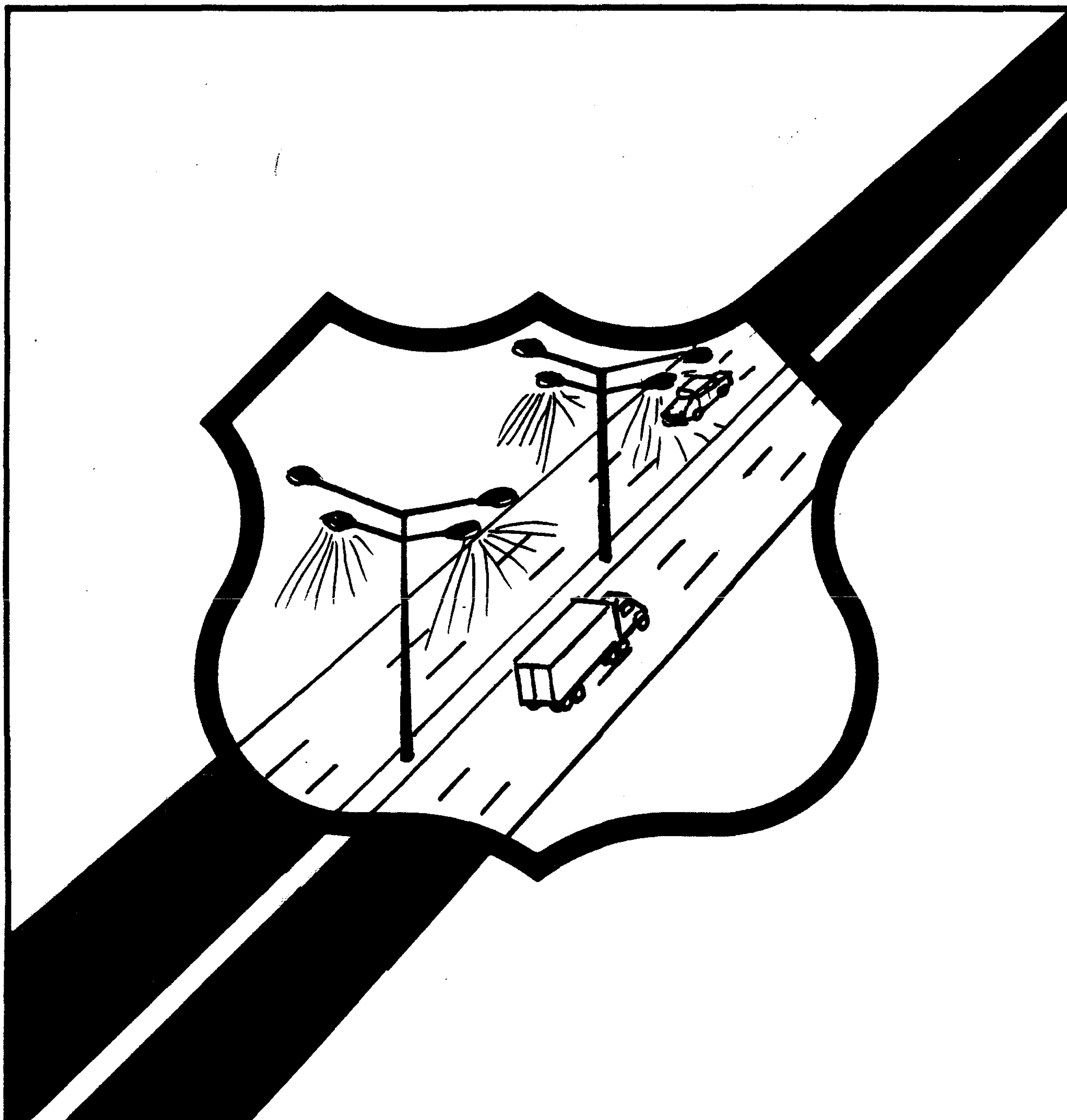
A RELATIVE EFFECTIVENESS ANALYSIS OF A SELECTED FIXED LIGHTING SYSTEM VERSUS VEHICLE HEADLIGHTS

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101

U.S. Department of Transportation
Federal Highway Administration

Report No.
FHWA/RD-86/033

Appendix to
Final Report No.
FHWA/RD-86/018
October 1985



Technical Report Documentation Page

1. Report No. FHWA/RD-86/033	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Relative Effectiveness Analysis of a Selected Fixed Lighting System Versus Vehicle Headlights		5. Report Date October 1985 6. Performing Organization Code
7. Author(s) L.K. Staplin and M.S. Janoff		8. Performing Organization Report No. 3222
9. Performing Organization Name and Address KETRON, INC. 5th & Chestnut Sts. Philadelphia, PA 19106		10. Work Unit No. (TRAIS) FCP 31P3-042 11. Contract or Grant No. DTFH61-83-C-00056
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		13. Type of Report and Period Covered Appendix to Final Report August 1983-August 1985 14. Sponsoring Agency Code

15. Supplementary Notes

Contracting officer's technical representative
J. Arens (HSR-30)

16. Abstract

The objective of this analysis was to evaluate the relative effectiveness of a selected fixed lighting system and vehicle headlights in providing the visual inputs needed by drivers to detect a defined category of roadway hazards. Key parameters in the analysis included the position (distance and orientation) of a vehicle operator with respect to a detection target in the roadway, the characteristics (size, shape/configuration, reflectivity) of the detection target, the reflectance characteristics of the road surface, the estimated target and background luminance levels for a fixed lighting system, the estimated target and background luminance levels for a vehicle-based source of illumination, and the position of opposing vehicles (if any) with respect to an observer/driver. A conceptual model incorporating published decision-sight-distance (DSD) formulations was employed.

Calculations were performed which indicated a marked superiority for fixed lighting systems as observer-target separation distance is increased and/or target reflectivity is decreased and/or an opposing vehicle is present and located (longitudinally) between the observer and the detection target/hazard. Road surface reflectance characteristics had a comparatively smaller impact on the present relative effectiveness calculations.

17. Key Words Lighting, Illumination, Luminance, Visibility, Driver, Performance, Detection, Safety, Light Reduction.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 41	22. Price

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized

PREFACE

The authors gratefully acknowledge the assistance of Mr. Billy Lee Shelby, ITT Lighting Fixture Division, Southaven, MS, who conducted computer analyses of simulated lighting systems essential to the visibility calculations contained in this report.

LIST OF FIGURES

Figure		Page
1.	Luminaire arrangement analyzed by Site-Lite program	9
2.	(a) Vertical illuminance on a plane facing south in the observer's lane of travel, at the road surface	10
	(b) Pavement luminance in the observer's lane of travel	10
	(c) Target luminance in observer's lane of travel	10
3.	Target versus background luminance through one luminaire cycle (R-1 road surface)	11
4.	Typical U.S. low-beam isocandela diagram (#4,000, 5 3/4" type 2 low-beam system)	13
5.	Coordinate system describing relative position of glare source, target, and observer	24

LIST OF TABLES

Table		Page
1.	Estimated values of target and background luminance (fL)	15
2.	(Pure) contrast values for conditions of interest in present analysis	16
3.	RCS factors, by age, for L_b conditions in present analysis	18
4.	Disability glare factor (DGF) values associated with RLS conditions included in the present analysis	20
5.	Expressions of effective contrast for the lighting conditions included in the present analysis	21
6.	Background and veiling luminance produced by low beams of an opposing vehicle	28
7.	(Combined) background and veiling luminance estimates for each condition of interest when opposing vehicle is present	29
8.	RCS factors for L_b levels obtained when opposing vehicle is present	29
9.	DGF values for each condition of interest when opposing vehicle is present	30
10.	(Pure) contrast values for conditions of interest in present analysis, given presence of opposing vehicle	31
11.	Effective target contrast for each condition of interest, given presence of opposing vehicle	32

This appendix to the Final Report* on an FHWA project investigating the impact of reduced lighting tactics evaluates the relative effectiveness of fixed lighting systems versus vehicle-based illumination, in providing the visual inputs required by a driver for the detection and subsequent avoidance of roadway hazards. Target visibility is acknowledged as the greatest influence on a driver's probability of (hazard) detection, with a specific focus on effective contrast--i.e., an expression of visibility derived by first obtaining the difference between the luminance of a detection target and the luminance of its background, then dividing this figure by the level of background luminance alone, and, finally, adjusting the quotient to take an observer's contrast sensitivity and the existing level of disability glare into account.[1]

Specifically, fixed and vehicle-based sources of visual information are compared through an analytical determination of the level of (effective) contrast each provides for a defined target stimulus, based upon current U.S. low-beam headlight performance specifications, a computer-simulation of illuminance and luminance levels produced by a typical fixed lighting system, and the recommended (1983) IES Standard Practice for Roadway Lighting.

Topic subheadings in this section are comprised principally of the key parameters affecting calculations of effective target contrast:

- The position (distance and orientation) of a vehicle operator with respect to a detection target in the roadway;
- The characteristics (size, shape/configuration, reflectance) of the detection target;
- The reflectance characteristics of the road surface;
- Estimates of target luminance and background luminance for fixed roadway lighting systems;
- Estimates of target luminance and background luminance for vehicle-based sources of illumination.

After these variables have been specified, values are derived for effective target contrast provided by a) fixed lighting, and b) the headlights of a single (driver's own) vehicle, for three varying combinations of observer position (i.e., separation distance from target), target reflectivity, and pavement reflectance. Finally, estimates of effective target contrast which include the influence of an opposing vehicle's headlights are derived for a single separation distance/target reflectivity/pavement reflectance situation.

*Staplin, L. K., Janoff, M.S., and Decina, L. E., "Reduced Lighting on Freeways During Periods of Low Traffic Density," FHWA, USDOT, Contract DTFH61-83-C-00056, Final Report. August, 1985.

