WARRANTING FIXED ROADWAY LIGHTING FROM A CONSIDERATION OF DRIVER WORK LOAD

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This paper evaluates whether efficient and effective vehicle control is probable within a given night driving environment. A warranting scheme for roadway lighting is developed based on whether efficient and effective vehicle control can be achieved. Driver visual work load is used as the measure of effectiveness for vehicle control. Driver task levels are defined for the computation of work load or information demand. The task levels are positional, primarily routine speed and lane position control; situational, changes in speed, direction of travel, or position as a result of changes in situations; and navigational, selecting and following a route. Information demand is defined to be the time, in seconds, required to fulfill a sequence of positional, situational, navigational, and redundant positional information searches. Information supply is defined to be the time, in seconds, representing the visibility distance ahead for a given operating speed. When information demand exceeds information supply without roadway lighting, then roadway lighting is assumed to be warranted. Formulas for the computation of information demand, information supply, warranting conditions, and priorities are included.

•FIXED roadway lighting has many benefits. It improves roadway visibility, traffic operations, and police surveillance. The relative benefits and need for fixed roadway lighting depend on the objectives and values of a particular group.

The system for justifying fixed roadway lighting discussed in this paper seeks to create a suitable night driving environment where driving tasks can be performed in an efficient manner. The key to this objective is contained within the framework of the driver-vehicle-roadway complex. Because the driver's vision is the most important part of this complex, there must be sufficient visual information available to accomplish the driving task.

DRIVING TASK

Three basic levels of driving have been identified—positional, situational, and navigational (1). These levels describe driving tasks and driver behavior. The information needs and priorities for each level are as follows:

1. The positional level must always be satisfied before other levels can be attended to. It consists primarily of routine speed and lane position control.
2. The situational level must be satisfied before navigational level is attended to but not before positional level is satisfied. It consists of change in speed, direction of travel, or position on the roadway because of a change in geometrics or in the operational or environmental situation.
3. The navigational level is performed only if levels 1 and 2 are satisfied. It consists of selecting and following a route from origin to destination.

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SUITABLE VISUAL NIGHT DRIVING ENVIRONMENT

A suitable visual night driving environment requires that a given driving population should always be able to perform all 3 levels of the driving task within a time frame without sacrificing safety and efficiency. In an overload situation, the driver sheds higher level tasks until an acceptable work load is reached. An environment that causes the driver to shed certain driving tasks could not be considered a suitable night driving environment. Shedding driving tasks, or load-shedding, results when the information processing and vehicle control demands exceed the capabilities of the driver to service and perform them. It is not specifically the amount of work that the driver is required to perform that results in load-shedding, but rather the rate at which the work must be accomplished. The rate at which the driver can perform depends on the time required and the time available to obtain the information needed for safety and efficiency. Although positional information is immediately used to implement a steering or speed control action, most situational and navigational information tasks require only information processing or scanning actions on the part of the driver. Few overt control responses are necessary. More situational information is needed as the driving environment becomes more complex. Navigational tasks increase as the number of alternate routes increases.

For a given operational and geometric situation, a driver's information demands are fixed; the only variable is the information supply in time. The information supply in time depends on the length of roadway visible and varies inversely with speed. The faster the motorist drives, the smaller the information supply is. Fixed roadway lighting is a design variable that not only improves the information processing capabilities of the driver, but also increases the supply of information available to the motorist by making a longer section of roadway visible. This increase in the supply of information reduces the rate at which driving work tasks must be done and thereby reduces the chance of load-shedding.

WARRANTING CRITERION

The basic criterion used for evaluating whether fixed roadway lighting is warranted is whether the model indicates that a suitable night driving environment is provided. For this model, a suitable night driving environment is defined as one that enables the driver to perform all 3 levels of the driving task without having to load-shed. Information demands on a driver using a roadway without fixed roadway lighting for varying traffic conditions are compared to the information supply. If the information supply is not adequate, then fixed roadway lighting is warranted.

DESIGN DRIVING TASKS

The design driving tasks and sequence in which the driver is assumed to service information needs follow a cyclic order dictated by the primacy concept (1). The cycle would take a form such as (a) positional information search and control; (b) situational information search; (c) navigational information search; and (d) positional information search and control.

