This paper addresses the problem of the specification of lighting for the automobile driving operation. The empirical relationship between a measure of driver visual performance and several methods of quantifying visibility is explored in an effort to develop roadway lighting specifications based on visibility needs. Physical contrast, equivalent contrast, relative contrast sensitivity, and glare exposure are discussed. Field measurements of the visual performance of 941 unalerted motorists are analyzed, and a precise method of quantifying visibility is identified. The form of the suggested visibility term uses physical contrast, contrast sensitivity, and a disability glare factor. A method of prescribing visibility in terms of safe stopping requirements is discussed. Follow-up research that will enhance the reliability of the measures, extend the general applicability of the concept, and further develop the prescription approach is outlined.

CONTRAST REQUIREMENTS OF URBAN DRIVING

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The purpose of this study was to develop a technique for quantifying and specifying the visibility needs of urban drivers in a manner consistent with state-of-the-art lighting engineering capabilities and practices.

Lighting specifications are typically given as units of average flux with limits of uniformity or dispersion. Warrants are typically related to traffic, geometric, and road use conditions. The specification of lighting has undergone much debate especially as attempts are made to provide international compatibility of standards. There has been much disagreement on the efficacy of specific warranting criteria and on the question of flux units. Many organizations have expressed lighting requirements in terms of pavement luminance. Since the eye requires reflected light to detect objects in space, this approach is clearly related to the needs of drivers. These units present a complex measurement dilemma, however, because pavement luminance cannot be predicted reliably based on the distribution of flux output of luminaires. This is mainly because light reflected off paving surfaces is not uniformly diffuse (1).

The eye responds to small differences in luminous intensity and exposure duration. The limitations of this information processing system must be considered in the context of the human operation under study. Therefore, the problem is addressed in terms of drivers' information and visibility needs. This study assesses the predictive strengths of various visibility concepts and formulations. The experimental conditions have been described in detail by Gallagher and Meguire (2).

EXPERIMENTAL CONDITIONS

Driver Performance Measure

The critical measure of driver visual performance was the time separation between the vehicle and a target when an evasive response was initiated. We measured the point of response as distinguished from the point of perception because the evasive response of a driver to a roadway obstacle of high visibility is largely unconstrained and the driver exercises considerable judgment concerning when he will brake or change lanes. However, when target visibility is lower, the time between perception and response is reduced largely because of the driver's interest in maintaining some personally acceptable comfort level (i.e., with respect to swerving or rapid deceleration). When target visibility is extremely low, drivers respond almost at the point of perception because their time (i.e., distance-velocity) separation is extremely short.

Test Site

The test site was 7th Street between Packer and Pattison Avenues in south Philadelphia. The site is six lanes wide and approximately 1,800 ft (550 m) long.

The lighting system used (Fig. 1) enabled the horizontal and vertical illumination levels and illumination uniformity to be varied. A detailed description of this system can be found elsewhere (3).

Target Placement

The target used was the bottom 18 in. (0.5 m) of a standard traffic cone (the top was cut off) painted to be 6 percent (gray) reflectant.

The targets were spaced at 50-ft (15-m) intervals in the center of the middle southbound lane (Fig. 1). This arrangement provided a full range of representative target placements with respect to the surrounding luminaires. Taken in conjunction with appropriate target visibility measurements (discussed below), these target positions enable determination of the visibility characteristics of the lane under various street lighting configurations. It then becomes possible to predict drivers' behavior in avoiding roadway obstacles of different visibilities based on the placement and reflectance characteristics of the target and roadway visibility.

VISIBILITY MEASURES

The comprehensive study (2) from which this report is derived reported on 10 visibility indexes. Three have been chosen for discussion because of their predictive power and their conceptual importance:

1. Classic contrast (7)

$$C_1 = \frac{\Delta L}{Lb}$$

2. Visibility index (2)

$$VI_1 = \left[\frac{C_1(RCS_{Lb})}{5.74}\right] (DGF)$$

3. Effective visibility level (5, 6)

$$VL_1 eff = \left[\frac{Ceq(RCS_{Lb})}{5.74}\right] (DGF)$$

Contrast

Visual perception, at least at the threshold level for simple stimuli, is the direct result of perceived differences in background (Lb) and target (Lt) luminances. This difference would be perceived contrast if subjective scales for brightness sensitivity were available. Since they are not, this sensation is approximated by a pure ratio of physically measured stimuli levels (7). This ratio is termed contrast C_1 and is defined as

$$C_1 = \frac{|Lb - Lt|}{Lb} = \frac{\Delta L}{Lb} \tag{1}$$

This form of the ratio can be used for objects either darker or brighter than the background inasmuch as ΔL represents the numerical difference of the two luminances.

As indicated, this ratio is an approximation of the visibility value of a specific luminance background condition. Because contrast sensitivity is related to background luminance, contrast in its pure form is useful only as a relative comparison of target visibilities under a single background luminance level. For a more universal application of this relationship, some information about contrast sensitivities is required. Blackwell has provided empirical data on relative contrast sensitivity for the low luminance levels typical of roadway lighting (Table 1).

Applying an appropriate relative contrast sensitivity (RCS) value to the calculated C_1 value permits comparison of contrasts calculated for diverse values of driver adaptation luminance.