Observer Position. Establishing the position of a driver in relation to a to-be-detected hazard in the roadway may be accomplished by first considering the highway environment from the perspective of information handling zones.(2) This notion provides a framework for dividing any potential problem location into zones corresponding to what the driver experiences approaching, driving through, and leaving the site. Upstream of a hazardous location, the roadway is partitioned into three zones: an advance zone, where the hazard does not yet affect the driver's task; an approach zone, identical to the decision sight distance; and, a nonrecovery zone, beginning at that point where a vehicle response must have been performed if a (man-machine-environment) system failure is to be avoided. (A hazard zone--the actual problem site--and a downstream zone are also included within this framework.)

Although perceptual feedback concerning a hazard in the roadway is likely to continue from some point in the approach zone well into the nonrecovery zone, a concept labeled decision sight distance (DSD) allows the temporal separation of driver response factors and vehicle response factors--a crucial distinction in the present analysis. Specifically, an additive model has been described, outlining a sequential chain of events beginning at the moment a hazard is first visible and ending when a hazard-avoidance maneuver has been successfully completed; the times required for each operation in the sequence (hazard detection, hazard recognition, driver decision of an appropriate course of action, driver response, and vehicle maneuver/response) are combined, with the resulting sum then translated into a minimum required distance to complete a given maneuver under a given level of roadway (visual) complexity, at a specified design speed.(3)

While the DSD approach has obvious application to the placement of warning devices in advance of known hazards, it can also be used to fix limits on the position of a driver in relation to a hazard--either known or unexpected--at any desired stage (e.g., hazard detection) in the sequence of (information-processing) operations listed in the preceding paragraph. First, a reliable estimate of vehicle velocity for the roadway environment of interest is needed. Conveniently, the Highway Statistics Division of the Federal Highway Administration, USDOT, has compiled extensive speed data for traffic on limited-access highways as part of a 55-mph monitoring program. For fiscal 1982, approximately 1800 monitoring stations nationwide reporting data on 37 million vehicles indicated 85th percentile speeds of 65.1 mph (104.8 km/h), 62.7 mph (100.9 km/h), and 62.1 mph (99.9 km/h) for rural interstate, urban interstate, and other freeways and expressways, respectively.* These figures reflect both daytime

*As per telephone conversation of September 7, 1983 with Mr. Bob Gish, Highway Statistics Division, FHWA.

and nighttime traffic operations; no significant differences in vehicle velocity as a function of time of day have been documented in this program.

Given the range of 85th percentile speeds (62.1 to 65.1 mph)/ 99.9 to 104.8 km/h) cited above, it is possible to determine the approximate distance at which a driver must detect and recognize the presence of a hazard in the roadway to have a high probability of successfully executing a specified avoidance maneuver. For low-volume conditions a lane-change is judged more likely than reducing speed or stopping on a freeway; consequently, component processing times and recommended DSD values associated with that particular maneuver (at 62 mph/99.8 km/h) are presented below:

*Recommended time(s)				
Detection and recognition	Driver decision and response	Maneuver (lane change)	Total	Recommended DSD (rounded)
2.0-3.0 s	4.7-7.0 s	4.3 s	11.0-14.3 s	1000-1300 ft

1 m = 3.28 ft

Next, the recommended DSD may be partitioned according to the fraction of the total time attributable to each component process. When using the minimum (rounded) value of 1000 ft (304.8 m), this calculation leads to the conclusion that detection/recognition must be accomplished roughly 820 ft (249.9 m) in advance of a hazard to result in a high probability that a driver will have enough additional time to then decide upon and initiate a response, and safely complete the vehicle maneuver. Considering how efforts to validate the DSD model in the field revealed that attributing 2 to 3 seconds for detection-plus-recognition probably is somewhat conservative, a slightly increased figure of 850 ft (259.1 m) may be designated as a worst-case "criterion detection-threshold distance." (4)

Alternately, although judged significantly less likely as a driver response to the detection of a hazard on a multilane highway, a braking maneuver--rather than a lane-change--may also be considered. The approximate distance at which a driver must detect and recognize a hazard to have a high probability of successfully accomplishing a braking maneuver is determined as

*Source: ref. (4), Table 1.

follows. At the measured 85th percentile speed of 62 mph (99.8 km/h), or 90.95 ft/s (22.7 m/s), the decision sight distance model indicates a minimum driver-decision-and-response interval (for a low to moderate complexity situation, such as that to be expected on a freeway under low traffic volumes) of 4.7 s. In this amount of time, the vehicle will travel 427 ft (130.1 m). In addition, the actual stopping distance--once the braking response has been initiated--can be calculated, according to:

$$\text{*Stopping distance in feet (on level roadway)} = \frac{V^2}{30 \times \underline{f}}$$

where V is vehicle velocity (must be in mph) and $\underline{f}$ represents the coefficient of friction between the vehicle's tires and the road surface. A reasonable estimate for the value of $\underline{f}$ given dry pavement conditions and tires with a moderate amount of wear, based on published research, is 0.60.(6) When V is set equal to 62 mph, then, stopping distance (in feet) on a dry, level roadway is roughly

$$\frac{62^2}{30 \times 0.60} = \frac{3844}{18} = 213.5$$

and the total distance at which a driver must detect and recognize the hazard is the sum of 427 ft and 213.5 ft, or approximately 640 ft (195.1 m).

Realistically, the most typical driver response to a detected hazard in the roadway probably involves both a slight change in heading <u>and</u> velocity. Certainly it does not follow that a lane-change maneuver must always be completed by the time the hazard location has been reached; nor is it likely that anything more than a momentary brake application---producing only a modest reduction in vehicle speed---will occur. In fact, under the <u>best</u> of circumstances, a time span only marginally exceeding the minimum decision-and-response interval cited above [4.7 s, or 427 ft (130.1 m) at 62 mph (99.8 km/h)] may be adequate for successful hazard avoidance. This would define a "best-case" criterion detection-threshold distance of roughly 450 ft (137.2 m).

The various intervals estimated as necessary for successful hazard detection and avoidance---each derived from a different set of assumptions--thus translate into a range of distances, with 450 ft (137.2 m) as the most favorable estimate and 850 ft (259.1 m) as the most conservative. It is not appropriate (and probably not possible) to definitively assess the relative likelihood that a driver will complete a lane-change maneuver, a braking reaction, or will perform some hybrid response within the context of this analysis, however. Accordingly, subsequent visibility

---

*Source: ref. (5), p. 139.

calculations will initially be based upon the intermediate detection-threshold distance of 650 ft (198.1 m). In addition, a shorter separation distance of 250 ft (76.2 m) will be considered, for comparison purposes. Though not consistent with the additive, DSD model, field observations have suggested that the 250 ft (76.2 m) separation distance is more realistic in terms of what drivers are able to detect at night.

Concerning the orientation of a driver with respect to a to-be-detected hazard, the most probable antecedents to avoidance maneuvers on freeways--and therefore an additional parameter in this investigation--are targets positioned in a head-on (same lane) location in the roadway.

Target Characteristics. The next variable to be specified in the comparison of fixed- and vehicle-based lighting sources is the nature of the target a driver is required to detect in the roadway; characteristics such as size, shape, and reflectance have a pronounced and well-documented effect on indices (e.g., speed and accuracy) of general visual task performance.[7] Disregarding stimuli used primarily in laboratory studies of visual acuity/discrimination (e.g., Landolt rings), three types of targets that have been included in detection experiments under actual lighting conditions may be described: 1) simulated pedestrians--either mannequins or visually equivalent objects; 2) flat, two-dimensional disks or squares which "stand up" vertically in the roadway; 3) three-dimensional objects, such as truncated cones.[8,9,1]

Pedestrians, first of all, are not common on freeways; further, by virtue of their size and highly familiar configuration, they cannot credibly be generalized--in terms of detection/recognition performance under actual lighting conditions--to the types of targets identified in the previous section as the focus of this investigation. Similarly, the degree of realism obtained by representing highway debris capable of resulting in damage or loss of control of a vehicle if hit at high speed (e.g., a detached muffler, construction materials, etc.) with two-dimensional, vertical targets leaves something to be desired. In this approach, the influence of horizontal illumination (E_H)--i.e., the vertical component of the illumination vector--on target visibility is completely ignored.

It is the third category of targets listed above that offers the greatest degree of realism, in terms of modeling roadway hazards. Only a three-dimensional configuration presents target surfaces to the entire range of horizontal and vertical incident illumination; specifically, a sphere might be used to ideally represent this class of objects. Next, it would make sense to limit the size of the sphere so that overall target height was in line with current AASHTO standards in this area--i.e., roughly 6 in (15.2c m) above the road surface.[5] Target reflectance, while somewhat arbitrary, might reasonably be set at 18 percent to approximate the observed 15th percentile pedestrian clothing reflectance.[10] In fact, a review of previous visibility research indicates the use of a detection target with characteristics almost identical to those just outlined: It combines a 7-in (17.8 cm) sphere with a cylindrical base of the same diameter--both painted a uniform, 18 percent gray.

The object described above thus provides an effective ideal, or reference, detection target for the purposes of this discussion. On a related issue, the modeling of hazards in experimental versus analytical investigations deserves some attention. Since the detection of real-world hazards is to some extent always influenced by factors such as horizontal illumination and internal contrast, the use of anything other than a three-dimensional target in studies of operator response under actual driving conditions is very difficult to justify. For purely analytical approaches and for laboratory studies where a high level of control is essential, however, a flat vertical plane has been deemed adequate in prior research efforts. For example, the recent CIE (19/2) publication describing the influence of lighting parameters on visual task performance incorporates such a (two-dimensional) target.[7]

In addition, the usefulness of two-dimensional models for roadway hazards can be expressed in terms of task detail size. This measure results from an interaction between the variables hazard size and observer-target separation: A hazard of any given size located at a sufficiently large distance from a driver effectively reduces to a point source of reflected illumination. (The obverse, of course, is also true.) When the visual task detail size falls to this level, calculations of target visibility based on two-and-three dimensional models logically must converge.