The premise is that safe and effective positional control can be maintained only if redundant positional information of the roadway ahead can be obtained each time the driver returns to positional information search and control. During situational and navigational information searches, the driver is assumed to be traveling without additional positional information. From a satisfactory design viewpoint, the driver should not be required to drive uninformed along a section of roadway he or she has never seen before. In this model, therefore, the driver must obtain positional information on the roadway ahead while still on a section previously evaluated during the last positional update.

COMPUTING INFORMATION DEMAND

Information demand is defined as the time required to fulfill a sequence of positional, situational, navigational, and redundant positional information searches. That is, the demand is

$$D = \sum (P_i + S_i + N_i + P_{i+1}) \quad (1)$$

where

D = information demand in seconds on a section of roadway,
P_i = time required to obtain positional information on cycle i,
S_i = time required to obtain situational information on cycle i,
N_i = time required to obtain navigational information on cycle i, and
P_{i+1} = next required positional information search update on cycle i + 1, which must be achieved within the section of roadway visible during P_i.

This model attempts to quantify the information demands arising from different geometric, operational, and environmental situations.

Positional Information Needs

Field studies in diagnostic team research efforts (2) have revealed that most positional information is obtained at night from lane lines, edge lines, curb lines, position of other vehicles, and a general view of the roadway. When viewing conditions are good, the driver can obtain positional information with peripheral vision. But, Gordon (3) and Rockwell et al. (4) have shown with eye mark studies that under night driving conditions a driver fixates on edge, curb, shoulder lines, and the roadway ahead more frequently.

Time required for visual perception of an information source is composed of latency, movement, and fixation times (5). Latency is the delay between the time the stimulus is presented and the time the eyes begin to move. Normally, the latency time averages about 0.2 second. The stimulus in this model is not a light or object but a continuous search for information, so no latency time is assumed to exist. The time required for eye movement varies between 0.029 and 0.10 second for movements of 5 to 40 deg respectively (5). A movement time of 0.05 second was assumed because of the relatively small angular movements required. After the eye has moved to the object, the eye must fixate on it. The mean fixation time for observing road and lane markers was found by Mourant, Rockwell, and Rackoff (6) to be 0.28 second. Luckeish and Moss (7) observed in the laboratory a mean fixation pause of 0.17 second in a range of 0.1 to 0.3 second. It is felt that the Mourant data more accurately reflect the positional information fixation under night driving conditions and, therefore, an average fixation duration of 0.25 second is assumed. Thus, the perception time required to sample the positional source would be 0.30 second.

The driving task model assumes that the driver can maintain satisfactory positional control if he or she can obtain redundant positional information. However, it is known that the positional information work load of lane tracking increases when the geometric complexity of the road increases. As the geometric complexity increases, a greater number of samples of positional information are required by the driver. Elementary field tests suggest that a driver can maintain satisfactory positional control on a tangent section of roadway for a period of about 0.3 second with sampling positional information. As average horizontal alignment increases in complexity, sampling times decrease.

Rather than the increase in sampling being expressed in terms of an increase in the number of samples of a fixed duration, it is accounted for by increasing sampling time above the minimum of 0.3 second to obtain an equivalent work load.

Personal driving experience also suggests that lane widths of less than 12 ft (3.7 m) require more positional information because the driver has less room and time for correctional control within the lane. This factor is accounted for by comparing the amount of space available in a 12-ft (3.7-m) lane to the given space provided by a lane of width W. An average vehicle width of 7 ft (2.1 m) is assumed.

The following equation is used for computing positional information demand:

$$P_t = 0.3\left(\frac{D^\circ}{2} + 1\right)\left(\frac{5}{W - 7}\right) \qquad (2)$$

where

P_t = positional information demand in seconds,
D° = average degree of horizontal curvature, and
W = average lane width in feet (m).

Because the driver obtains redundant positional information, it is assumed that only small steering control corrections are necessary. To implement these small control corrections, a minimal amount of cognitive and physical effort is required by the driver. This permits the driver to implement physical control correction while he or she begins to search for situational information needs. Therefore, no additional time is required to effect a positional information search and control update.

Situational Information Search

Situational information needs arise from changes in the geometric, operational, or environmental situation. Because the driver does not know where a hazard may be, he or she carefully looks for possibly hazardous areas. Eye mark studies (3, 4) have shown that the driver believes the roadway ahead to be a potentially hazardous area. Areas where traffic movements may conflict with the driver's path are also searched for situational information by the driver. Rockwell's eye mark studies indicate that drivers scan more potentially hazardous areas as they increase in number (4).