The Franklin Institute Research Laboratories uses the immediate target surround for background luminance; glare luminance is measured separately and included in some formulations as a separate entity. The terms used were

Lb = background luminance measured at 200-ft (61-m) separation, 43-ft (13-m) photometer elevation, and 30-min photometric aperture

Lv = veiling luminance measured under the same conditions as Lb by using calibrated Fry lens (4)

$\overline{Lb}$ = arithmetic average of Lb along the length of roadway

$$\overline{Lb} = \frac{\Sigma Lb}{N}$$

$\overline{Lb}'$ = arithmetic average of Lb plus Lv at the spot

$$\overline{Lb}' = \frac{\Sigma[(Lb + Lv)/1.074]}{N} \tag{2}$$

Equation 2 is derived rather loosely from Blackwell's $L' = L + L_v/1.074$ and represents an average value of Lb′ assuming that the Lv of the roadway is not restricted to a single spot. The value 1.074 is a correction for sphere-base glare.

The adjustment of the C_1 ratio can be accomplished most directly by using the RCS value for the luminance most closely approximating the adaptation level of the driver's eye (5). Because the driver is moving through a nonuniform luminance field, only a crude approximation is possible.

The best estimate uses the product of C_1 and the RCS relative to $\overline{Lb}$:

$$C_2 = \left(\frac{\Delta L}{Lb}\right)\left(RCS_{\overline{Lb}}\right) \tag{3}$$

C_2 may be termed effective contrast or C_2eff. It should be noted that the RCS value increases as $\overline{Lb}$ increases. This is a source of some difficulty, for it is not sensitive to differences in Lv. Lv degrades visibility by reducing contrast. However, as Blackwell has indicated, veiling luminance also contributes somewhat to visibility by raising the level of adaptation. Therefore, the following form is proposed:

Figure 1. Test site.

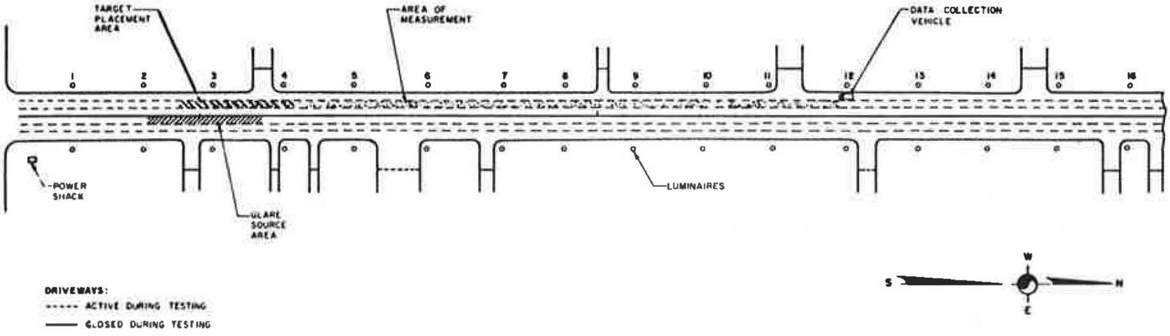


Table 1. Relative contrast sensitivity as a function of luminance for low luminance levels.

RCS	L(ft-L)	RCS	L(ft-L)	RCS	L(ft-L)
17.2	0.473	13.5	0.292	9.9	0.166
17.1	0.467	13.4	0.288	9.8	0.163
17.0	0.461	13.3	0.284	9.7	0.161
16.9	0.456	13.2	0.279	9.6	0.158
16.8	0.450	13.1	0.275	9.5	0.155
16.7	0.444	13.0	0.271	9.4	0.153
16.6	0.438	12.9	0.267	9.3	0.150
16.5	0.432	12.8	0.263	9.2	0.148
16.4	0.429	12.7	0.259	9.1	0.145
16.3	0.423	12.6	0.255	9.0	0.143
16.2	0.418	12.5	0.252	8.9	0.140
16.1	0.412	12.4	0.248	8.8	0.138
16.0	0.409	12.3	0.244	8.7	0.135
15.9	0.403	12.2	0.240	8.6	0.133
15.8	0.397	12.1	0.237	8.5	0.131
15.7	0.394	12.0	0.233	8.4	0.128
15.6	0.388	11.9	0.230	8.3	0.126
15.5	0.383	11.8	0.226	8.2	0.123
15.4	0.380	11.7	0.223	8.1	0.121
15.3	0.374	11.6	0.219	8.0	0.119
15.2	0.368	11.5	0.215	7.9	0.116
15.1	0.365	11.4	0.212	7.8	0.114
15.0	0.359	11.3	0.208	7.7	0.112
14.9	0.353	11.2	0.205	7.6	0.110
14.8	0.347	11.1	0.201	7.5	0.107
14.7	0.345	11.0	0.199	7.4	0.105
14.6	0.338	10.9	0.195	7.3	0.103
14.5	0.336	10.8	0.192	7.2	0.101
14.4	0.330	10.7	0.189	7.1	0.099
14.3	0.327	10.6	0.186	7.0	0.097
14.2	0.321	10.5	0.183	6.9	0.094
14.1	0.318	10.4	0.180	6.8	0.092
14.0	0.312	10.3	0.177	6.7	0.090
13.9	0.310	10.2	0.174	6.6	0.088
13.8	0.304	10.1	0.171	6.5	0.086
13.7	0.301	10.0	0.169	6.4	0.084
13.6	0.295				

Note: 1 ft-L = 3.4 cd/m^2

$$C_3 = \left(\frac{\Delta L}{Lb}\right)\left(RCS_{\overline{Lb}}\right)\left(\frac{Lb}{Lb + Lv}\right) \quad (4)$$

Equation 4 treats the problem of viewing a certain target-to-background relationship while the eye is adapted to other than simple background luminance and includes a correction for loss of contrast due to glare.