With respect to the target described above, a task detail size of approximately 2.5 arc minutes is subtended at the eye of an observer positioned at the 650 ft (198.1 m) criterion detection-threshold distance. [Given a 250 ft (76.2 m) separation distance, a task detail size of 6.8 minutes is obtained.] Significantly, the quantitative expression for the effect of task detail size on visual performance presented in CIE 19/2 is based on threshold data for targets of 1 minute to 60 minutes of arc; while both the 2.5-minute and 6.8-minute figures may marginally exceed the dimensions of a "point-source," they certainly are near the extreme lower limit of any behaviorally-meaningful target size range.[7] Toward the objective of providing a relative measure of the effectiveness of fixed and vehicle-based lighting systems, the more mathematically straight-forward treatment of the detection target as a vertical plane will therefore be incorporated in the analysis which follows.

Finally, it should be noted that the target, although painted a uniform 18 percent gray, results in a nonuniform pattern of luminance across its curved surface as measured along a driver's line of sight. Consequently, overall directional reflectance for a head-on observer will be a weighted average somewhat less than 18 percent, as a relatively greater proportion of incident illumination will be reflected to the driver's eyes from the central apex of the curve (i.e., that segment of the cylinder's curved surface nearest the driver) than from the left and right edges of the target. If a vertical plane of uniform reflectance is to be used to accurately represent this target, the "true" reflectance of such an object under actual roadway conditions must be derived.

This is accomplished in the following manner. The distribution of luminance across the curved face of the target varies according to a cosine function---specifically, the cosine of the angle (Ø) between 1) the driver's line of sight and 2) a line radiating from the target's center of curvature to any point on its surface---affecting the proportion of incident illumination that is reflected in the direction of the driver. For any point on the target's surface directly in the driver's line of sight, this angle is 0 degrees, the cosine is 1.0, and a full 18 percent of the incident illumination is reflected to the driver. All points off the viewing axis are associated with angles greater than 0 degrees and cosine values less than 1.0, however, causing something less than 18 percent of incident illumination to be reflected to the driver. The net result of this effect may be calculated using a root-mean-square (RMS)* formula, which indicates that the proportion of illumination incident upon the surface of the target that will be reflected to the eyes of an observer is equal to the maximum (18 percent) reflectance value multiplied by .707. Calculations of target luminance for the 2.5-minute vertical plane used in the present analysis will therefore assume a directional reflectance value of (18 x .707) 12.7 percent.

(As noted earlier, effective target contrast will be calculated based upon a 250 ft (76.2 m), as well as a 650 ft (198.1 m) separation distance. A further change will include a uniform reflectance level of 30 percent for the to-be-detected target at the shorter distance, which translates to a directional reflectance value of [30 x .707] 21.2 percent according to the logic described above.)

Luminance Estimates With Fixed Roadway Lighting. Estimates of target and background (pavement) luminance for fixed lighting systems under simulated operating conditions are now determined. This task can be exceedingly complicated, due to the list of variables affecting lighting level at any given point in a luminaire cycle, and the practically endless number of possible values associated with each of those variables. Lamp and luminaire type, a light depreciation factor, roadway dimensions and pavement attributes, luminaire arrangement, spacing, mounting height, and overhang all must be designated. Clearly, luminance values

---

*RMS = $2\sqrt{\frac{1}{2n}\int_{o}^{n}\cos^{2}\text{Ø}\,d\text{Ø}}$, where n=90° and Ø is the angle defined in the text above.

derived for even a single combination of these variables involve a set of calculations whose extent and complexity define a quite formidable manual analysis.

Accordingly, an outdoor lighting analysis program--Site-Lite*--was employed to calculate relevant luminance and illuminance values for a photometric test-point grid superimposed on a road surface, based initially on the following set of parameters:

Lamp type: (ITT) 200-watt high-pressure sodium (HPS), 22,000 lumens

Luminaire specifications: Medium cutoff, type III distribution

Spacing: 68 ft (20.7 m) staggered arrangement

Mounting Height: 30 ft (9.1 m)

Overhang: 2 ft (0.6 m)

Light loss (depreciation) factor: 0.81

Pavement type: Worn Portland cement, C.I.E. R-1 surface characteristics

Road width: 104 ft (31.7 m)

These parameters, for the most part, reflect conditions found along Interstate Route 95 in the city of Philadelphia, and have been chosen as being reasonably representative of a "typical" lighting system for a divided, limited-access highway in the U.S. (A subsequent run of the Site-Lite program was conducted using an R-3, rather than R-1, road surface, but holding all other variables constant.)

The Site-Lite program takes into consideration a total of ten luminaries, arranged longitudinally along a freeway section as shown in figure 1 on the following page, for the present analysis.

The output from the Site-Lite program of particular interest in gauging the effectiveness of roadway lighting is that which describes 1) the level of illuminance on a (target) plane facing south, located downstream and in a head-on orientation

---

* Site-Lite is a copyrighted program developed by Lighting Sciences, Inc., Scottsdale, AZ.

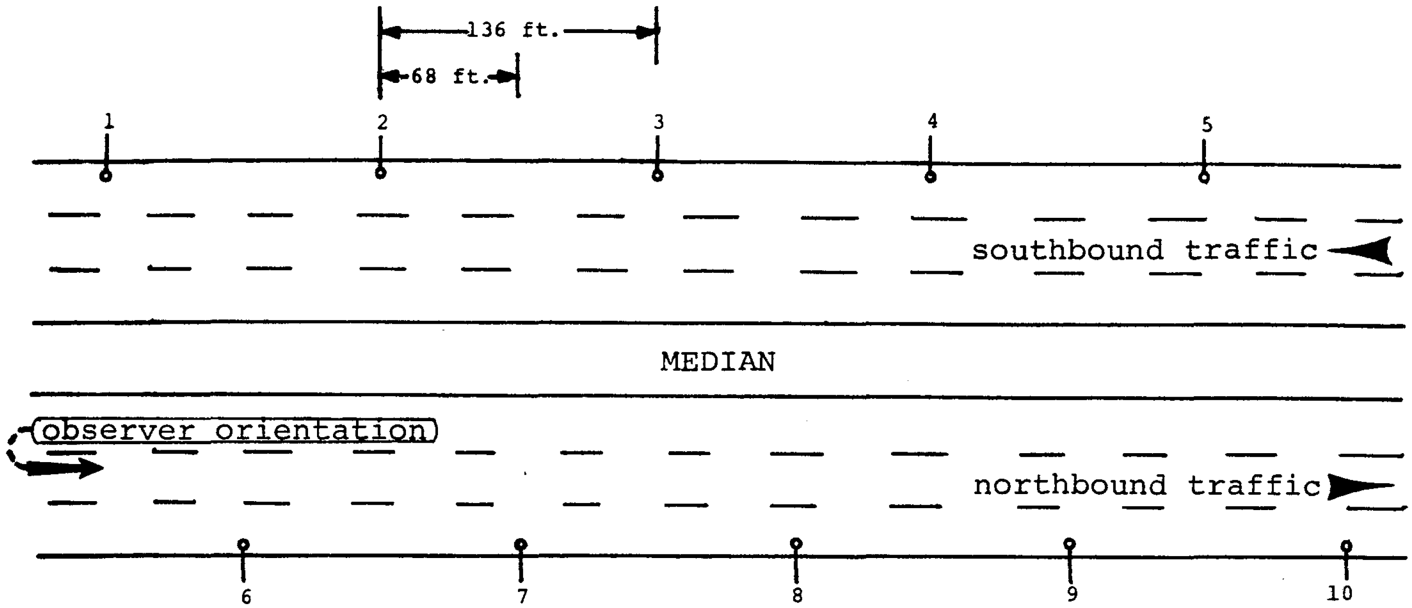


Figure 1. Luminaire arrangement analyzed by Site-Lite program (not drawn to scale). 1 m=3.28 ft

with respect to an observer traveling in the center lane on the northbound side of a six-lane divided freeway, and 2) the pattern of pavement luminance downstream in the observer's lane of travel. This information is presented in figure 2 (a) and (b), respectively, which shows expanded views of the observer's lane only for a roadway section bounded longitudinally by luminaires number 2 and 3 in figure 1. Based on the vertical illuminance figures, target luminance may be calculated for the 12.7 percent directional-reflectant vertical plane defined previously in this section, over the course of an entire luminaire cycle. When the appropriate calculations are performed (i.e., vertical illuminance X .127), the longitudinal pattern of target luminance described by figure 2 (c) is obtained, for the observer's lane of travel.

(Similar calculations are performed for the 21.2 percent directional reflectant plane, but are not included in the information presented in figures 2 and 3; also, the output from the SiteLite program run which included an R-3, rather than R-1, road surface is not pictured.)

Figure 3 has been prepared to give a graphical representation of the variability in target and background luninance through a single luminaire cycle. From this figure it is apparent that the widest separation between the two curves is found a little over 60 ft (18.3 m) downstream from reference luminaire #2 (see figure 1). This location is associated with the maximum pavement luminance value of 1.036 fL (3.55 cd/m^2) and the near-minimum target luminance value of .017 fL (0.058 cd/m^2) , both of which occur slightly in advance of the nearest downstream luminaire on the observer's side of the roadway (i.e., luminaire #7 in figure 1).

number of feet downstream of reference luminaire (#2 in Figure 1)	(a) vertical illuminance (fc)	(b) pavement luminance (fL)	(c) target luminance (fL)
136.0	1.40	0.765	.178
129.2	1.42	0.765	.180
122.4	1.36	0.709	.173
115.6	1.27	0.604	.161
108.8	1.34	0.566	.170
102.0	1.39	0.560	.177
95.2	1.49	0.636	.189
88.4	1.37	0.715	.174
81.6	1.01	0.736	.128
74.8	0.77	1.030	.098
68.0	0.11	1.016	.014
61.2	0.13	1.036	.017
54.4	0.16	0.759	.020
47.6	0.19	0.744	.024
40.8	0.26	0.642	.033
34.0	0.41	0.563	.052
27.2	0.60	0.569	.076
20.4	0.85	0.587	.108
13.6	1.18	0.683	.150
6.8	1.34	0.739	.170
0.0	1.40	0.765	.178

N

Figure 2. (a) Vertical illuminance on a plane facing south in the observer's lane of travel, at the road surface.
(b) Pavement luminance in the observer's lane of travel.
(c) Target luminance in observer's lane of travel.