A summary of the situational task scan areas, conditions that warrant fixed roadway lighting, and guidelines are given in Table 1. Six types of situational information sources are considered. Four of these situational scan areas—intersectional, internal, medial, and marginal friction—can be on 1 or both sides of the driver, requiring 2 eye movements. The development of these 4 situational search demands is lengthy and is presented in another publication (2). It is assumed that the driver scans each of these situational areas to ensure safe and efficient operation when a potential hazard is visible 25 percent of the time. The fifth situational search area is the roadway ahead. Traffic signals, stop signs, and yield signs form the sixth situational scan area. At least 2 per mile are required on a roadway for continuous lighting to be warranted. Thus, almost all streets in an urban area have at least 2 warranting situational scan areas—the road ahead and traffic control devices that allocate the right-of-way.

Because of the increased complexity of the object and scene being viewed, the mean fixation time of situational information tasks is slightly longer than that of positional tasks. Mourant et al. (6) found that the mean fixation duration of vehicles, signs, and other objects was about 0.31 second. Because several scan areas are considered, and each is somewhat closer to the next, the visual angle required to shift from one to another is relatively small. As a consequence, the visual eye movement time is assumed to require 0.04 second. Thus, the total time required to satisfy the situational level information tasks, S_t, is obtained by multiplying the total number of warranting situational information scan areas (Table 1) by 0.35 second. $S_t = 0.35 \times$ sum of scan areas.

Navigational Information Tasks

According to the primacy concept, the driver can search for navigational information only after he or she has fulfilled the positional and situational driving information needs. The information sought would be the direction-finding type. The amount required would depend on the driver's previous experience in reaching the destination, previous information on the route, and the complexity of the required navigational decisions.

Mitchell and Forbes (8) derived an expression for the time to read 3 familiar words on a sign to be N/3 or 0.33 second per word. A value of 0.32 second per word is used in this study. Eye movement time is assumed to be 0.03 second. Thus, each word is assumed to require an average of 0.35 second to find and read.

Table 1. Situational information demands.

Scan Area and Facility Type	Minimum ADT Volume Warrant 1 Side	Both Sides
Intersectional friction		
Freeways[a]	1,000	–
Streets and highways[b]	1,000	2,000
Streets and highways[bc]	50	–
Interchanges[d]	5,000	10,000
Internal traffic friction		
4-lane freeways	20,000	–
6-lane freeways	30,000	57,000
8-lane freeways	40,000	76,000
10-lane freeways	50,000	95,000
4-lane streets	5,000	–
6-lane streets	5,000	9,000
8-lane streets	5,000	9,000
Medial friction		
Undivided unsignalized facilities	5,000	–
Undivided signalized facilities	4,000	–
Facilities with median divider less than 30 ft	10,000	–
Median-type facilities (curbed or discontinuous)	–	–
Marginal friction		
Driveways and minor intersections[ef]	30	60
Curb parking or bus stops[fg]	Any	Any
Pedestrians[fg]	Noticeable	Noticeable
2-way frontage roads[f]	–	5,000
Roadway ahead	0	–
Traffic signals[h]	Any	–

[a] To warrant continuous lighting, there must be at least 1 warranting entrance ramp per mile.

[b] Total cross roadway traffic. To warrant continuous lighting, there must be at least 2 warranting intersections per mile.

[c] Total left-turn traffic at intersection per peak night hour.

[d] Total cross roadway traffic. To warrant continuous lighting, there must be at least 1 warranting interchange per 1½ miles.

[e] Vehicles per peak night hour per 500 ft of roadway. Divide minor intersection volumes by 3.0 before adding.

[f] To warrant continuous lighting, there must be at least 2 warranting 500-ft sections per mile.

[g] On near side only for divided facilities.

[h] To warrant continuous lighting, there must be at least 2 signals, stop signs, or yield signs per mile.

Table 2. Uninformed-motorist minimum ADT.

Type	Rural	Suburban	Urban
Interchange			
Diamond	18,000	23,000	30,000
Cloverleaf	13,000	17,000	22,000
Directional	9,000	11,000	15,000
Partial cloverleaf	9,000	11,000	15,000
Y	9,000	11,000	15,000
Trumpet	9,000	11,000	15,000
Intersection	5,000	10,000	15,000

It would seem reasonable to assume that an informed driver, one who knows the facility, would need only 1 visual cue or 1 word to satisfy his or her navigational needs. The informed driver would then require only about 0.35 second per cycle to satisfy his or her navigational needs. The geometric complexity of the intersection or interchange would have little effect on the navigational information needs of informed motorists. All junctions should provide for at least this navigational task capability.