Inasmuch as glare is not restricted to the point of regard (i.e., target location) but is spatially distributed such that a moving observer experiences an adaptational effect with respect to glare, a more general term may be substituted.

$$C_4 = \left(\frac{\Delta L}{Lb}\right)\left(RCS_{\overline{Lb}}\right)\left(\frac{\overline{Lb}}{\overline{Lb'}}\right) \quad (5)$$

The extension of C_1 to C_4 represents an attempt to account for the exposure of drivers to physical conditions.

Visibility Concepts

Blackwell (5, 6) developed a conceptual framework and instrumentation for measurement of the visibility level. This quantity is measured with a visual task evaluator (VTE), which reduces the perceived contrast of a complex target to threshold and thereby establishes its visibility (for the background luminance under study) relative to laboratory data derived from a large sample (young adults), known target size (4 min), and brief exposure duration (0.2 sec).

As with other instruments requiring subjective matching, especially where color mismatches are expected (e.g., a roadway), a high degree of variability is accepted. Perhaps the most important limitation, however, is the subjective threshold criteria used by the operator, which is applied to the complex target. Whatever informational aspect of the target is chosen must be used consistently. If a nonuniform target is viewed against a nonuniform background, almost any movement of viewer or target will produce markedly different measures. Thus, although large variability is characteristic of the measures to be discussed, the theoretical framework provided by Blackwell is sufficient to extend the derivation of visibility measures to the furthest extent possible.

Effective Visibility Level

Blackwell defines effective visibility level as

$$VL_{eff} = VL \times DGF \times TAF \quad (6)$$

(Blackwell's original nomenclature refers only to VL_{eff}. We have added subscripts 1, 2, and 3 for clarity while manipulating the various terms. Blackwell also uses a generic L for his background conditions, and we have altered this for clarity.)

The disability glare factor (DGF) accounts for glare produced by the light source as well as other reflective sources in the field of view. DGF has two components.

$$DGF = \frac{Lb}{Lb'} \times \frac{RCS_{Lb'}}{RCS_{Lb}} \quad (7)$$

where $Lb' = (Lb + Lv)/1.074$.

The DGF has two components because, according to Blackwell, Lv both increases task background luminance (and thus contrast sensitivity) and decreases task contrast. DGF in Eq. 7 is, of course, related to the spot luminance immediately surrounding the target. Because an automobile driver has a more dynamic exposure, this effect may be simulated through use of DGF'.

$$DGF' = \frac{\overline{Lb}}{\overline{Lb}'} \times \frac{RCS_{\overline{Lb}}'}{RCS_{\overline{Lb}}} \tag{8}$$

This is similar logic to that applied in the development of Eq. 5.

The other component required in the estimation of effective visibility level is VL. This is determined through subjective readings by using the VTE or photometrically by calculating task contrast.

The transient adaptation factor (TAF) (5, 6) compensates for losses in visibility due to exposure to levels of luminance different from that of the fixated region when normal scanning occurs. TAF obviously relates directly to the role of headlighting in the determination of adaptation level. The measurement procedure and data treatment of this parameter are being explored (6).

The classic form of Blackwell's formulation uses the DGF expressed in Eq. 7. The VL component is developed as

$$VL = \frac{Ceq}{C^*} \tag{9}$$

where $C^* = 5.74/RCS_{Lb}$. The term Ceq is provided by using the VTE and applying known values of the operator's contrast sensitivity thresholds. [We have substituted the nomenclature C^* for Blackwell's term C_1 to avoid confusion. Blackwell defines C_1 as the "numerical values of threshold contrast corresponding to values of the visibility reference function VL_1, at different levels of task luminance" (5).]

A simple substitution into Eq. 9 yields the basic expression for VL_{eff}:

$$VL_1 eff = \left[\frac{Ceq(RCS_{Lb})}{5.74}\right] (DGF) \tag{10}$$

Blackwell has indicated the equivalence of the Ceq term and photometric contrast under certain conditions so that valuable information can be gained through a substitution of C_1 for Ceq in Eq. 10. The expressions using photometric contrast are termed visibility index (VI).

$$VI_1 = \left[\frac{C_1(RCS_{Lb})}{5.74}\right] (DGF) \tag{11}$$

$$VL_2 eff = \left[\frac{Ceq(RCS_{\overline{Lb}})}{5.74}\right] (DGF) \tag{12}$$

$$VI_2 = \left[\frac{C_1(RCS_{\overline{Lb}})}{5.74}\right] (DGF) \tag{13}$$

$$VL_3eff = \left[\frac{Ceq(RCS_{\overline{Lb}})}{5.74}\right](DGF') \tag{14}$$

$$VI_3 = \left[\frac{C_1(RCS_{\overline{Lb}})}{5.74}\right](DGF') \tag{15}$$

EXPERIMENTAL RESULTS

Figures 2, 3, and 4 show the relationship of visibility measures and driver performance. Table 2 gives the raw data plotted in those figures. Although the regression lines in the figures were calculated from all of the raw performance data points (N = 941), the scattergram in the figures and the performance points (TTT) in Table 2 are the means of the performance points for each measured visibility condition. Standard deviations are also given in Table 2. Statistical measures for nonnormal kurtosis and skewness indicated that all 15 distributions were within the probabilistic limitations of the normal distribution for the sample sizes measured.