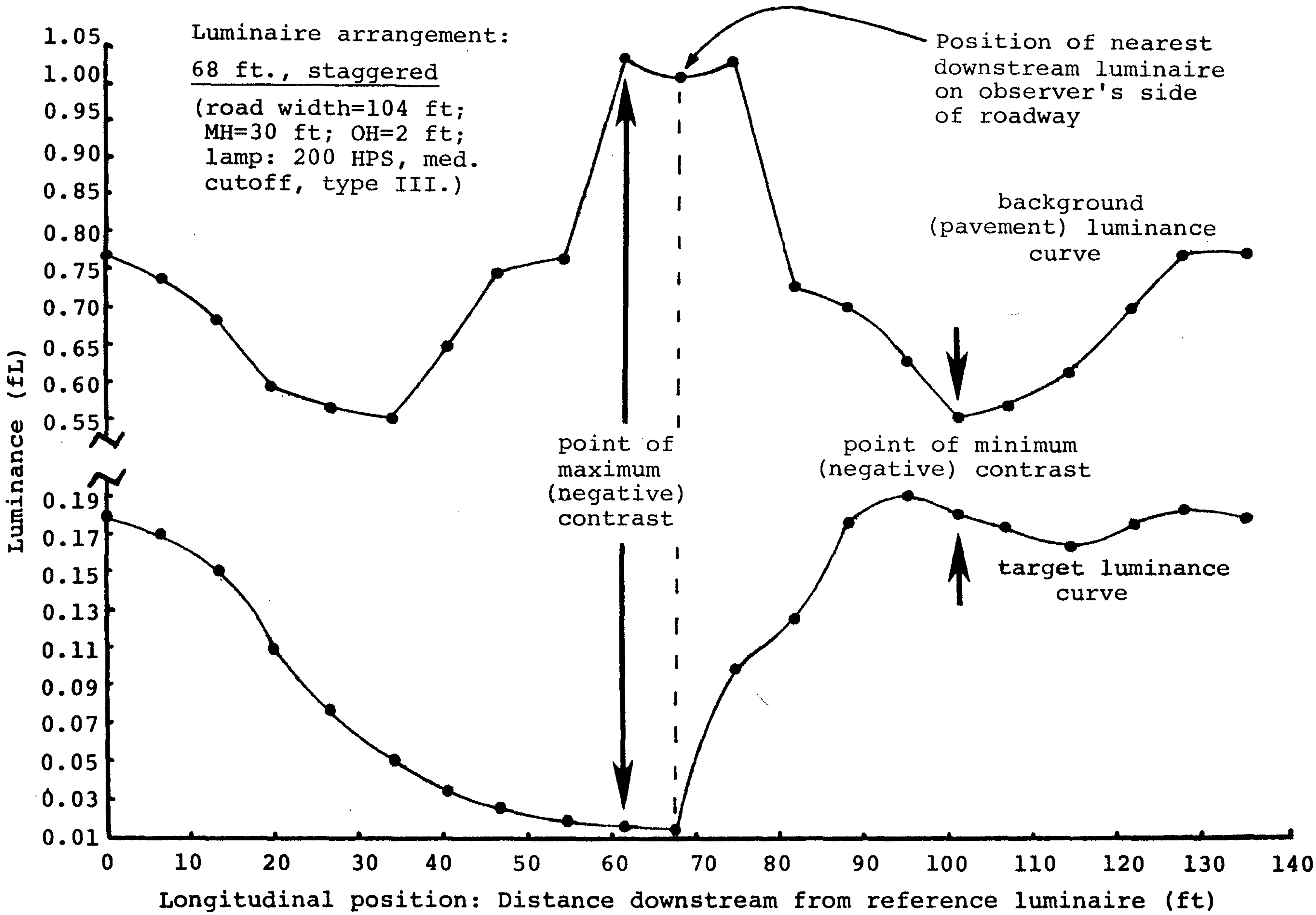


Figure 3. Target versus background luminance through one luminaire cycle.

This combination of values results in the highest level of (negative) contrast, given the type of target and set of lighting parameters included in this analysis. Similarly, the narrowest separation between the two curves is associated with the minimum pavement luminance value of .560 fL (1.919 cd/m^2) and the near -maximum target luminance value of .177 fL (0.606 cd/m^2); this combination of values results in the lowest level of (negative) contrast, and occurs--as indicated in figure 3--roughly half a cycle past the nearest downstream luminaire on the observer's side of the roadway. Further discussion of target contrast which may be obtained with fixed roadway lighting will follow the derivation of corresponding luminance estimates for vehicle-based lighting sources.

The locations of maximum and minimum contrast within the luminaire cycle are preserved for the alternative conditions involving 21.2 percent target reflectance [at 250 ft (76.2 m) separation from observer] and R-3 road surface [holding all other variables in present analysis constant as described in text example]. Target and background luminance values for these alternative conditions are calculated in the same manner as that described for the text example, and are summarized several pages later in this section.

Luminance Estimates With Vehicle-Based Lighting. Initially, the objective identified in this section heading was addressed by determining the candlepower output of (low-beam) headlamp systems currently in use in the U.S., based on extensive data obtained by researchers in the automobile industry.[11] As shown in the isocandela diagram presented in figure 4, a #4000, round 5 3/4 inch (14.6 cm) type 2 lamp provides an intensity in the range of 2,000 to 4,000 cd at an aim point of between 0 degrees and 1/2 degrees down in a head-on orientation in the roadway [i.e., the aim point associated with both a 650 ft (198.1 m) and a 250 ft (76.2 m) detection distance]. Unfortunately, none of the photometric design test points incorporated in the SAE (J579c) Standard for sealed beam headlamp units are located precisely in the position of interest in this analysis, so interpolations from published isocandela diagrams must suffice. By comparison to the above example, a newer halogen lamp (#H4656, type 2A1) provides a low-beam output that falls in a similar intensity range--2,000 to 5,000 cd--at the identical aim point.[11] Since the aim point of interest lies close to the midpoint between the boundary lines (for both types of lamps) separating the indicated candela ranges, an estimate of 3,000 cd per headlamp is designated as an appropriate candlepower output to use in the following calculations involving vehicle-based lighting systems.

Based on this figure (3,000 cd), an approximation of the maximum pavement luminance provided by the low-beam system on a single vehicle may be calculated, according to the equation presented below:

$$L_b = \frac{I_1 + I_2}{D^2} \times R_p \qquad [1]$$

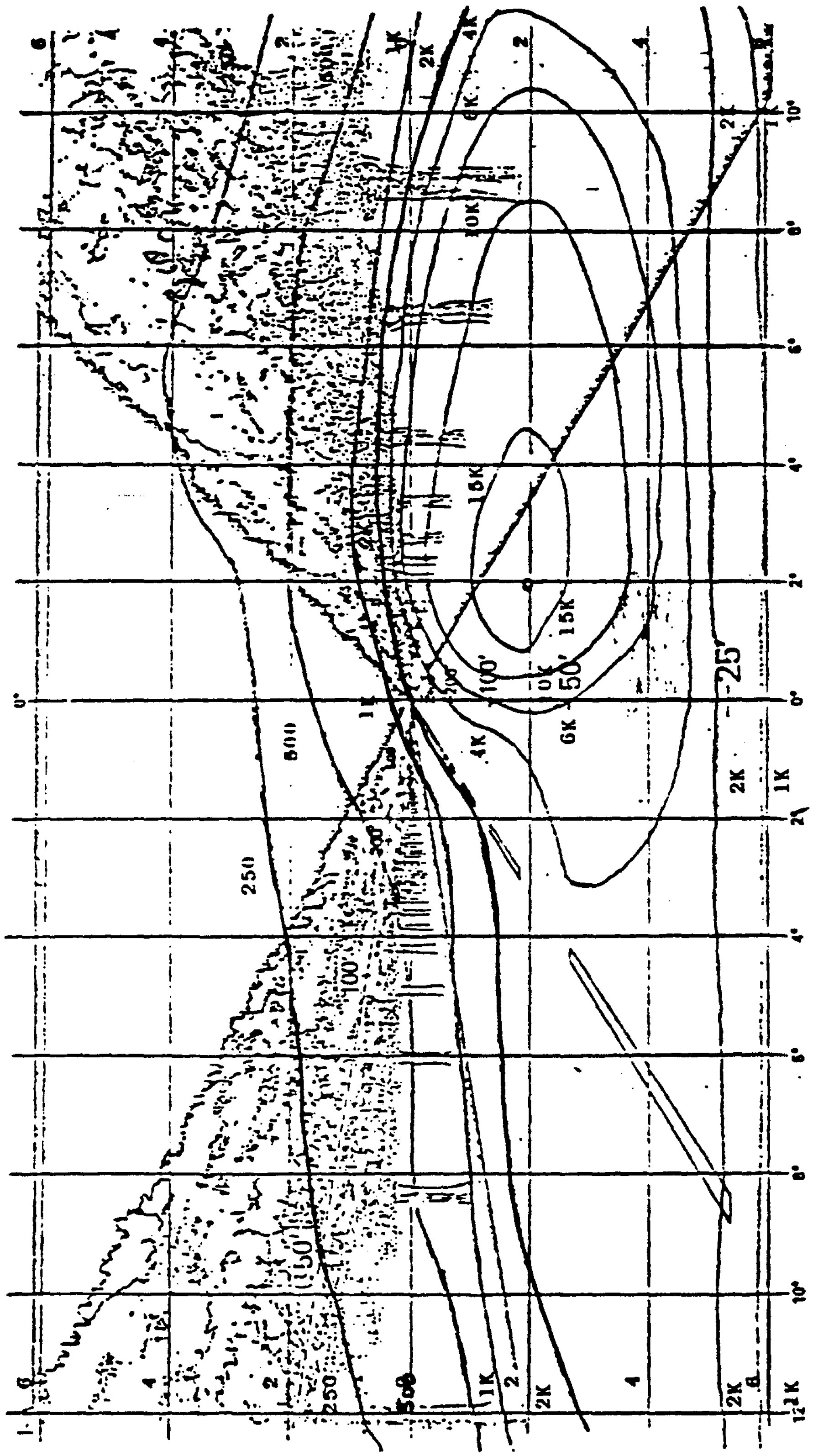


Figure 4. Typical U.S. low-beam isocandela diagram. (# 4,000, 5 3/4" type 2 low-beam system).

where L_b = background (pavement) luminance, I_1 and I_2 represent the candlepower output (in the direction of the pavement point of interest) of a low-beam headlamp system, D is the separation distance from the vehicle to the roadway point, and R_p is the (retro)reflectance coefficient of the (dry) road surface.