The uninformed or nonlocal motorist requires more time and information to make an efficient navigational decision than an informed motorist. In searching for the desired information, the uninformed motorist may read at least 1 uninformative word for every lane but 1. This is because most multilane facilities, especially freeways, have 1 overhead guide sign per lane approaching an interchange. After locating the correct overhead guide sign, the motorist must read at least 2 informative navigational words describing the appropriate route number or control city and the direction or lane assignment. Thus, the time, T_N, required by an uninformed motorist to satisfy navigational information needs at an interchange or intersection would be

$$T_N = 0.35\left(\frac{\ell}{2} + 1\right) \tag{3}$$

where ℓ is the total number of through lanes.

For an interchange to be considered an uninformed-motorist interchange, at least 1 uninformed motorist per minute would have to pass in each direction 75 percent of the night-design hour. If a Poisson distribution is used, this would require a minimum of 230 uninformed motorists per hour for both directions. It is assumed that 25 percent of the motorists on freeways in rural areas are uninformed, 20 percent in suburban areas, and 15 percent in urban areas. The ratio of the night-design hourly volume to average daily traffic (ADT) for all cases is assumed to be 0.05 percent.

The geometric complexity of the interchange and what the driver expects should be considered in evaluating navigational information tasks and difficulties. Diamond interchanges are perhaps the most expected and the easiest to navigate. Cloverleafs are assumed to be approximately a third more demanding. Partial cloverleaf, Y, trumpet, and directional interchanges are not expected by the uninformed driver and frequently are more difficult to negotiate. These types of interchanges are assumed to be 50 percent more demanding than the simple diamond interchange.

Table 2 gives the minimum interchange and intersection ADT volumes to warrant their being called uninformed-motorist interchanges and intersections. The volumes are the sum of the roadways' through, exiting, and entering volumes at the interchanges and intersections for each direction. The crossing roadways have an ADT of at least 20 percent of the values shown. All intersections and interchanges require at least 0.4 second of navigational information task time. To warrant continuous lighting there must be at least 2 warranting intersections per mile or, on freeways, at least 1 warranting interchange per 1½ miles.

COMPUTING POSITIONAL INFORMATION SUPPLY WITHOUT FIXED ROADWAY LIGHTING

Lane lines, edge lines, and curb delineation are the most critical and most needed positional information. All other situational and navigational tasks depend on the sufficiency of these visual inputs.

Model of Positional Information Supply

The supply of positional information is computed from the following equation:

$$C = \frac{\overline{L}}{1.47\,V_r} \tag{4}$$

C = positional information supply in seconds,
V_r = running speed of the traffic in miles per hour (km/h), and
$\bar{L}$ = average visibility distance of the critical source of positional information ahead of the driver without fixed roadway lighting.

The supply of positional information increases as visibility distance increases and decreases as speed increases. The critical source of positional information in this model is assumed to be the lane lines.

The visibility distance of a lane line depends on its contrast, brightness as determined by low-beam headlights, width of the lane lines, and the amount of disabling glare in the driver's field of view. This model was developed from the visibility research findings and theory of others and then calibrated with data obtained in a controlled field study to ensure that satisfactory visibility distances would be obtained.

The basic visibility equation was developed from research presented by Adrian (9). The following were presented: (a) brightness of the background; (b) minimum target size having a 100 percent probability of detection; (c) relationships among brightness differences; and (d) relationship between the target and its background. In this model, the target is the lane lines and the background is the pavement. The following equation, which relates the visual angle to the brightness and brightness differences, was developed from Adrian's research:

$$\alpha = \frac{1.66B_p^{0.327}}{(B_\ell - B_p)^{0.654}} \tag{5}$$

where

α = minimum visual angle in minutes of arc,
B_p = brightness of the background pavement in footlamberts (cd/m^2), and
B_ℓ = brightness of the lane lines in footlamberts (cd/m^2).