The empirical results indicate that local measures of target contrast are the most important and that these vary little over the response distances measured.

The visibility separation distance was 200 ft (61 m). The maximum measured response separation distance was 477 ft (145 m), and the minimum separation distance was (a collision) 0. Given that the mean driver eye height is 43 in. (1.1 m), the following elevation angles are obtained for representative separation distances:

Separation, ft	Elevation Angle
50	4° 5' 43"
200	1° 1' 31"
500	0° 24' 46"

The differences in elevation angle are not great, and, despite the fact that asphalt reflectance is believed to change at shallow vertical angles, the differences are not felt to be important within the range of angles discussed.

Table 3 gives the luminance and glare measures characterizing the test conditions. Table 4 gives detailed descriptions of the various lighting configurations.

Table 5 gives the correlation coefficients for each of the 15 visibility conditions and all performance data points (N = 941).

It is clear from this table that all measures were convincingly significant. Those measures using C_1 provided the strongest predictive expressions. The simplest form of VLeff proved to be the most reasonable of the VL measures.

The factor providing the greatest amoung of information about the visibility is $\Delta L/Lb$.

The factors related to the immediate surround of the target are more meaningful than the average values of either Lb or Lv. These differences are not great, but in the interest of uncovering the most conservative expression we have attempted to discriminate among several equally powerful alternatives. The first choice, of course, is simply $\Delta L/Lb$. However, it is doubtful whether this form would hold up under more disparate conditions.

Blackwell's terms developed in the laboratory under uniform luminance conditions proved to be better estimates of visibility than the time history of luminance exposure of the driver. The reasons for this are not clear, but it may be that the simple arithmetic mean used ($\overline{Lb}$) is not a good estimate of adaptation luminance.

The difference in influence of the twin components of DGF,

Figure 2. Regression line for C_1 and all performance points measured.

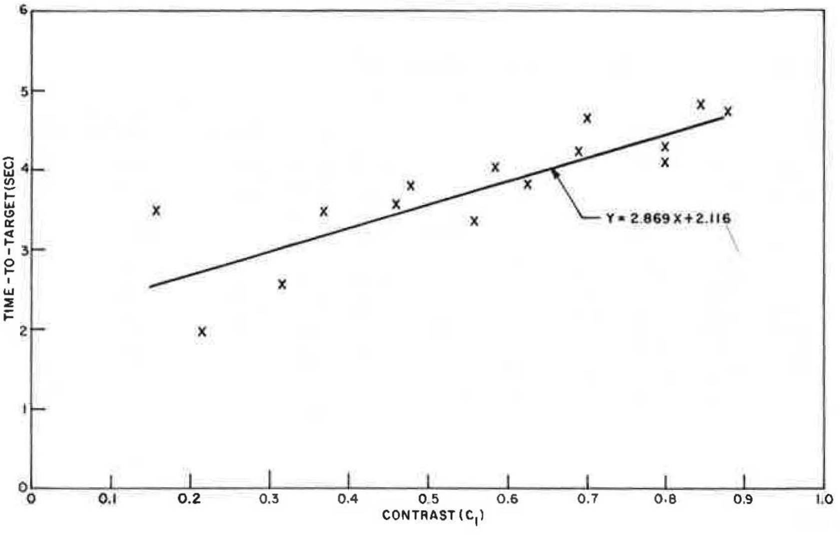


Figure 3. Regression line for VI_1 and all performance points measured.

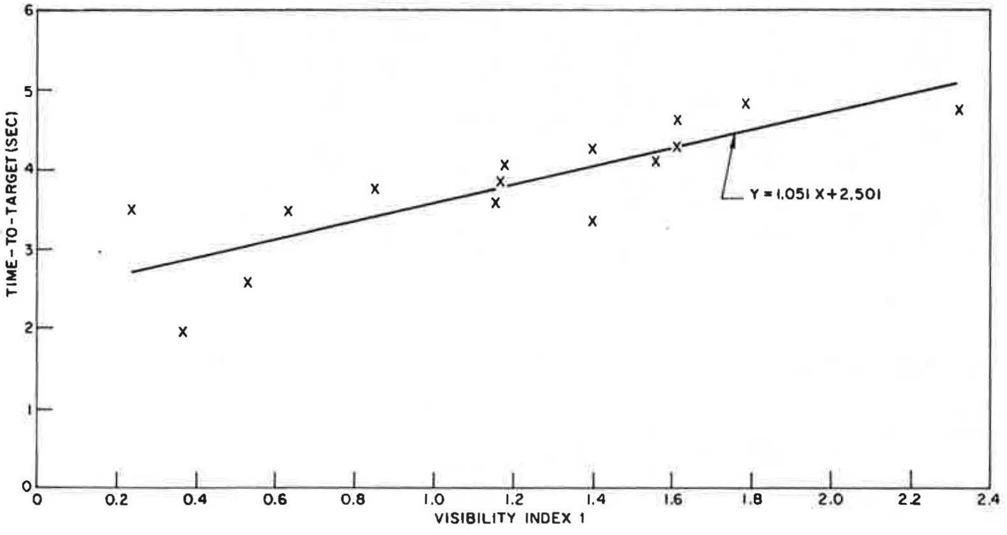


Figure 4. Regression line for VL_1eff and all performance points measured.

