be an estimated potential savings (based on an energy cost of \$0.03/kW•h) of about 1500 miles x \$700/mile = \$1 000 000/year.

Traffic Safety

Traffic safety is a less tangible quantity than energy savings. The supporting data on which to base the recommended lighting levels indicate that traffic safety increases with lighting level up to an inflection value (18). The relation is not linear. There are rapid gains in safety for increases in low lighting levels, but a point of diminishing returns is reached as the levels are increased. A practical upper limit is in the range of 1-2 footcandle illumination or 0.30- to 0.60-footlambert luminance. Traffic safety is considered to be a function of traffic volume, time of day, speed, weather, and the state of alertness of drivers and pedestrians, among the important variables. All of these variables are aided by good roadway lighting. The hours of darkness are known to be more hazardous for vehicle operations. When all known factors except darkness are isolated and eliminated from accident records, reduced visibility at night is shown to be a prime causal factor in vehicle accidents.

Pedestrian Safety

Pedestrian safety is a matter of prime concern on city streets (12). Accident records show more pedestrian-vehicle accidents in cities than any other type. Again, increases in the lighting levels at the lower end of the scale are more significant in improving the visibility of pedestrians than increases at the higher levels. The fundamental seeing problem is one of developing contrast between the pedestrian and the background. In most situations, the pedestrian will be perceived in silhouette as a dark object against a lighter background. If the roadway has a reasonably uniform luminance pattern, even though at a low level, a dark object can be perceived, especially if motion is involved. Headlamps help for objects in the foreground in such areas, but fixed lighting ensures that pedestrian safety will be improved (15,17).

Adjacent Property Security

Adjacent property is always lighted to some extent by street lighting. This has both good and bad points. The good points are the following:

1. The light that does not fall on the traveled portion of the roadway will illuminate the parking areas, the sidewalks, the building facades (if any), and the yards and porches that may be adjacent to the road.
2. The spill light will broaden the visual field and raise the adaptation level of the driver.
3. Visual guidance and orientation information for the driver is increased.
4. A feeling of security and well-being is induced in pedestrians and residents along the street by a reasonable amount of spill light.
5. Street crime is generally lower on lighted streets and sidewalks than on unlighted streets (20).
6. Civic pride is enhanced, and this results in improved maintenance and cleanliness in lighted areas.

The bad points have to do with light trespass and atmospheric light pollution. There are situations in which spill light causes problems by shining in windows or on objects that should remain dark, such as certain plants that require a diurnal cycle of light and dark. Other special problems, such as insect control, discomfort glare, or claims of invasion of privacy, may also develop. Furthermore, in some localities spill light is of great concern to astronomers, both professional and amateur (21).

On balance, light on adjacent property in the amounts that may be produced by residential street lights is welcomed. In commercial, industrial, and retail business areas, the spill light may be requested by businessmen to aid in accenting business activities and to provide security lighting.

Visibility

Visibility as applied to roadway lighting has a subjective meaning that is generally associated with the perception, recognition, and reaction to the visual scene and the details within the scene. The specification of visibility as a measurable quantity has been a goal of researchers and engineers for many years, but as yet it has not been satisfactorily quantified. Much of the work has been related to threshold values and to indicate how far above threshold a particular object might be. A number of thresholds can be used, such as size of object, time for observation, motion and color of object, and luminance contrast. Generally, the contrast and size thresholds are most commonly used as a visibility metric (7).

Several field instruments have been devised that can be used to reduce the contrast of a given object to threshold without changing the adaptation level of the observer. These instruments are useful for special-purpose tests and research, but they have not gained wide acceptance for field measurements. Basically, there is too much variation in the subjective measurements (22-24).

Another approach to visibility measurement and specification is that used in England, called the "revealing power" of the lighting system (13). This is a statistical approach in which the percentage of locations where a pedestrian can be seen is determined. Conditions are specified regarding reflectances, size, time, background luminance, and so on. The higher the revealing power, the better is the system. This system has been available for many years, but it has never gained wide acceptance outside England.

The work of Blackwell in the United States has led to yet another way of quantifying visibility. This is the "visibility level" (VL) method (24) or the "visibility index" (VI) method (25), which is a spinoff. The basis for both is the idea that at a given adaptation level the eye has a specific threshold contrast sensitivity. Laboratory research data on contrast detection are used as the basis for comparing field objects with the reference data. Visibility levels are then established that relate to how far above threshold the objects are in the given visual environment. The concept is good, but the fundamentals have yet to be translated into a workable index of roadway visual performance.