An empirically derived equation for (dry) pavement retroflectance (not differentiated between R-1 and R-3 pavements) found in the technical literature is shown below.(11)

$$R_p = 0.0331 + (7.578 \times 10^{-5} \times D), \qquad [2]$$

where D is separation distance

When the distance-from-vehicle variable is fixed at the 650 ft (198.1 m) criterion detection-threshold distance, a figure of roughly 8 percent results for R_p. With a 250 ft (76.2 m) separation distance, R_p equals approximately 5 percent.

Substituting the appropriate values into eq.[1] thus results in a value for background (pavement) luminance--L_b--of 1.14×10^{-3} fL (3.91×10^{-3} cd/m^2) at a separation distance of 650 ft(198.1 m), and 4.80×10^{-3} fL (1.65×10^{-2} cd/m^2) at a 250 ft (76.2 m) separation distance.

With respect to target luminance, a similar calculation is appropriate, with the hemisphere-plus-cylinder object described earlier treated (i.e., modeled) as a vertical plane of uniform reflectance. Target luminance, L_t, is thus approximated as,

$$L_t = \frac{I_1 + I_2}{D^2} \times R_t \qquad [3]$$

where I_1, I_2, and D are defined as 3000 cd, 3000 cd, and 650 ft, respectively, and R_t represents target, rather than pavement, reflectance. With a designated (directional) target reflectance of 12.7 percent, L_t may be shown to equal 1.8×10^{-3} fL (6.2×10^{-3} cd/m^2). When R_t is designated as 21.2 percent, and D is 250 ft (76.2 m), L_t may be shown to equal 2.05×10^{-2} fL (7.02×10^{-2} cd/m^2).

[NOTE: SAE Standards prescribe a headlight mounting height of not less that 24 inches (61 cm) nor more than 54 inches (137.2 cm) above the road surface, and a headlight lateral spacing of the maximum practicable separation on vehicles having a width of less than 80 inches (203.2 cm). For a typical passenger vehicle, an informal survey of current models indicated that most headlamps are positioned near the 24-inch (61 cm) minimum mounting height and roughly 2 to 3 ft (.6 to .9 m) on each side of a line running longitudinally down the center of the vehicle. Therefore, an exceedingly small correction factor (on the order of .000003 percent) might justifiably be applied to the distances involved in the above calculations. Considering that these calculations are only intended to be approximations of target and pavement luminance, however, this precaution seemed wholely unwarranted.]

<u>Target Contrast Determinations</u>. Numerical approximations of the degree of (effective) contrast provided solely by fixed versus vehicle-based sources of roadway lighting, with respect to the present conditions of interest, are performed in this section. First, to review the work in the preceding pages, table 1 summarizes the luminance estimates derived for both fixed illumination and vehicle-based lighting, at the 650 ft (198.1 m) separation/18 percent uniform reflectance target/R-1 pavement, 650 ft (198.1 m) separation/18 percent uniform reflectance target/R-3 pavement, and 250 ft (76.2 m) separation/30 percent uniform reflectance target/R-1 pavement conditions. It is these figures that provide the starting point for subsequent determinations of (effective) target contrast.

Table 1. Estimated values of target and background luminance (fL).

	Fixed Roadway Lighting Source [RLS] (Maximum Contrast Conditions)		Fixed Roadway Lighting Source [RLS] (Minimum Contrast Conditions)		Vehicle (headlamp) Lighting Source [VLS] (low beams only)	
Visibility Parameters	L_t	L_b	L_t	L_b	L_t	L_b
650 ft separation, 18%-reflective target, R-1 pavement	.017	1.036	.177	.560	.00180	.00114
650 ft separation, 18%-reflective target, R-3 pavement	.017	.725	.177	.392	.00180	.00114
250 ft separation, 30%-reflective target, R-1 pavement	.028	1.036	.295	.560	.0205	.0048

1 m = 3.28 ft
1 cd/m^2 = 0.2919 fL

As defined in the technical literature), the formula most commonly used to calculate contrast, C, is shown below.(1, 7) This quantity, C, is labeled "pure" contrast in the present analysis.

$$C = \frac{|\text{target luminance } (L_t) - \text{background luminance } (L_b)|}{\text{background luminance } (L_b)} \qquad [4]$$

Inserting the values appearing in table 45 into the contrast formula defined in eq. [4] yields the results presented in table 2.

Table 2. (Pure) contrast values for conditions of interest in present analysis.

Visibility Parameters	Lighting System	Contrast Condition	*Contrast Value (C)
650 ft separation,	Fixed/Roadway (RLS)	Negative, maximum	0.98
18%-reflective target,	Fixed/Roadway (RLS)	Negative, minimum	0.68
R-1 pavement	Vehicle-Based (VLS)	Positive	0.58
650 ft separation,	Fixed/Roadway (RLS)	Negative, maximum	0.98
18%-reflective target,	Fixed/Roadway (RLS)	Negative, minimum	0.55
R-3 pavement	Vehicle-Based (VLS)	Positive	0.58
250 ft separation,	Fixed/Roadway (RLS)	Negative, maximum	0.97
30%-reflective target,	Fixed/Roadway (RLS)	Negative, minimum	0.47
R-1 pavement	Vehicle-Based (VLS)	Positve	3.27

1 m = 3.28 ft

*[Due to an artifact of the contrast formula, the maximum negative contrast value that can be attained is 1.0 (when target luminance falls to zero), while the upper limit on positive contrast theoretically is infinity. The implicit bias in this computation in a sense serves to understate the relative visibility of targets viewed under negative contrast conditions.]

Next, a critical adjustment to the pure contrast values shown in table 2 must be performed, to take the driver's relative contrast sensitivity (RCS) factor into account. It has been established that a human's sensitivity to visual contrast is affected by the existing background luminance; specifically, a driver's eyes will reach a higher adaptation level in response to increased background luminance, producing a relatively higher sensitivity to contrast on the part of the visual system.(7) A scale developed by the CIE assigns a contrast sensitivity of 1.0 for an observer viewing a background luminance equal to 100 candelas per square meter.(7) Given the wide range of background luminance values included in this analysis, it is important to incorporate RCS data when comparing the visual inputs provided to drivers by fixed versus vehicle-based lighting systems.

Accordingly, expressions developed by the CIE were consulted, which allow the calculation of RCS values as described in equations [5] and [6] below.(7)

$$RCS = n\left[\left(\frac{S}{tL}\right)^{.4} + 1\right]^{-2.5} \qquad [5]$$

and

$$n = \left[\left(\frac{S}{100t}\right)^{.4} + 1\right]^{2.5} \qquad [6]$$

In these expressions, L refers to the level of background luminance (in cd/m^2), and t and S are defined as follows: t is related to an observer's age (A), such that for age 20 to 30 years, log t = 0; for age 30 to 44 years, log t = -0.01053(A-30); for age 44 to 64 years, log t = -0.1474 to 0.0134(A-44); for age 64 to 80 years, log t = -0.4154 to 0.0175(A-64). The remaining parameter, S, is related to the detail size of the visual task under consideration, its location relative to the observer's line of sight, and the age of the observer. Specifically, log S = 0.5900 - 0.6235logd - 0.1980X - s, where d = size of the visual task in minutes, X = number of degrees a visual task is off the line-of-sight axis, and s is a function of an observer's age. When age (A) is between 20 and 44, s = 0; when age is 44 to 64, s = 0.00406(A-44); when age is 64 to 80, s = 0.0812 + 0.00667(A-64).

Equations [5] and [6] above may be applied to generate RCS factors for any of the functionally distinct age groups identified by the CIE, when assuming the 2.5-minute or 6.8-minute targets presently under consideration are located in a head-on orientation with respect to an observer/ driver. When these calculations are performed, the multiplication factors listed in table 3 are obtained, showing the difference between the RCS factor for a 20 to 30 year old observer versus a 64-year-old observer under each of the various background luminance (L_b) conditions defined previously (see table 1).

Table 3. RCS factors, by age, for L_b conditions in present analysis.

Visibility Parameters	Contrast Condition	Background Luminance (fL)	RCS Multiplier Observer age: 20-30	Observer age: 64
650 ft separation, 18%-reflective target, R-1 pavement	RLS/negative (maximum)	1.036	.363	.291
	RLS/negative (minimum)	.560	.270	.206
	VLS/positive	.00114	.00240	.00136
650 ft separation, 18%-reflective target, R-3 pavement	RLS/negative (maximum)	.725	.307	.239
	RLS/negative (minimum)	.392	.223	.165
	VLS/positive	.00114	.00240	.00136
250 ft separation, 18%-reflective target, R-1 pavement	RLS/negative (maximum)	1.036	.427	.348
	RLS/negative (minimum)	.560	.330	.257
	VLS/positive	.0048	.01358	.00792

1 m = 3.28 ft
1cd/m^2 = 0.2919 fL

With reference to table 3, there is a clear difference in the calculated RCS value for 20 to 30-year-old observers versus 64-year-old observers, within a given level of background luminance. This raises the issue of what the appropriate "design driver" should be for the present analysis. A general and well-documented pattern of decreasing contrast sensitivity with age is characterized by a gradual (upward) threshold shift after 40, followed by a sharply accelerated loss in sensitivity beginning at age 60 to 65.(12) Older persons, however, do a disproportionately low amount of driving at night, while younger, more visually proficient drivers do a disproportionately high amount.(13) Older drivers are thus more at risk, as individuals, yet as a group are involved in much lower absolute numbers of accidents at night, relative to younger drivers. Perhaps most important is the fact that the influence of inexperience or substance abuse, for example, weighs more heavily in accident involvement with young drivers, whereas the impact of visual quality alone -- exclusive of other factors -- is felt most strongly among the elderly driving population. Accordingly, the RCS values in table 3 associated with the older, age 64 observer will be incorporated in subsequent calculations of effective contrast.