The size of the visual angle of the target is assumed to be determined by the width of the lane line, R, in inches (mm) and the resulting visibility distance of the lane line, L. Substituting a value of 287 R/L for α results in the following equation for the visibility distance, L:

$$L = 173\,\frac{R(B_\ell - B_p)^{0.654}}{B_p^{0.327}} \tag{6}$$

The effects of headlights of the oncoming vehicle can be included in the visibility distance equation by adding disabling glare, G, to the initial brightness of the object and background. Glare, G, is the sum of all glare effects from oncoming vehicles in the driver's field of view. The visibility equation thus becomes

$$L = 173\,\frac{R[B_\ell + G - (B_p + G)]^{0.654}}{(B_p + G)^{0.327}} \tag{7}$$

or

$$L = 173\,\frac{R(B_\ell - B_p)^{0.654}}{(B_p + G)^{0.327}} \tag{8}$$

The intensity of low-beam illumination on the lane lines and pavement surface near the anticipated visibility distance was estimated from photometric headlight data provided by a national manufacturer of highway signing materials. From these data the illumination in footcandles (lx) was estimated by

$$D = \frac{5000}{d^2} \tag{9}$$

where d is the distance from the vehicle to the location on the lane line where the intensity of illumination is desired. Here, this desired distance is the visibility distance, L.

Knowing the intensity of illumination, E, in footcandles (lx), we computed the brightness of the lane line from $B_\ell = \rho_\ell E$, where ρ_ℓ is the reflectance factor of the lane lines. The brightness of the pavement surface was computed from $B_p = \rho_p E$, where ρ_p is the reflectance of the pavement surface. Thus, the visibility equation becomes

$$L = 173R \frac{\left(\frac{5000\rho_\ell}{L^2} - \frac{5000\rho_p}{L^2}\right)^{0.654}}{\left(\frac{5000\rho_p}{L^2} + G\right)} \tag{10}$$

Glare per oncoming vehicle was computed from the generalized Holladay-Stiles formula

$$g = \frac{10\pi\ E_v}{\Theta^n} \tag{11}$$

where

g = glare in footlamberts (cd/m^2),
E_v = illumination striking the plane of the driver's eyes,
Θ = incident angle of the glare source in degrees, and
n = generalized exponent.

The amount of oncoming headlight glare depends on the lateral separation between an oncoming vehicle and the vehicle affected, s, and the longitudinal separation, X, between the 2 vehicles. The distance between the 2 vehicles would then be

$$h = \sqrt{X^2 + s^2} \tag{12}$$

It is recognized that vehicle headlights form a directionally oriented beam of light and do not act exactly as a point source of light. However, to simplify the calculations, the light was assumed to be a point source and the effective candlepower was determined by calibration to the photometric data at approximately 200-ft (61-m) longitudinal separation and 9-ft (2.7-m) lateral separation. From this calibration, the average effective left-side candlepower for dim lights was assumed to be 2000 candelas at the driver's eye height.

Substituting E cos Θ for E_v in the Holladay-Stiles glare equation where $\cos \Theta = X/(X^2 + s^2)^{1/2}$ and letting $E = 2000/h^2$ result in

$$g = \frac{10\pi}{\Theta^n} \frac{X\ 2000}{(X^2 + s^2)^{1/2} (X^2 + s^2)} \tag{13}$$

Assuming that $\Theta = \sin \Theta$ in radians (actually $\Theta = \sin^{-1} \Theta$, but the assumption $\Theta = \sin \Theta$ reduces the complexity of the equation with little effect on the result) and converting Θ in radians to degrees yield

$$g = \frac{10\pi \times 2000}{(57.3)^n \frac{s^n}{(X^2 + s^2)^{n/2}} (X^2 + s^2)^{1/2} (X^2 + s^2)} \tag{14}$$

Several values for the exponent n were tested in the range from 1.0 to 2.0. A value of n = 1.0 was found to correlate best with the field data recorded in this research and a value of 1.0 also simplifies the glare equation. Thus, using 1.0 for the exponent n results in

$$g = \frac{10\pi \text{ X } 2000}{57.3\ (X^2 + s^2)s} \tag{15}$$

Since the total glare (g in Eq. 11) is the sum of the individual glare values (g in Eq. 15), the visibility distance equation (Eq. 10) becomes

$$L = 173R \frac{\left(\frac{5000\rho_\ell}{L^2} + \frac{5000\rho_p}{L^2}\right)^{0.654}}{\left(\frac{5000\rho_p}{L^2} + \sum \frac{10\pi \text{ X } 2000}{57.3(X^2 + s^2)s}\right)^{0.327}} \tag{16}$$

or

$$L = \frac{2800R\ (\rho_\ell - \rho_p)^{0.654}}{L^{1.346}\left[\frac{\rho_p}{L^2} + 0.022\sum \frac{X}{(X^2 + s^2)s}\right]^{0.327}} \tag{17}$$