An attempt to adapt the VL system to roadways was made by the Federal Highway Administration (FHWA) through a research contract with the Franklin Institute (25). This work resulted in the VI method, which does calculate a number that is intended to be a measure of "visibility" on a roadway. There are many problems with the technique. One has to do with the fundamental definition of contrast. Other problems relate to the shape, size, and reflectance of the standardized target, the method of specifying the background luminance, the computation of roadway luminance, and so on. All of these indeterminate factors, plus the lack of experience with the method and the requirement for a computer to make the calculations, have retarded the use of this system.

The program for the VI method is available and can be used for the evaluation of selected streets. The VI values can be used in the overall selection of systems, but they are not a part of the recommendations given in Table 1. The VI levels are normally the average values for the roadway. A VI_{15} value indicates the level above which 85 percent of the points on the roadway will lie. It may be noted that the developers of the system state that a VI of 1.50 represents their standard target in moonlight with a perception-reaction time of about 1.5 s for a driver going 30 mph. No recommendations are given for specifying VI levels.

Application of Lighting Standards

Types of Roadway Lighting

Most roadway lighting standards are focused on the lighting of continuous stretches of straight, uninterrupted roadways. Walkways, bikeways, natural or delineated pathways, sharp changes in route direction, intersections, diverging and merging areas, fixed hazards, and destinations are given little attention. Destinations in this case would include rest, waiting, and parking areas; bus stops; entries; exits; toll gates; terminals; and so on. "Curb-to-keyhole" security lighting has been almost totally ignored, although it is usually assumed that conventional roadway lighting will provide some security lighting.

Emphasis Lighting of Critical Traffic Areas

The main point to be made here is that proper design of the lighting for critical areas has been largely ignored by codes and standards. But an excellent way to save traffic-lighting energy is to put that lighting where it is most needed in these critical areas and use less lighting in less critical areas.

Freeway lighting is a very specialized case of critical-area roadway lighting. It is worth noting that the State of California has long emphasized partial interchange lighting as opposed to continuous freeway lighting. Partial interchange lighting consists of lighting at critical traffic areas (off-ramps, ramp connections to crossroads, on-ramps, and merging and diverging areas). The lighting of city streets, of course, involves different problems.

But the lighting of critical traffic areas (mainly intersections) is more important than lighting roadways between intersections, especially in local-service areas. The greatest number of traffic events occur at intersections, and this is where lighting should have the greatest visual effectiveness. The lighting of critical areas calls for accent lighting--lighting with a strong visual attention effect (1,12).

Luminaire layouts for accent lighting should fit the geometry of the site. Generally, the uniformity of lighting within the accent area is much better than along a continuous ribbon of roadway. However, it is more difficult to specify and calculate average illumination for an area that is not as geometrically simple as a ribbon of roadway (streetside coefficient of utilization figures apply only to continuous ribbons of roadway). The basic rule for accent lighting layouts is to place a luminaire just beyond the traffic conflict area from the point of view of an approaching driver or pedestrian. At a simple cross intersection of two wide roadways, for example, a luminaire should normally be placed at the far right corner from the point of view of each approach direction (four luminaires). The design of a lighting layout for more complex intersection geometry is more difficult, but it still involves the application of the basic rule given above.

In order to achieve major savings in the energy consumed by city street lighting, the lighting of critical traffic areas should be considered of first importance. Low levels of illumination are not adequate for critical traffic areas, even though they might be sufficient for roadway delineation lighting and curb-to-keyhole security lighting. Since critical traffic areas are relatively small areas, the amount of power consumed in the lighting of these areas is likewise relatively small. If the same levels of illumination are specified for continuous roadways as for critical traffic areas, then the total power required goes up tremendously.