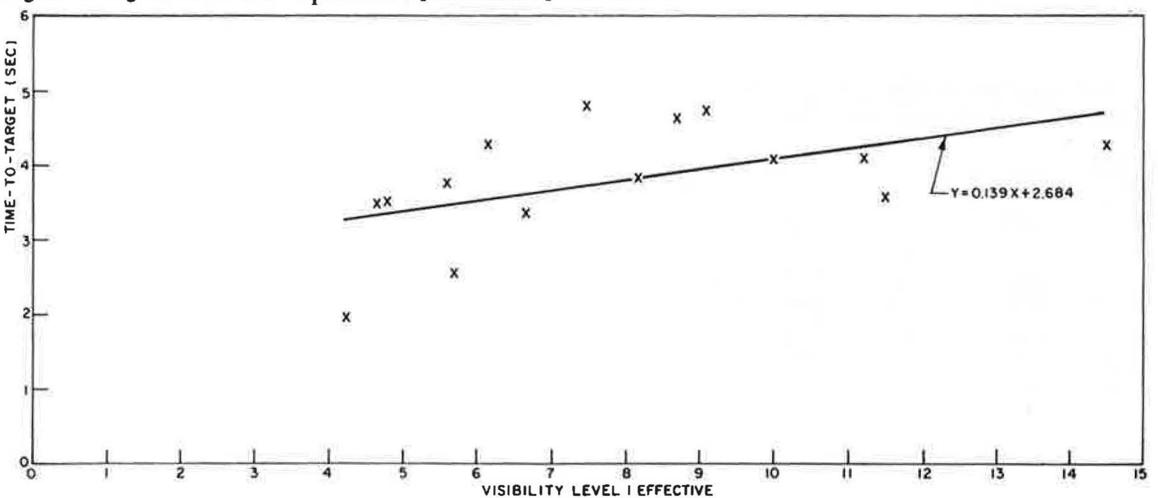


Table 2. Visibility parameters and performance measures for lighting conditions studied.

Lighting Condition	Target Position	VL_1eff	VI_1	VL_2eff	VI_2	VL_3eff	VI_3	C_1	C_2	C_3	C_4	Mean TTT[a]	Standard Deviation	Sample Size
3	5	8.686	1.617	9.164	1.706	9.266	1.725	0.703	11.297	8.531	8.755	4.638	1.936	58
3	6	6.647	1.394	6.578	1.380	6.548	1.374	0.560	8.995	7.028	6.971	3.360	1.631	60
5	5	8.169	1.171	8.880	1.273	9.277	1.330	0.627	8.591	6.157	6.739	3.826	1.615	60
5	6	4.224	0.366	5.098	0.441	5.243	0.450	0.214	2.935	2.148	2.302	1.977	1.845	60
5	8	9.102	2.317	7.585	1.930	7.338	1.868	0.881	12.068	10.239	9.467	4.720	1.720	59
6	5	14.532	1.404	15.322	1.480	15.563	1.503	0.690	9.959	7.196	7.468	4.241	2.346	60
6	6	11.504	1.160	10.835	1.092	10.768	1.085	0.464	7.103	5.574	5.479	3.568	1.367	40
6	11	10.027	1.177	11.401	1.338	11.674	1.370	0.586	8.969	6.535	6.917	4.035	1.622	70
8	3	5.597	0.848	4.728	0.716	4.995	0.756	0.480	5.054	3.308	3.611	3.765	1.724	60
8	4	4.800	0.244	4.708	0.240	4.891	0.249	0.158	1.663	1.105	1.188	3.490	2.386	50
8	6	11.241	1.558	9.213	1.277	9.141	1.267	0.804	8.464	6.297	6.047	4.096	1.891	123
8	8	4.648	0.633	4.188	0.571	4.272	0.582	0.369	3.889	2.715	2.779	3.471	1.752	59
8	9	5.716	0.329	8.684	0.500	8.637	0.498	0.316	3.325	2.209	2.376	2.556	1.909	60
11	4	6.172	1.609	5.514	1.438	5.670	1.478	0.800	9.617	7.050	7.386	4.261	2.259	62
11	8	7.477	1.785	6.680	1.595	6.540	1.561	0.845	10.156	8.218	7.800	4.802	2.149	60

[a]Total sample.

Table 3. Luminance and glare values.

Lighting Condition	Target Position	Lb (ft-L)	$\overline{Lb}$ (ft-L)	Lt (ft-L)	Lv (ft-L)	Lb′ (ft-L)	$\overline{Lb'}$ (ft-L)	Ceq	C_1	DGF	DGF′
3	5	0.370	0.411	0.110	0.120	0.480	0.530	3.774	0.703	0.867	0.876
3	6	0.420	0.411	0.185	0.118	0.538	0.530	2.667	0.560	0.881	0.876
5	5	0.255	0.300	0.095	0.101	0.356	0.383	4.378	0.627	0.850	0.888
5	6	0.210	0.300	0.165	0.077	0.287	0.383	2.474	0.214	0.864	0.888
5	8	0.430	0.300	0.051	0.077	0.507	0.383	3.463	0.881	0.918	0.888
6	5	0.300	0.332[a]	0.093	0.115	0.415	0.442[a]	7.143	0.690	0.853	0.867
6	6	0.420	0.374	0.225	0.115	0.535	0.404	4.006	0.464	0.882	0.877
6	11	0.290	0.374	0.120	0.108	0.398	0.484	4.994	0.586	0.856	0.877
8	3	0.250	0.184	0.130	0.132	0.382	0.257	3.170	0.480	0.813	0.859
8	4	0.190	0.184	0.160	0.096	0.286	0.257	3.104	0.158	0.827	0.859
8	6	0.265	0.184	0.052	0.091	0.356	0.257	5.801	0.804	0.866	0.859
8	8	0.222	0.184	0.140	0.096	0.318	0.257	2.711	0.369	0.842	0.859
8	9	0.095	0.184	0.065	0.048	0.143	0.257	5.481	0.316	0.864	0.859
11	4	0.290	0.234	0.058	0.106	0.396	0.304	3.068	0.800	0.858	0.882
11	8	0.290	0.234	0.045	0.068	0.358	0.304	3.539	0.845	0.901	0.882