In the field test, a white beaded paint was used for 4-in. (102-mm) wide dashed lane lines on a concrete pavement. The reflectance factor was assumed to be 0.3 for the pavement and 0.7 for the reflective paint. These assumptions and R equal to 4.0 yield

$$L = \frac{5100}{L^{1.346}\left[\frac{0.3}{L^2} + 0.022\sum \frac{X}{(X^2 + s^2)s}\right]^{0.327}} \tag{18}$$

The model was then calibrated with field data to ensure acceptable legibility results. The calibration analysis revealed that the coefficient should be 4000 instead of 5100. Figure 1 shows the final calibrated results as compared to the field data.

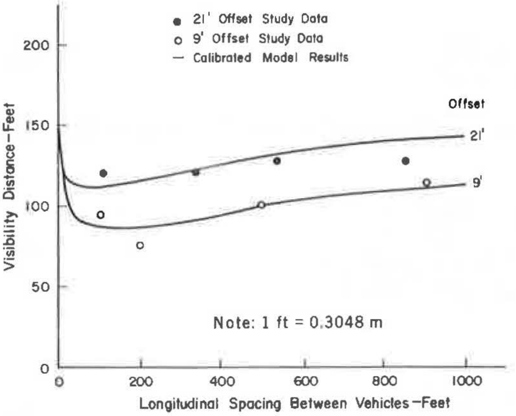
The difficulty in computing the visibility distance is that it results from trial and error. The lane line visibility distance has to be assumed to compute its brightness, which in turn affects the visibility distance.

Visibility of the roadway ahead of the driver is reduced because of oncoming vehicle headlight glare. As the volume and density of oncoming vehicles increase, visibility decreases. However, visibility increases as the lateral separation between opposing traffic flows is increased. These facts are reflected in the results of the application of the visibility model to various traffic operational conditions shown in Figure 2. These results were obtained by summing the glare caused by every vehicle in the opposing traffic stream within 1,000 ft (305 m) of the driver. The effects of 500 vehicles were computed. A uniform spacing was assumed in the opposing traffic flow with the first vehicle positioned at half the average spacing in front of the affected motorist.

The oncoming vehicle headlights produce glare in the driver's eyes. Environmental lighting also produces glare. Certainly, the glare caused by different roadside establishments varies widely. But, it seems impractical to require that they be counted or that their effects be measured directly. The objective is to develop a practical method of incorporating roadside lighting into the approach being developed.

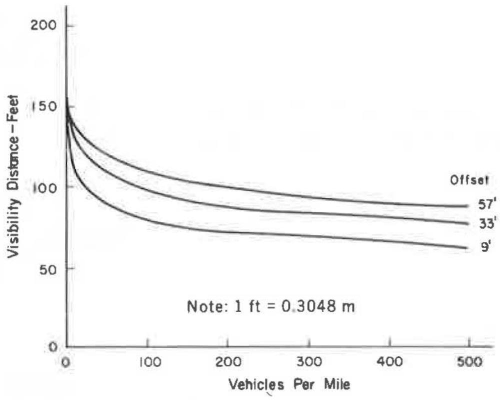
If it is assumed that 52.8 ft (16 m) of frontage of an establishment that is lighted at night has a glare equivalent of 1 oncoming vehicle, then a traffic facility that has 100 percent roadside lighted development on 1 side would be equivalent to a vehicle light-source density (as shown in Fig. 2) of 100 vehicles per mile (161 vehicles per km). A 100 percent lighted development on both sides would be equivalent to 200 vehicles per mile (322 vehicles per km).

Figure 1. Visibility distance of 4-in. (102-mm) lane line as a function of lateral offset and distance of oncoming headlights.