Next, prior research has indicated that a loss of contrast occurs as a consequence of glare, when a driver's visual system is adapted not only to background (pavement) luminance but also to luminance provided by other light sources.(7) This phenomenon, labeled veiling luminance (L_v) in the technical literature has prompted the inclusion of an additional correction factor in expressions of contrast under real-world conditions: the disability glare factor (DGF).(1)

Fixed lighting installations, by virtue of the same (vertical) component of illumination that provides target luminance, also produce some degree of veiling luminance. To include the potential effect of this phenomenon in the present analysis, a reasonable worst-case situation can be defined in terms of I.E.S. Roadway Lighting design requirements* limiting the maximum ratio of veiling luminance to average pavement luminance to 0.3 to 1. Based on the pavement luminance values (associated with the example including R-1 pavements) shown earlier in figure 2, for the observer's lane of travel, average L_b is readily calculated as .723 fL (2.48 cd/m^2); for the purposes of the present analyses, then, the accompanying magnitude of veiling luminance from fixed lighting installations will be assumed to be no more than .22 fL (.75 cd/m^2).

[Assuming an R-3 road surface, average pavement luminance for the lighting system included in these analyses is calculated to be slightly over .50 fL (1.71 cd/m^2); accordingly, veiling luminance for this condition is assumed to be no more than .15 fL (.51 cd/m^2).]

The calculation of DGF for a specific contrast condition is accomplished according to

$$DGF = \frac{L_b \times RCS_{\left(\frac{L_b+L_v}{1.074}\right)}}{\left(\frac{L_b + L_v}{1.074}\right) \times RCS_{L_b}} \qquad [8]$$

where the definitions for all terms are consistent with those already presented in this appendix. When the appropriate luminance values and (age 64 observer) RCS factors are inserted into this

*From ANSI/IES RP-8 (1983).

equation, the DGF for the roadway [RLS] contrast conditions can be obtained as shown in table 4.

[NOTE: No DGF is associated with the VLS conditions given a single (observer's) vehicle in the absence of a RLS.]

Table 4. Disability glare factor (DGF) values associated with RLS conditions included in the present analysis.

Pavement Reflectance	Contrast Condition	DGF Value
R-1	RLS/Negative (maximum)	.944
	RLS/Negative (minimum)	.895
R-3	RLS/Negative (maximum)	.949
	RLS/Negative (minimum)	.908

In both cases, the DGF values are less than--but close to--1.0, indicating only a marginal reduction in effective contrast due to the effects of the glare produced by fixed lighting.

Expressions of effective target contrast may thus be generated by multiplying the previously obtained (pure) contrast figures (see table 2) by the appropriate RCS values from table 3 and, then, again multiplying this product by the appropriate DGF value from table 4, according to this equation:

$$\text{Effective contrast } (C_{eff}) = C \times RCS \times DGF \qquad [9]$$

When these calculations are performed the resulting expressions of effective contrast shown in table 5 are the result. It is these values that provide the initial basis for conclusions about the relative effectiveness of fixed versus vehicle-based lighting.

Table 5. Expressions of effective contrast for the lighting conditions included in the present analyses.

Visibility Parameters	Contrast Condition	C_{eff} Value
650 ft separation, 18%-reflective target, R-1 pavement	RLS/Negative (maximum) RLS/Negative (minimum) VLS/Positive	.27 .13 .00079
650 ft separation, 18%-reflective target, R-3 pavement	RLS/Negative (maximum) RLS/Negative (minimum) VLS/Positive	.22 .08 .00079
250 ft separation, 30%-reflective target, R-1 pavement	RLS/Negative (maximum) RLS/Negative (minimum) VLS/Positive	.32 .11 .026

1 m = 3.28 ft

[NOTE: While the headlights of an oncoming vehicle are obviously another potential source of glare during nighttime driving, the present analysis has been restricted to a consideration of the lighting conditions associated with a single (observer's) vehicle on the highway. The case involving multiple vehicles, where L_v (and L_b) attributable to opposing headlights is a necessary additional consideration when deriving estimates of (effective) target contrast, is analyzed separately for a single separation distance/target reflectivity/pavement reflectance condition following a statement of the conclusions which may be drawn for the single-vehicle cases.]

From the results of the analyses performed thus far, it may be concluded that overhead lighting reaches a level of effectiveness over 300 times greater--and is minimally at least 150 times more effective--than vehicle headlights alone, given an 18 percent-reflective target, 650 ft (198 m) separation distance, and an R-1 road surface. Given the same target and separation distance but an R-3 road surface, it may be concluded that overhead lighting reaches a level of effectiveness over 250 times greater--and is minimally at least 100 times more effective--than vehicle headlights alone. However, given a 30 percent-reflective target and a 250 ft (76.2 m) separation (with R-1 surface), it may be concluded that overhead lighting is at best only 12 times more effective--and may be as little as 4 times as effective--when compared to vehicle headlights alone.

Before concluding this section, the potential effects of an opposing vehicle's (low beam) headlights on pavement luminance and disability glare need to be addressed, for at least one set of visibility parameters. In one sense, this effect does not seem likely to be a significant factor in the specific context of interest--under late night, low-volume conditions where the expected frequency of oncoming vehicles is minimized, and the lateral separation between vehicles traveling in, say, the middle lanes on each side of a six-lane freeway is at least 30 feet (9.1 m) and possibly a good deal more. Nevertheless, these additional calculations make the present analysis more comprehensive, and serve to further demonstrate the relatively powerful influence of fixed roadway lighting on effective target contrast. The specific set of visibility parameters considered in these supplemental calculations will be the 650 ft (198.1 m) separation/18 percent-reflective target/R-1 pavement combination.

First, when an opposing vehicle is positioned downstream of a target (relative to the observer's position), the luminous intensity of its headlights will contribute to background (pavement) luminance in the vicinity of the target. In this situation, as before, background luminance is determined using eq. [1].

$$L_b = \frac{I_1 + I_2}{D^2} \times R_p \qquad [1]$$

Besides the need to assign new values for the intensity and distance variables, however, one other important difference exists in the way eq. [1] is applied in this situation relative to the earlier calculations of L_b for a VLS. It is the <u>forward</u> reflectivity, not the retroreflectivity, of the road surface that influences the level of background luminance provided to an observer by an opposing vehicle's headlights.

To obtain estimates of forward R_p, an expression was used which relates this variable to the angle of incidence (between the roadway and the headlight/glare source), the reflectance angle (of the departing ray toward the observer's eye), and the included (horizontal) angle between the glare source and the observer's line-of-sight. This expression, shown below, was derived from over 500 field measurements of (dry) pavement luminance made using a Fry lens with a Pritchard photometer. (11)

$$\text{Forward pavement reflectance} = .25\left[\frac{1}{i^{0.50} \times r^{0.76} \times h^{0.103}}\right], \qquad [10]$$

where i, r, and h, respectively, are the incident, reflectance, and included angles described above.

For convenience, a 1-degree angle of incidence is assumed. The reflectance angle may be easily computed by assuming the C.I.E. Standard driver eye height of 1.45 m (approximately 57 inches), dividing this figure by the observer-target separation distance, and then obtaining the arc-tangent of the quotient. For the 650 ft (198.1 m) separation distance adopted earlier in this analysis, this yields an angle of 0.42 degrees. The third factor--the included angle--depends upon the exact position of the opposing vehicle.

The longitudinal position of the opposing vehicle may initially be fixed at the distance downstream from a target such that the 1-degree angle of incidence between that vehicle's headlights and the road surface in the target's vicinity is obtained. This distance is the quotient of the headlights' height above the road surface and the tangent of the incident angle. Assuming a 2 ft (0.6 m) headlight height and using a value of .0175 for the tangent of 1 degree, the longitudinal separation between the opposing vehicle and the target is fixed at 115 ft (35.1 m). With respect to the lateral, or horizontal, separation between the observer-target line-of-sight and the opposing vehicle's headlights, it is assumed that both vehicles are traveling in the center of three lanes on opposite sides of a six-lane freeway, with a 12-ft (3.7 m) (flat) median strip. Given a lane width of 12 ft (3.7 m), this results in a lateral separation distance of approximately 45 ft (13.7 m) between the midpoint of the opposing vehicle's two headlights and an observer positioned one-quarter of a lane's width from the (median-side) lane boundary of his own center lane. The included angle can now be computed by dividing the 45 ft (13.7 m) horizontal separation by the 115 ft (35.1 m) longitudinal separation, and then obtaining the arc-tangent of the quotient. This calculation results in an (included) angle of 21.4 degrees.

The values derived above for the incident, reflectance, and included angles are substituted into eq.[10] to yield a forward pavement reflectance value of approximately 35 percent at an observer-target separation distance of 650 ft (198.1 m).

Before proceeding with the calculation of the background luminance (L_b) provided by the opposing vehicle's headlights, values for the intensity of the glare source and its total separation distance (in three dimensions) from the pavement in the vicinity of the target must be derived. Total separation distance, first, includes the 115 ft (35.1 m) longitudinal separation, the 45 ft (13.7 m) lateral separation, and the 2 ft (0.6 m) vertical separation (i.e., the headlights' height above the pavement) described above. Taking all three dimensions into account, total separation distance between the opposing (glare) vehicle's headlights and the target may be expressed as

$$D = \sqrt{115^2 + 45^2 + 2^2} = 123.5 \text{ ft } (37.6 \text{ m})$$

Regarding the intensity of the opposing vehicle's headlights, the separation distances involved describe an aim point (i.e., road surface where the target is located) of 21.4 degrees left ($\arctan \frac{45}{115}$) and 1.0 degrees down ($\arctan \frac{2}{115}$). Since the widest angle included among the SAE Standard photometric design test points--15 degrees L, 2 degrees D--is associated with a minimum low beam output of 700 cd, and other left-of-center aim points (6 degrees and 9 degrees) are associated with a 750 cd minimum output, the slightly lower figure of 500 cd does not seem an unreasonable estimate for the aim point now under consideration.