The lighting of "downtown" roadways between intersections is a special case. Higher levels of illumination are generally prescribed, not so much for traffic safety as to create a sense of security and to develop a phototropic effect that helps to attract people to business centers. But in outlying commercial, industrial, and residential areas, there is no need to have high levels of illumination between intersections. In the case of residential areas, minimum lighting at moonlight levels can be adequate. As a matter of fact, the American Standard Practice recommendation for walkway lighting currently specifies a minimum illumination level of 0.02 footcandle. As we know, the lighting of the moon, at about 0.02-0.05 footcandle, provides reasonable navigational night lighting; the only problem is that it is not always there. The energy-saving approach to city street lighting emphasizes the need for lighting at intersections and other critical traffic areas and implies that lower light levels can provide adequate visibility on roadways between intersections. The approach maximizes energy savings without compromising safety. Improved visibility at traffic conflict areas should improve safety; it certainly will not decrease safety! On the other hand, reducing light levels everywhere in order to save energy will reduce safety.

Because of the relatively close luminaire spacing required in traffic conflict areas, it is reasonable to use sharp-cutoff luminaires in these locations. Cutoff luminaires can improve visibility by enhancing visual attention to roadway objects and by reducing glare. If cutoff luminaires are used at intersections, noncutoff luminaires may be used between intersections. Then the possibility of confusing intersection lights with others will be minimized, and there will be increased contrast between intersection areas and the street areas between intersections. Such a layout would provide a desirable visual attention effect for critical traffic areas.

The use of sharp-cutoff luminaires at intersections and noncutoff units between intersections is given as only one example of how to achieve effective accent lighting for traffic conflict areas and relatively low-output diffuse lighting for intermediate roadway areas and for curb-to-keyhole security lighting.

ENERGY-SAVING CONVERSIONS

Street Classifications

In the following paragraphs, the recommended lighting standards are reviewed for each of the street classifications in the Portland, Oregon, study (19). Summary data for typical Portland streets are given in Table 2.

Class 1: Major Traffic, Regional Transit

The present system of 1000-W Hg lamps in refractor-type luminaires approximately meets the recommended lighting standard for regional-type roadways (Table 1). The glare values are generally high and the uniformity ratios are not entirely satisfactory, but the system is reasonably acceptable except for the energy consumption. The circuit wiring and controls, including the photocell actuators, appear to be in good working order. The mast arms and poles can be used "as is" for the present luminaires or for conversion to a new set of luminaires. If a new system is installed, it will probably be a 400-W HPS with core-coil ballast or a 310-W HPS with solid-state ballast system, so the present wiring controls and auxiliary equipment can be used with only minor changes. If a switching circuit is desired so that some lights can be selectively turned off and on, a modification in the wiring will be required.

The recommended lighting values can be met by using (a) 400-W HPS lamps on standard ballast or (b) 310-W HPS lamps on electronic-controlled ballasts, in suitable, commercially available fixtures. This assumes the use of existing poles, a mounting height of approximately 40 ft, and 150-ft average pole spacing along one side of the roadway.

Cost calculations for various types of systems for class 1 streets, based on data available at the time of the study, are given in Table 3.

Class 2: Major Traffic, Major Transit

The poles in the study area are located on both sides of the road in a more or less staggered configuration. The typical pole spacing ranges from 188 to 200 ft along each side; however, some poles are as close as 80 ft and as far apart as 400 ft. The calculations are based on an average pole spacing of 196 ft, a mounting height of 29.7 ft, and an overhang of 7 ft.

Because of the variations in pole spacings, the calculated uniformity values will not be achieved in a field installation. There will be short stretches where the E and L values will be higher and more uniform while other stretches with longer spacings will have lower E and L values and higher ratios of

Table 2. Nighttime pavement illumination and luminance values for Portland streets.

Street Classification	Street	Illumination (footcandles)						Luminance (footlamberts)		
		Horizontal			Vertical					
		Average	Ave/min	Max/min	Average	Ave/min	Max/min	Average	Ave/min	Max/min
Regional trafficway	Northeast Columbia Boulevard	1.1	3.67	10.67	–^{a}	–	–	0.30	3.24	8.53
Major traffic, major transit	Northeast Sandy Boulevard	0.79	4.79	12.41	0.268^{a} 0.468^{b}	3.83^{a} 2.75^{b}	9.57^{a} 6.94^{b}	0.21 0.17^{c} 0.39^{d}	2.6	6.78
Neighborhood collector										
Major transit	North Vancouver Avenue	0.84	3.52	7.62	–^{e}	–	–	0.24	4.6	13.8
Minor transit	Southeast Lincoln Street	0.86	3.05	5.48	0.430^{a} 0.366^{b}	7.4^{a} 7.3^{b}	15.9^{a} 20.0^{b}	0.18	7.58	
Local service	Northeast 53rd Avenue	0.36	33.2	75.0	–^{e}	–	–	0.04	20.9	69.0

[a] Value for eastbound traffic lanes.
[b] Value for westbound traffic lanes.
[c] Average of six points with dry pavement.
[d] Average of same six points as in footnote c with wet pavement.
[e] Vertical illumination not measured.