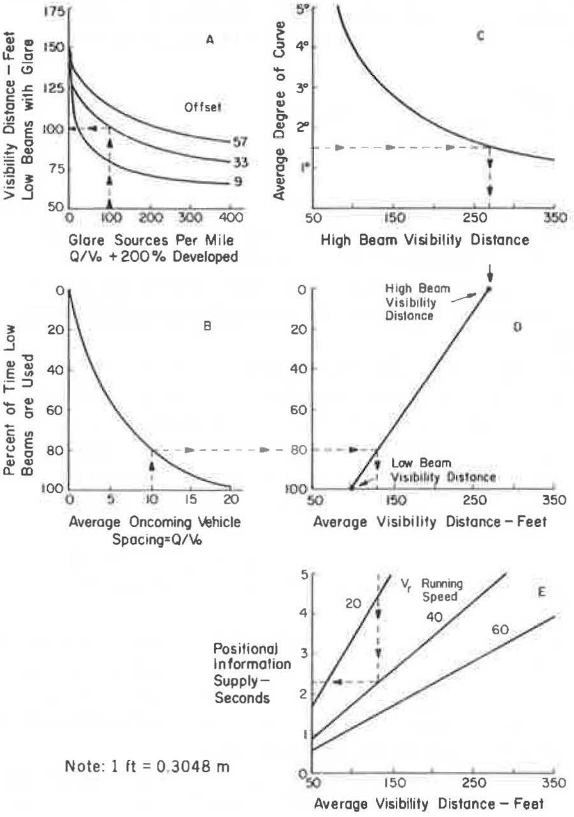
Note: 1 ft = 0.3048 m

Figure 2. Low-beam positional visibility distance as a function of oncoming vehicle density and lateral separation.



Note: 1 ft = 0.3048 m

Figure 3. Information supply.



Note: 1 ft = 0.3048 m

This process is simplified by the assumption that roadside lighting is located at the same offset as the oncoming vehicle headlights. Although this assumption may seem unjustified, the principal objective is to include the roadside environmental effects in some reasonable way rather than to neglect them entirely.

Procedure for Computing Positional Information Supply

The following procedure, shown in Figure 3, is presented to compute the positional information supply. The procedure considers general visibility as previously discussed, including glare from oncoming vehicles and roadside development; the percentage of time the driver will be using high and low beams; the average horizontal alignment; and the average speed of the driver.

Step A—The first step is to compute the visibility distance of the lane lines as shown in Figure 3A. Four items of data are required: (a) the opposing traffic stream volume during the night-design hour, Q; (b) the operating speed of the opposing flow for the previous volume, V_o; (c) the average lateral offset of the opposing stream flow with respect to the inside lane in the driver's flow; and (d) the average percentage of development along the facility.

Assume that the facility has four 12-ft (3.7-m) lanes and an 18-ft (5.5-m) median. The lateral offset is $3 + 18 + 24/2 = 33$ ft (10 m). The directional volume, Q, is assumed to be 300 vehicles per hour during the night-design hour. Because of traffic signals, the operating speed in the opposing flow, V_o, which includes delay time, is 30 mph (48 km/h). The flow or speed is assumed to be the same in each direction. The average roadside development that has exterior lighting is 45 percent for both sides.

According to Figure 3A, the number of glare sources per mile is $(Q/V_o) + 200 \times$ development percentage or $(300/30) + 200 \times 45$ percent $= 10 + 90 = 100$. Using this result and the 33-ft (10-m) lateral offset shown in Figure 3A gives a low-beam visibility distance of 100 ft (30 m). This answer will be used later in the procedure in Figure 3D.

Step B—A driver traveling along a roadway at night generally uses both high- and low-beam headlights. The driver would use mainly high beams on low-volume rural highways, and low beams in urban areas. These facts must be taken into account to estimate the average positional information supply. Figures 3B and 3D were developed to satisfy this requirement.

Figure 3B gives the average percentage of time a driver would use low beams as a function of the traffic volume in the opposite direction, Q, and its average operating speed, V_o. This figure is based on Poisson distribution and on the assumption that opposing drivers dim their lights at a 1,000-ft (305-m) longitudinal separation distance. Again, based on the data given, $Q = 300$, $V_o = 30$, Figure 3B shows that 80 percent of the time the affected driver would use low beams. This answer will be transferred to Figure 3D.

Step C—The next step is to compute the average high-beam positional visibility distance. The maximum high-beam visibility distance of positional information on a straight roadway is assumed to be 400 ft (122 m) without fixed source roadway lighting. But, as the average degree of curvature of the roadway increases, the visibility of the pavement surface and lane lines decreases because the roadway is curving away from the headlights. The curve shown in Figure 3C is based on the assumption that a vehicle's high-beam headlight pattern will permit lane lines to be visible up to a 2.0-deg angle of divergence with the longitudinal axis of the vehicle.