Values of 500 cd, 123.5 ft (37.6 m), and 35 percent are therefore inserted into eq.[1] to yield an estimated .023 fL (.079 cd/m^2) of background luminance (L_b) provided by an opposing vehicle's headlights in the vicinity of a target located 650 ft (198.1 m) downstream from an observer.

The remaining issue to consider is the veiling luminance (L_v) attributable to the opposing vehicle's headlights, which must be quantified before a new DGF value can be calculated. This is accomplished using an expression known as the Fry formula shown below.(11)

$$L_v = 10\pi \sum_{i=1}^{2} \frac{E_i \cos \theta_i}{(\theta + 1.5)\,\theta_i} \qquad [11]$$

In this equation E represents the illumination of each glare headlamp measured at the observer's eyes, and θ is the angle (in three dimensions) between the observer-target line-of-sight and the intensity vector (I) emanating from the glare headlamp(s) toward the observer. With reference to figure 5 below, the relationship between the glare source and the observer may be described in terms of longitudinal separation (measured on the x-axis), lateral separation in the roadway (y-axis), and vertical separation (z-axis).

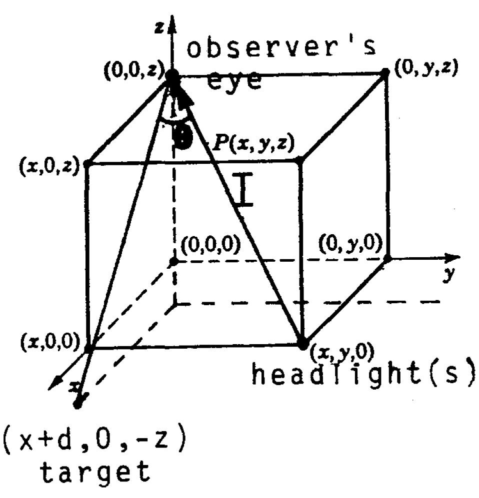


Figure 5. Coordinate system describing relative position of glare source, target, and observer.

While keeping in mind that the diagram in figure 5 is not drawn to scale, it may be useful to refer to it to help visualize the separation distances upon which the calculations that follow are based. When 1) the longitudinal separation distance x is first fixed at 765 ft (233.2 m) [i.e., the 650 ft (198.1 m) observer-target separation plus the 115 ft (35.1 m) target-glare source interval], 2) lateral separation distance y is fixed at a constant value of 45 ft (13.7 m) [for the midpoint of both headlights on the opposing vehicle], and 3) the vertical separation distance z--the difference between the 57-inch (144.8 cm) driver eye height and the 24-inch (61 cm) glare headlight height--remains a constant 33 in (83.8 cm), or 2.75 ft (.84 m), then the coordinates of the driver's eye may be expressed as (0, 0, 2.75) and those of the glare source as (765, 45, 0). All that remains is to express the target position in the same coordinate system. Since it is located in a head-on orientation with respect to the observer, its y value is 0; its x value is plus-or-minus some distance d [in this case, negative 115 ft (35.1 m)] relative to the location of the glare source, and its z value is its vertical distance below the height of the headlights [or, in the case of a 6-inch (15.2 cm) target, roughly 1.5 ft (0.46 m)]. The target coordinates are therefore (650, 0, -1.5).

The lengths of the sides of a triangle connecting the positions of the observer, target, and glare source can be determined, based on the coordinates presented above. Toward this objective, the sides may be designated as possessing magnitudes a, b, and c to describe the target-glare source distance, observer-glare source distance, and observer-target distance, respectively.

Specifically, then,

$$a = \sqrt{(765 - 650)^2 + (45 - 0)^2 + (0 - (-1.5))^2}$$

$$= 123.5 \text{ ft } (37.6 \text{ m})$$

$$b = \sqrt{(765 - 0)^2 + (45 - 0)^2 + (0 - 2.75)^2}$$

$$= 766.3 \text{ ft } (233.6 \text{ m})$$

$$c = \sqrt{(0 - 650)^2 + (0 - 0)^2 + (2.75 - (-1.5))^2}$$

$$= 650.0 \text{ ft } (198.2 \text{ m})$$

and the desired angle, θ, can be obtained according to the cosine law, which is applied to the present example in the form of this expression:

$$\cos \theta = \frac{b^2 + c^2 - a^2}{2bc} \qquad [12]$$

When the values of a, b, and c derived above are inserted into eq.[12], the angle θ obtained as a result is 3.42 degrees.

One additional quantity needed to apply the Fry formula [eq. 11] to calculate veiling luminance produced by the opposing vehicle's headlights is the illumination (E) of the glare source at the observer's eyes. This quantity is an expression of the candlepower output of the opposing headlamps, I_1 and I_2, attenuated by the square of the distance separating the observer and glare source, 766.3 ft (233.6 m). By examining the appropriate tangent relationships among the longitudinal, lateral, and vertical separation distances between the observer and the glare source [765 ft (233.2 m), 45 ft (13.7 m), and 2.75 ft(.84 m), respectively], the opposing vehicle headlight aim point-of-interest is defined as 0.21 degrees up (arctan $\frac{2.75}{765}$) and 3.37 degrees left (arctan $\frac{45}{965}$); if the isocandela diagram shown earlier in figure 4 is again consulted, a headlight intensity slightly in excess of 500 cd is indicated at this aim point. Fixing I at, say, 600 cd results in a value of E (for each headlamp) equal to 600 divided by $(766.3 \text{ ft})^2$ or 0.00107 footcandles (fc).

Inserting the values for E and cos θ derived previously into eq. [11] indicates that the veiling luminance produced by each headlight on the opposing vehicle, at a longitudinal separation distance of 765 ft (233.2 m) from an observer, is .0019 fL ($6.5 \times 10^{-2} cd/m^2$). Total L_v produced by both headlights on the opposing vehicle is therefore .0038 fL ($1.3 \times 10^{-2} cd/m^2$).

To complete this anaylsis, it is instructive to consider one additional case involving an opposing vehicle---i.e., when the opposing vehicle is located upstream of a detection target, such that its headlights produce an increased level of veiling luminance for an observer but make no contribution whatsoever to background (pavement) luminance in the vicinity of the target. To briefly illustrate the visibility conditions in this driving situation, an example consistent with the work already performed may be considered. Specifically, the opposing vehicle and the observer will both again be positioned laterally in the center of three lanes on their respective sides of a six-lane divided highway with a 12-foot (3.66 m) median, thus maintaining a lateral separation distance of 45 ft (13.7 m). Now, however, the opposing vehicle's longitudinal position will be fixed at 115 ft (35.1 m) downstream from the observer, rather than from the target.

Before veiling luminance (L_v) can be calculated, the angle θ between the observer-target line-of-sight and the intensity vector (I) emanating from the glare headlights toward the observer must be determined. With reference to figure 5, the x, y, and z coordinates describing the relative position of the glare source, target, and observer are now (115, 45, 0), (650, 0, -1.5), and (0, 0, 2.75), respectively. The sides of a triangle possessing magnitudes a, b, and c---which describe the target-glare source distance, observer-glare source distance, and observer-target distance, respectively---may thus be calculated as follows:

$$a = \sqrt{(115-650)^2 + (45-0)^2 + (0-(-1.5))^2}$$

$$= 536.9 \text{ ft } (163.6 \text{ m})$$

$$b = \sqrt{(115-0)^2 + (45-0)^2 + (0-2.75)^2}$$

$$= 123.5 \text{ ft } (37.6 \text{ m})$$

$$c = \sqrt{(0-650)^2 + (0-0)^2 + (2.75-(-1.5))^2}$$

$$= 650.0 \text{ ft } (198.2 \text{ m})$$

and the desired angle Ø, which is obtained according to equation [12] is determined to be 21.4 degrees.

Next, the illumination (E) of the opposing vehicle's headlights reaching the observer's eyes must be known. This quantity is an expression of the candlepower output of the opposing headlamps, I_1 and I_2, attenuated by the square of the distance separating the observer and glare source, 123.5 ft (37.6 m). By examining the appropriate tangent relationships among the longitudinal, lateral, and vertical separation distances between the observer and glare source [115 ft (35.1 m), 45 ft (13.7 m, and 2.75 ft (.84 m), respectively], the opposing vehicle headlight aim point-of-interest is is defined as 1.37 degrees up (arctan $\frac{2.75}{115}$ and 21.4 degrees left (arctan $\frac{45}{115}$). Since no SAE photometric test points are near this aim point, an estimate of the illumination provided by each headlight is derived from an extrapolation of the isocandela contours shown in figure 4. A generous estimate, which would be valid even if the opposing vehicle was positioned in the median --rather than the center--lane on his side of the freeway (i.e., the lane nearest to the observer laterally), is in the neighborhood of 250 cd. This intensity results in a value of E (for each headlamp) equal to 250 divided by $(123.5 \text{ ft})^2$, or .0164 footcandles (fc).

Inserting appropriate values for E and cos θ into eq. [11] indicates that the veiling luminance produced by each headlight on the opposing vehicle in this driving situation, at a longitudinal separation separation of 115 ft (35.1 m) from an observer, is .00098 fL ($3.37 \times 10^{-3} cd/m^2$). Total L_v produced by both headlights in this situation is therefore approximately .0020 fL.

Table 6 summarizes the estimates of background luminance (L_b) and veiling luminance (L_v) calculated for the conditions where an opposing vehicle is positioned 765 ft (233.2 m) and 115 ft (35.1 m) longitudinally downstream from a (64-year-old) observer, whose task is to detect a target located 650 ft (198.1 m) downstream in his own lane of travel.

Table 6. Background and veiling luminance produced by low beams of an opposing vehicle.

Longitudinal observer-glare source separation distance	L_b (fL)	L_v (fL)
765 ft	.023	.0038
115 ft	---	.0020

1 m = 3.28 ft
1 cd/m^2 = 0.2919 fL

Finally, the net effects (in terms of effective target contrast) can now be determined for driving situations which include the effects of an opposing vehicle in conjunction with an observer's vehicle alone, and with fixed roadway lighting installations. This effort involves first summing the various contributions to L_v and L_b under each condition of interest, to arrive at the appropriate RCS (relative contrast sensitivity) and DGF (disability glare factor) values to apply in calculations of effective contrast.