Note: 1 ft-L = 3.4 cd/m^2.

[a]Measurements made after substantial pavement wear.

Table 4. Lighting configurations studied.

Lighting Configuration	Average Horizontal Illumination (ft-c)	Average-Minimum Illumination	$\overline{LB}$ (ft-L)	Average-Minimum Luminance	Luminaires[a] Spacing (ft)	Luminaires[a] Geometry
3	1.03	1.7:1	0.41	1.4:1	110.5	Opposite
5	0.50	1.7:1	0.30	2.1:1	221	Staggered
6	0.75	1.7:1	0.33	1.8:1	110.5	Single side, near
8	0.38	5.4:1	0.18	1.8:1	221	Single side, near
11	0.44	4.4:1	0.23	3.0.1	221	Opposite

Note: 1 ft-c = 1.07 lx; 1 ft-L = 3.4 cd/m^2; 1 ft = 0.3 m.

[a]The luminaires were 400 W mercury vapor and 30 ft (9.1 m) high.

Table 5. Correlation coefficients for visibility indexes and all performance data points.

Visibility Measure	Correlation Coefficient	z Transform	Z	Significance
C_1	0.3104	0.3209	9.828	$>10^{-5}$
VI_1	0.3084	0.3188	9.764	$>10^{-5}$
C_2	0.3019	0.3116	9.544	$>10^{-5}$
VI_3	0.3007	0.3103	9.503	$>10^{-5}$
VI_2	0.3004	0.3100	9.493	$>10^{-5}$
C_3	0.2980	0.3073	9.413	$>10^{-5}$
C_4	0.2959	0.3050	9.342	$>10^{-5}$
VL_1 eff	0.1959	0.1985	6.079	$>10^{-5}$
VL_2 eff	0.1136	0.1141	3.494	$>10^{-3}$
VL_3 eff	0.1089	0.1093	3.349	$>10^{-3}$

$$\frac{Lb}{Lb'} \text{ and } \frac{RCS_{Lb'}}{RCS_{Lb}}$$

is evident. We do know, that the first term is larger in all cases and provides the more meaningful contribution if considered separately. The combined form is, of course, more conservative and is therefore highly desirable. Numerically, however, the term using DGF (VI_2) did not fare so well as the equivalent term without the second DFG component (C_3). These differences have little practical meaning however.

It appears that the RCS terms for $\overline{Lb}$ or Lb have little effect on the performance correlations except that the average values provide correlations somewhat lower than the spot background measure.

Contrast

The correlation of C_1 with driver performance was surprisingly strong. It is apparent that, within the range of variables studied, this represents the most important element in determining visibility. This is a serendipitous finding, of course, and indicates that visibility even in a system as complex as the roadway may be described in these terms. Some caution is warranted, however, for it may be necessary to provide adjustments to the pure form for visual situations of even greater complexity. This is especially true when high glare sources and nonuniform luminance conditions are present.

The range of Lb in this study was relatively limited, 0.095 to 0.430 ft-L (0.32 to 1.47 cd/m^2). Although these conditions are representative of a very large number of urban lighting conditions, the average luminance values and uniformities by no means exhaust even the most commonly encountered designs.

The contribution to the power of the visibility indexes of the correction factors for glare and time-averaged luminance was quite weak. Specifically, the variability of luminances was considerable under some configurations and, although no factor was applied with the intent of correcting for this exposure (except indirectly through the use of $\overline{Lb}$ and $\overline{Lb}'$), it is difficult to envision a meaningful contribution from such an effort. However, because conditions of both high luminance variability and glare can be anticipated in many installations, continued research on the effects of these factors on the adaptation state is needed.

Visibility Level

VL_1, the purest form of VL, proved to be the best predictor. Given the range of luminance under study and the magnitude of the differences of background and average luminance within a lighting configuration, the control for these differences was meaningless. The variability of the Ceq term contributed heavily to this outcome.

The visibility level component Ceq is a subjective measure and consequently is relatively unreliable. The choice of visual criteria for the determination of threshold is difficult and apparently resulted in a higher variance for this term. Hence, as subscripts were added to the VL_1 term, correlations with driver performance tended to decrease.

It should be recognized, however, that the target used was of relatively low internal contrast, and, although detection of a target such as a pedestrian is more complex, it was selected as a photometric expedient. The Ceq is most useful in a scene of greater complexity with a task of greater internal contrast where physical measures are inadequate as measures of visibility.

The VL_1eff expression did result in a highly significant correlation with the performance measures as noted. The substitution of C_1 for Ceq (producing VI_1) resulted in a somewhat more reliable measure in the present context.