Table 3. Owning and operating costs for various lighting systems on class 1, 2, and 3 streets in Portland.

System	Annual Owning Cost ($/mile)	Annual Operating Cost ($/mile)	Total Annual Owning + Operating Cost ($/mile)	Annual Saving Over Present System	
				Amount ($/mile)	Percent
Class 1					
Present 1000-W Hg	0	4850	4850	–	–
New 400-W HPS	535	2120	2655	2195	45
New 310-W HPS with electronic ballast	613	1907	2520	2330	48
Class 2					
Present 400-W Hg	0	1564	1564	–	–
New 150-W HPS	416	874	1290	274	18
New 135-W LPS	559	942	1501	63	4
Class 3					
Present 250-W Hg	0	2121	2121	–	–
New 150-W HPS	493	1292	1785	336	16
New 90-W LPS	666	977	1643	478	23

Note: The lighting systems do not produce equal lighting conditions on the roadway in terms of E, L, or glare. All are greater than or equal to minimum specifications (see Table 1).

average/minimum and maximum/minimum. At the sections with very long spacings (on the order of 300 ft between poles), the values will drop to unacceptable levels. Additional poles and fixtures will therefore be required at such locations.

For class 2 streets, considerations other than lighting performance may be significant. For instance, the servicing of lights would be simpler and safer if relatively short mast arms (4-6 ft) were used so that the service truck could park at the side of the road. In addition, since these are major transit streets with many commercial businesses and passenger loading zones along the route, spill light to the side is desirable. Hence, a type III luminaire may be a good choice rather than a type II.

The color of the light is relatively unimportant insofar as traffic operations are concerned. The recommended light levels are high enough and the uniformity ratios are adequate for any available color of light (e.g., Hg, MH, HPS, or LPS) to reveal typical street objects and pedestrians to a normal attentive driver. However, color may be significant for other reasons, such as aesthetics or for color discrimination tasks.

The present luminaires and mast arms should be replaced to bring the roadway on class 2 streets up to recommended design standards. The present illumination and luminance values are not too far from the recommended average values (Table 2), but the uniformity and glare values are not acceptable. The existing poles can be used provided their remaining service life is determined to be adequate and provided that a considerable amount of variation in E and L values can be accepted due to the variations in pole spacings. The use of additional poles is recommended to improve the uniformity.

The present 400-W Hg luminaires could be replaced by 200-W or 150-W luminaires that use HPS or 135-W LPS lamps to achieve substantial energy savings and improved quality and quantity of light.

The results of cost calculations in the study project for class 2 streets are given in Table 3.

Class 3 and Class 4 Streets

There are many variations in the conditions that affect the lighting on class 3 and 4 streets. Some areas have many trees that are not trimmed. Some areas have parking and/or sidewalks on one side only. Some areas have commercial businesses whereas others are mostly residential. In most cases, the present lighting in the study areas meets the minimum recommended quantity standards proposed in this paper. However, the quality as measured by uniformity and glare is not good.

The present poles, mast arms, wiring, and switching controls can be used as is and used in a conversion program with either (a) luminaires with retrofitted lamps and ballasts or (b) new luminaires with self-contained ballasts. A conversion will save a substantial amount of energy since the present 400- or 250-W Hg lamps can be changed to 150-, 100-, or 90-W HPS or equivalent LPS lamps, depending on the location. The present mast arms can be used provided that the struts are modified to take the occasional high wind loads. Intersection lighting along the streets should be reviewed and, where necessary, additional poles and luminaires should be installed.

The potential savings of a 150-W HPS system over a present 400- or 250-W Hg system could be quite large. One does not have to perform the detailed cost analysis to estimate the energy savings, which would be approximately in the ratio of 150/400 or 150/250.

Cost data for a class 3 street in one of the study areas are given in Table 3.