Summed values for background and veiling luminance are determined for each condition of interest by combining the L_b values presented earlier in table 1, and the 0.22 fL (.75 cd/m^2) L_v (RLS conditions only) figure appearing in table 5, with the appropriate figures from table 6, above. The results of these simple addition operations, shown in table 7, provide the basis for the specification of RCS and DGF values for each lighting condition of interest. [NOTE: L_b figures for the 115 ft (35.1 m) observer-glare source separation distance remain unchanged from previous (table 1) values, since an opposing vehicle in this position makes no contribution to pavement luminance in the vicinity of the target.]

Table 7. (Combined) background and veiling luminance estimates for each condition of interest when opposing vehicle is present.

Lighting system/ contrast condition	Longitudinal observer-glare source separation distance	Combined L_b (fL)	Combined L_v (fL)
RLS/negative (maximum)	765 ft	(1.036+.023) 1.059	(.22+.0038) .2238
RLS/negative (minimum)	765 ft	(.560+.023) .583	(.22+.0038) .2238
VLS/positive	765 ft	(.00114+.023) .02414	.0038
RLS/negative (maximum)	115 ft	1.036	(.22+.0020) .2220
RLS/negative (minimum)	115 ft	.560	(.22+.0020) .2220
VLS/positive	115 ft	.00114	.0020

1 m = 3.8 ft
1 cd/m^2 = 0.2919 fL

In Table 8, the RCS factors associated with the L_b levels for each condition of interest are presented, as calculated using equations [5] and [6]. [NOTE: RCS values for conditons with 115 ft observer-glare source separation distance remain unchanged from table 3, since L_b level is unaffected.]

Table 8. RCS Factors for L_b levels obtained when opposing vehicle is present.

Lighting system/ contrast condition	Longintudinal observer-glare source separation distance	RCS value
RLS/negative (maximum)	765 ft	.294
RLS/negative (minimum)	765 ft	.211
VLS/positive	765 ft	.0212
RLS/negative (maximum)	115 ft	.291
RLS/negative (minimum)	115 ft	.206
VLS/positive	115 ft	.00136

1 m = 3.28 ft

Next, eq. [8] is applied to generate DGF values for each condition of interest, as shown below in table 9.

Table 9. DGF values for each condition of interest when opposing vehicle is present.

Lighting system/ contrast condition	Longitudinal observer-glare source separation distance	DGF value
RLS/negative (maximum)	765 ft	.944
RLS/negative (minimum)	765 ft	.898
VLS/positive	765 ft	.990
RLS/negative (maximum)	115 ft	.942
RLS/negative (minimum)	115 ft	.896
VLS/positive	115 ft	.942

1 m = 3.28 ft

(Pure) target contrast values given the presence of an opposing vehicle are now calculated for each condition of interest, based on the estimates of target luminance presented earlier in table 1 and the (combined) background luminance estimates shown in table 7 above. To accomplish this, the appropriate figures are inserted into eq. [4], resulting in the contrast values indicated in table 10. [NOTE: Contrast values for conditions where observer-glare source separation distance is 115 ft (35.1 m) remain unchanged from those presented earlier in table 2.]

To complete the treatment of the conditions including the presence of an opposing vehicle, the RCS values from table 8 and the DGF values from table 9 must be applied to the (pure) contrast values shown in table 10 (above). Using eq.[7] and eq.[9], these calculations yield the revised effective contrast values presented in table 11.

The conclusions which may be drawn concerning the relative effectiveness of fixed roadway (RLS) versus vehicle-based (VLS) lighting systems, given the presence of an opposing vehicle and the 650 ft (198.1 m) separation/18 percent-reflective target/R-1 pavement visibility parameters are as follows. Because of the substantial background luminance provided by an opposing vehicle's headlights in the vicinity of the detection target--assuming the opposing vehicle is <u>downstream</u> of the target--the hazard visibility resulting from the use of the (observer's) VLS alone (i.e., when

Table 10. (Pure) contrast values for conditions of interest in present analysis, given presence of opposing vehicle.

Lighting system/ contrast condition	Longintudinal observer-glare source separation distance	(Pure) contrast value (C)
RLS/negative (maximum)	765 ft	.98
RLS/negative (minimum)	765 ft	.70
*VLS/negative	765 ft	.92
RLS/negative (maximum)	115 ft	.98
RLS/negative (minimum)	115 ft	.68
VLS/positive	115 ft	.58

1 m = 3.28 ft

*VLS contrast condition changes from positive to negative as the result of additional background luminance provided by opposing vehicle's headlights.

no fixed lighting is present) benefits from the application of an RCS multiplier well over an order of magnitude larger than in the previous level of analysis where no opposing vehicle was present. In addition, the added L_b causes the target to now be seen under negative contrast conditions, leading to a value for C almost twice as large as that obtained under positive contrast conditions (i.e., when no opposing vehicle is present downstream of the target). Together, these effects result in significantly greater effective contrast values for the VLS condition when an opposing vehicle is present, provided it is positioned downstream of a to-be-detected target/hazard. When an opposing vehicle is present but positioned upstream of a detection target (i.e., between the observer and the target, along the longitudinal axis), the facilitative effects noted above are lost. In fact, with the opposing vehicle providing no additonal L_b in the vicinity of the target but still producing an added component of glare, this driving situation results in a slightly lower effective contrast value than that obtained for a VLS in isolation (see table 5).

Table 11. Effective target contrast for each condition of interest, given presence of opposing vehicle.

Lighting system/ contrast condition	Longitudinal observer-glare source separation distance	Effective target contrast(C_{eff}*)
RLS/negative (maximum)	765 ft	.27
RLS/negative (minimum)	765 ft	.13
*VLS/negative	765 ft	.019
RLS/negative (maximum)	115 ft	.27
RLS/negative (minimum)	115 ft	.13
VLS/positive	115 ft	.00074

1 m = 3.28 ft

*VLS contrast condition changes from positive to negative as the result of additional background luminance provided by opposing vehicle's headlights.

The additional L_b provided by an opposing vehicle is, however, still relatively small compared to that provided by fixed lighting. Consequently, the effective contrast values for RLS conditions show no difference when an opposing vehicle is present versus when one is not. The observed shift in the relative effectiveness of the two systems from one driving situation to another (i.e., opposing-vehicle-absent versus opposing-vehicle-present) thus results entirely from a raised VLS effective contrast value.

When an opposing vehicle is positioned <u>downstream</u> of a to-be-detected target (hazard) on a freeway, the effective contrast values in table 11 indicate that a fixed roadway lighting system under maximum contrast conditions is slightly over an order of magnitude (x14 times) more effective than a VLS alone in providing the key visual input needed by nighttime drivers. Under minimum contrast conditions, a fixed lighting system retains an edge in effectiveness over a VLS alone equal to slightly less than an order of magnitude (x7). Assuming the presence of an opposing vehicle positioned <u>upstream</u> of a target (hazard), however, a fixed lighting system under minimum and maximum contrast conditions, respectively, is roughly 175 to 350 times more effective than a VLS alone.

It should also be noted that when an opposing vehicle is present downstream of a target/hazard, the ratio of effectiveness of a RLS to a VLS increases, rather than decreases, as the observer-target separation is reduced. This is due to the drop in L_b provided by the opposing vehicle as it draws nearer to the observer, and the (incident) angle at which its headlights' illumination strikes the pavement in the vicinity of the target gets sharper: A very flat angle results in the highest levels of forward pavement reflectivity, and thus the greatest contribution to L_b.

Finally, the situation where an opposing vehicle is positioned upstream of a detection target must be emphasized as representing the overwhelming bulk of the encounters between (opposing) vehicles. Regarding the situation where an opposing vehicle is downstream of a target, the period of time where the headlamps of the on-coming car silhouette a hazard in the road is very brief, and it is doubtful if a driver/observer can realistically rely on this input for target/hazard detection.

REFERENCES

1. Gallagher, V.P. and Meguire, P.G., "Contrast Requirements of Urban Driving," In: Driver Visual Needs in Night Driving, TRB Special Report No. 156, 1975.

2. Alexander, G. and Lunenfeld, H., "Positive Guidance in Traffic Control," USDOT, FHWA Office of Traffic Operations, April 1975.

3. McGee, H., et al., "Decision Sight Distance for Highway Design and Traffic Control Requirements," FHWA (Final) Report No. RD-78-78, 1978.

4. McGee, H., "Decision Sight Distance for Highway Design and Traffic Control Requirements," TRR 736, 1979.

5. AASHTO, "A Policy on Geometric Design of Highways and Streets," 1984.

6. Shelbourne, T. and Sheppe, R., "Skid Resistance Measurement of Virginia Highways," Highway Research Board Report No. 5-5, 1948.

7. CIE, "An Analytic Model for Describing the Influence of Lighting Parameters Upon Visual Performance," Report #19/2, 1981.

8. Bhise, V.D., "Quantifying the Driver's Night Visual Scene," Proceedings of 15th Annual Workshop on Human Factors in Transportation, Transportation Research Board, 1982.

9. Blackwell, O.M. and Blackwell, H.R., "Individual Responses to Lighting Parameters for a Population of 235 Obsevers of Varying Ages," Journal of the Illuminating Engineering Society, July 1980.

10. Janoff, M.S. et al., "Effectiveness of Highway Arterial Lighting," FHWA-RD-77-37, July 1977.

11. Bhise, V., Farber, E., et al., "Modeling Vision with Headlights in a Systems Context," Paper presented to Society of Automotive Engineers, February 28, March 4, 1977, Detroit, MI.

12. Pulling, N.Y., et al., "Headlight Glare Resistance and Driver Age," Human Factors, 1980, 22(1), 103-113.

13. Compton, S., "Night-Driving Patterns and Characteritics of Older Drivers," 1980, (unpublished manuscript).

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. **Highway Design and Operation for Safety**
Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. **Traffic Control and Management**
Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. **Highway Operations**
This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. **Pavement Design, Construction, and Management**
Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. **Structural Design and Hydraulics**
Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. **RD&T Management and Coordination**
Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.