DISCUSSION OF RESULTS

Stopping Time Requirements

Figure 5 shows plots of the regression line for the 50th, 15th, 5th, and 1st percentile responders. These target separation gaps are expressed in units of time. The 15th percentile, for instance, represents the upper limit separation time evidenced by the worst 15 percent of the responders. These extreme cases are explored so that we can develop some lighting design concepts related to both visibility and braking time requirements.

It would be speculative to attempt to identify casual factors related to the extreme cases of response performance. However, such extremes are truly representative of the driving public. We have sampled the diversity of scanning habits, acuity, and glare and luminance sensitivities as well as a host of situational factors such as attentional conflict and alcohol or drug use. In addition, some vehicular factors play a role, especially windshield condition (dirt and pitting) as related to glare experience or visual aberrations. Exploration of the extremes of performance although statistically somewhat less reliable is fundamental to the development of a design criterion.

The plot of performance versus VI_1 for the 15th percentile driver, then, provides extremely useful information. Because the ordinate is a time measure of the separation of response point and the target, it is possible to supply a time criterion for roadway operations on these visibility measures. The following are stopping time requirements for several commonly encountered vehicle velocities:

Velocity (fps)	Mean Braking Time (sec)
29.3	1.43
36.7	1.75
44.0	2.09
51.3	2.45
58.7	2.80
66.0	3.15
73.3	3.49
88.0	4.20
102.7	4.89

These requirements are for the response point through 0 velocity [at a uniform deceleration rate equal to $\approx$20 fps^2 (6.1 m/s^2)] for average vehicles (i.e., 50th percentile) and do not include any reaction or (leg) movement time component. This omission is justified because the performance measures are response measures occurring after the cognitive and motor activities of reaction-movement time are completed.

By using Figure 6 we can determine the minimum visibility that must be provided for a target to be seen at a satisfactory separation distance by 85 percent of the driving public. It may be desirable to provide even greater contrast as a design requirement so that adequate visibility is provided for 95 to 99 percent of the drivers at distances sufficient to permit safe braking.

These plots can be used for any of the lower design speeds to determine the required minimum visibility level. The values related to the higher design speeds and probabilities were extrapolated and represented as linear as indicated. Additional research is required for complete confidence in the required VI_1 at high levels.

Figure 5. Regression lines for driver responses and VI_1.

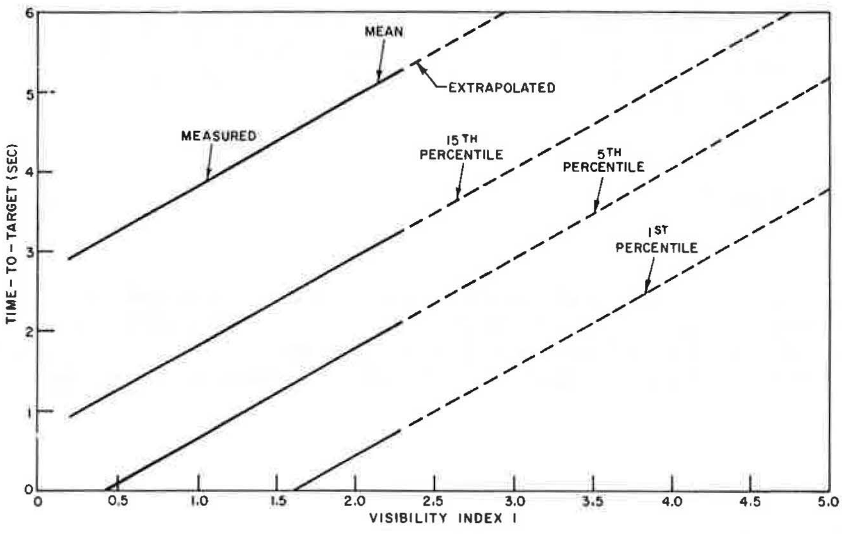
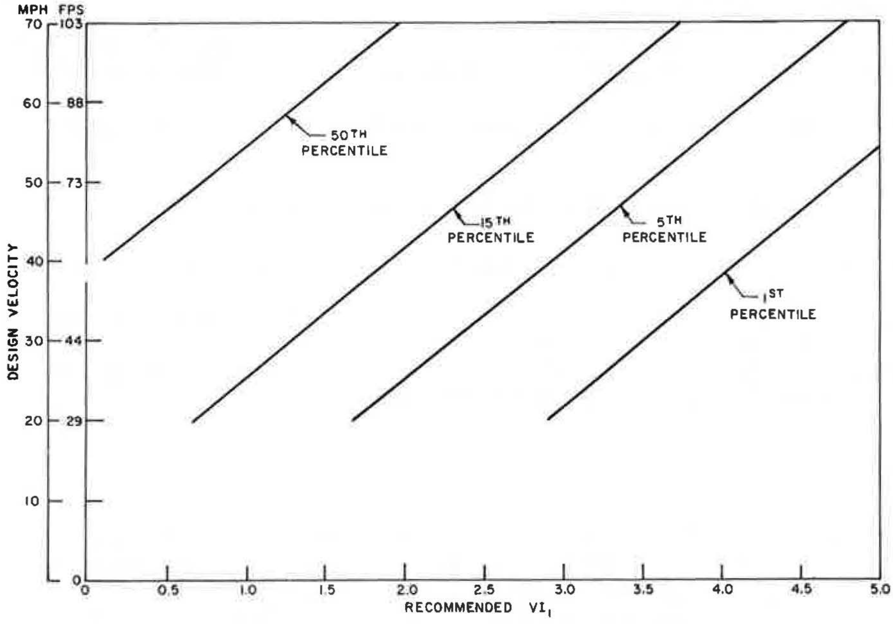


Figure 6. Suggested VI levels for various design speeds and driver populations (extrapolated data).