Class 5: Local Service

A large portion of the street mileage in most cities is of the class 5 type. These are the residential and local collector streets. The lighting requirements are minimal, but they are important.

Class 5 streets in the study area are currently lighted by 175-W Hg lamps in various types of luminaires, located principally near the intersections of the local streets. Many of the block grids are 200x400 ft and have one light at midblock on the 400-ft leg and one light at the intersection.

The total amount of light on these local-service roadways from the 175-W Hg lamps is adequate, but the distribution of the light leaves much to be desired. The light is concentrated in the general vicinity of the pole, and the glare factors are quite high. A better distribution would spread the light along each roadway with a sharper cutoff at high angles. A four-way distribution at the intersections would be better, but it may not be possible to install such a system because of physical and cost limitations.

With luminaires installed on one side of the street, minimum lighting values can be met (marginally) by using the present 175-W Hg lamps or by using 70-W HPS lamps either in new commercial luminaires or retrofitted into present luminaires. It may also be possible to meet the requirements by using commercially available 55-W LPS luminaires (not evaluated).

With luminaires installed on two sides of the street in a staggered pattern, the minimum values can easily be met by using 70-W HPS lamps in commercial luminaires, 70-W HPS lamps retrofitted into existing luminaires, or 35-W LPS lamps retrofitted into existing luminaires.

Cost analysis for class 5 streets cannot be generalized because the local conditions vary greatly. For very low energy rates--such as 2.67¢/kW•h, the rate in Portland at the time of these studies--it would not be cost effective to change the 175-W Hg luminaires to new or retrofitted HPS or LPS sources because the capital and maintenance costs would be too high. However, if the improved visual conditions are considered to be necessary, then conversion of the class 5 streets is justified. As energy rates increase, the conversion becomes more viable.

Cutout Switching Systems

The lighting systems in the study area (19) are operated on single-phase circuits and on various voltages (e.g., 120, 240, or 480 V). Groups of four to six luminaires are controlled by a photocell actuator to turn the lights on and off at preset ambient illumination levels.

Studies indicate that it would be technically feasible to operate the lamps on circuits so that every other lamp along a run could be turned on or off on a preset schedule (e.g., off at midnight and on at 5:00 a.m.). The present photocell controllers could still be used to control the basic on-off cycle based on ambient light, or a single photocell could be used at a control center.

The payback period for a switching system would be relatively short, depending on the cost of energy. For example, by changing to 150-W HPS lamps on one class 2 street, the annual savings per mile were calculated to be about $1290. If a switching circuit were to be installed, an additional $1290 x 0.23 = $297/mile/year could be saved. On a 20-year, 7 percent basis, this $297 would represent an initial investment of $3143/mile. Thus, it may be very cost effective to install the system. At a higher interest rate, the plan would be even more attractive.

CONCLUSIONS

1. Nighttime roadway visibility can be greatly improved over present conditions, and energy can be simultaneously reduced.
2. The changes required in city street lighting systems to achieve improved visual conditions with substantial energy savings are cost effective.
3. Study areas show energy savings of 50-60 percent and that adequate visibility is maintained at night on city streets.
4. The overall owning and operating cost for a relighted city street will probably show a substantial reduction in cost over a present system that approximately meets existing lighting recommendations.
5. Whereas energy savings are easy to develop on a factual basis, total owning and operating costs are very difficult to develop. Each specific job must be analyzed separately by using local costs for labor, materials, interest, energy, inflation, taxes, etc., to arrive at a specific answer.

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Radio Control of Highway Lighting

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Reduction in energy consumption and in public criticism of sporadic control of lighting and the need for flexibility in providing lighting under adverse weather conditions were the bases for installing radio control of freeway lighting in the Chicago metropolitan area. The problems leading to the recommendation of this type of installation are described, and the various systems available for lighting control, as well as the advantages and disadvantages of each, are discussed. The decision to use the existing Illinois Department of Transportation voice radio system as a signaling medium for control of some 166 lighting power centers was made after several trial installations of different methods of control, including radio and power-line carrier systems, were tested. The installed system is automatic in operation and has manual override. It provides instantaneous control over the entire system of some 20 000 luminaires, over individual control cabinets, or over whole freeways. Encompassed in the system are seven two-way transmitter-receiver units that feed