The average degree of curvature of a roadway is computed by summing the degrees of curvature at each 100-ft (30-m) station and dividing the sum by the number of stations considered. In this example, it is assumed that the average degree of curvature is 1.5 deg. That results in an average high-beam visibility distance of 270 ft (82 m).

Step D—As shown in Figure 3D, after the visibility distances for high beams and low beams are plotted at 0 percent and 100 percent low-beam use, an average positional visibility distance, $\overline{L}$, of 134 ft (41 m) is computed for the 80 percent low-beam operation existing in the example. This figure solves the equation

$\bar{L}$ = percent low beam (L) + (100 percent - percent low beam) ($L_{\text{high beam}}$)

Step E—The final step is to compute the positional information supply in seconds from the average visibility distance in feet (meters), $\bar{L}$, here 134 ft (41 m), and the average running speed in miles per hour (km/h), V_r, here 40 mph (64 km/h). Figure 3E shows that the positional information supply, C, is 2.3 seconds. Figure 3E solves the equation $C = \bar{L}/1.47\ V_r$.

WARRANTING FIXED ROADWAY LIGHTING AND ESTABLISHING PRIORITIES

The approach used here to warrant fixed roadway lighting is based on the driver's information needs to perform his or her driving task on the facility in question within the driving environment present. From this viewpoint, fixed roadway lighting is warranted along a section of roadway or at interchanges or intersections when the information demand exceeds the information supply without fixed roadway lighting.

The information demand is the time required to fulfill the sequence of positional, situational, navigational, and redundant positional information searches. Demand is given in Eq. 1. The time required by the driver to make a positional update, P_i, is computed from Eq. 2. But, 2 positional updates are required, each of the same duration, within a given supply time. The time required to satisfy the situational information needs, S_i, for a facility is computed by using Table 1. The time required to make a navigational update is 0.0 second between junctions, 0.4 second where intersections and interchanges do not warrant a higher level, and 0.35 ($\ell/2 + 1$) second where this higher level is warranted as given in Table 2.

Substituting the results from Eq. 2 for both P_i and P_{i+1}, determining S_i from Table 1, and evaluating N_i from Table 2, give an information demand of

$$D = 1.5\left(\frac{D^\circ + 2}{W - 7}\right) + S_i + \left[0.0,\ 0.4,\ 0.35\left(\frac{\ell}{2} + 1\right)\right] \qquad (19)$$

where

D = information demand in seconds,
D° = average degree of horizontal curvature in degrees,
W = average lane width [for a 1-lane turning roadway use 5 ft pavement width (1.5 m)],
S_i = situational information time demand, using Table 1, and
ℓ = number of facility lanes, using Table 2.

The positional information supply depends on the suitability of the night driving environment without fixed roadway lighting. The positional information supply in seconds, C, is computed from Figure 3.

To check a section of roadway to determine if fixed roadway lighting is warranted, the information index, I, is computed as follows:

$$I = \frac{D\ (\text{information demand})}{C\ (\text{information supply})}$$

Fixed roadway lighting is warranted if the information index, I, is greater than 1. It is recommended that 500-ft (152-m) sections of roadway be analyzed.

Noncontinuous Warranting

On roadways that do not warrant continuous lighting, the interchanges or intersections should be evaluated without the continuous lighting requirements. Interchanges and intersections will warrant lighting, even though the roadway itself may not warrant continuous lighting. These should be considered for area lighting. Partial interchange lighting might be based on an individual movement analysis.

Establishing Priorities

The decision-maker, who allocates funds to various competing warranting lighting projects, needs a rational approach to use in allocating funds to maximize benefits to motorists. One such approach is to compute an equivalent priority index, P_x, for any warranting lighting project, X, and to compare it to all other competing projects. If all competing priority indexes were ranked in order from highest to lowest, then selections would be made from the top until either all available funds were spent or some minimum acceptable priority spending level was reached based on historical needs. The recommended procedure for computing the priority index for a warranting lighting project is

$$P_x = \frac{\sum_{i=1}^{D} I_i Q_i d_i}{C_i}$$

where

P_x = priority index of warranted lighting project X,
I_i = information index of roadway section i,
d_i = length of roadway section i,
Q_i = ADT on roadway section i,
D = number of sections warranted on roadway, and
C = present cost of lighting, operating, and maintaining the complete project.

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