Field Calculation

As noted, the pure form of contrast proved to be the most reliable predictor. This ignores, however, the known influences of contrast and glare sensitivities. To avoid any situational factors having a bearing on the data reported here we recommend the more general form as represented by

$$VI_1 = \left[\frac{C_1(RCS_{Lb})}{5.74}\right](DGF) \quad (11)$$

Although there is little difference in the forms DGF and DGF′ as they affect the reported data, situations of higher luminance levels are often accompanied by higher glare, and therefore the use of DGF′ may be justified. However, if the target measurement area is unique with respect to the balance of the system in terms of glare, then VI_1 is preferred.

CONCLUSIONS

1. For a simple target, pure contrast ratio predicts driver visibility with considerable accuracy.
2. The influence of glare is largely undifferentiated under the lighting conditions tested.
3. Spot background luminance is a good predictor of adaptation level given the luminance variability reported on here.
4. Visibility index in the form VI_1 proved to be the most reasonable predictor, suggesting that in more variable situations (or as a general form) this measure should be used.
5. Ceq seems relatively sensitive to subjective factors causing this value to be highly variable.

Follow-up research should deal with the following conceptual areas:

1. Validation of the reported findings through the use of visual tasks other than target detection,
2. Extension of the independent variables into higher and lower levels of VI_1 for verification of the extrapolated curves, and
3. Development of a criterion and methodology for the evaluation of current roadway practices in terms of minimum visibility requirements.

REFERENCES

1. L. E. King. Illuminance Versus Luminance. HRB Special Report 134, 1972.
2. V. P. Gallagher and P. G. Meguire. Visibility Requirements of Urban Drivers: Interim Report, Vol. 1. Federal Highway Administration.
3. V. P. Gallagher et al. Interaction Between Fixed and Vehicular Illumination Systems: Interim Report on Phase II. Federal Highway Administration, Report FHWA-RD-72-23, March 1972.
4. G. A. Fry, B. S. Pritchard, and H. R. Blackwell. Design and Calibration of a Disability Glare Lens. Illuminating Engineering, Vol. 48, No. 3, March 1963.
5. Recommended Method for Evaluating Visual Performance Aspects of Lighting. International Commission on Illumination, Rept. 19, 1971.
6. O. M. Blackwell. A Prescription for Roadway Lighting. Lighting Design and Application, Vol. 4, No. 2, Feb. 1974.
7. H. R. Blackwell. Contrast Thresholds of the Human Eye. Journal of Optical Society of America, Vol. 36, No. 11, 1946.

Because the rates of nighttime accidents are higher than daytime accidents, much research has been directed to the unique problems of night driving. Many researchers concur that the driver receives most of his or her information through the visual system. During night driving, the visual cues normally available during daytime are reduced. Whether this paucity of visual information is related to the higher night accident rate is not known. A basic approach to the problem is to identify through visual search patterns the driver's use of night driving cues. Identification of driver visual needs in night driving can eventually lead to improved night driving safety. This paper discusses and presents the results of two studies to investigate drivers' visual search patterns in night driving. The first study compares nighttime visual search behavior to daytime behavior on freeways and rural highways. The second study develops methods of using driver visual search data to evaluate illumination at rural highway intersections, which have high rates of nighttime accidents.

DRIVER SEARCH AND SCAN PATTERNS IN NIGHT DRIVING

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An essential step to the identification of driver visual needs is the understanding of where drivers visually search the environment. With the support of the Ohio Department of Transportation and the Federal Highway Administration, the Driving Performance Laboratory (DPL) of the Ohio State University has developed a method for measuring drivers' visual search behavior during night driving and has conducted several studies of this search behavior at night.

The system developed is a vehicle-based television system that records drivers' eye movements. The system continuously records on video tape the driver's direction of gaze while he is driving an instrumented car. The record contains a small light spot on the moving picture of the driving scene corresponding to the driver's point of fixation. This record and subsequent computer summaries of various measures enable quantitative analyses of visual search behavior (e.g., percentage of time viewing specific areas, fixation times, spatial distribution of fixation locations, eye travel distances).

THE RECORDING SYSTEM

The television system used in this study to record eye movement has been described in detail in another paper (2) and is shown in Figure 1. The driver wears a helmet that is securely located on the head by means of 16 separately adjusted pads on the helmet. In addition, an individually molded bite bar is fitted to the upper teeth and also fastened to the helmet by support brackets. When clamped, the helmet provides a stable unit for supporting the scene camera, light source, and reflection pickup lens. The scene camera provides a 54 by 41-deg view of the road scene ahead. For the night system, this camera was modified to operate at nighttime illumination levels. The light source shines a narrow beam of infrared light onto the driver's cornea, which then reflects from the cornea. As the eye moves this reflection also moves and is received by a pickup lens. This eye spot image is transmitted to a television camera via a high-resolution 3-ft fiber optic cable. The image of the moving eye from this camera is superimposed (faded) onto the driving scene depicted by the camera worn by the driver. The resulting combined image is displayed by a small television monitor in the vehicle, which permits calibration and constant checking of data quality. The resulting picture is recorded on video tape, which provides a permanent record of the data. When prop-