Predicting Target-Detection Distance With Headlights

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This paper presents results of field research conducted to study the applicability of laboratory threshold visibility data in predicting seeing distances to stand-up and road-surface targets by use of different headlight beam patterns. A vehicle equipped with a precision odometer system was used to measure detection distances of 12 subjects under different target-background-glare conditions. The subject testing was followed by extensive photometry to measure the target, background, and veiling brightness of each target condition. The reflectance properties of the pavement and road shoulder were also mapped. Detection distances were predicted from directly measured brightnesses and brightnesses computed from target and background reflectance data, ambient brightness, and assumed head-lamp beam patterns. A comparison of field-observed and predicted seeing distances showed good to excellent agreement. The necessary contrast multipliers needed to account for factors such as complexity of road surface delineation and transient adaptation are also discussed.

One widely accepted criterion for evaluating vehicular headlighting is seeing distance: the distance at which an object on or near the road first becomes visible to the driver. Field testing to determine seeing distances with different head lamps, however, is costly, and an analytic approach for accurately predicting seeing distance to targets is needed.

The visibility of objects on the road at night depends primarily on the brightness contrast between the object and its immediate background. Human contrast detection performance has been studied extensively in the laboratory (1, 2, 3, 4) and subsequently refined to account for factors such as nonhomogeneous backgrounds (5), glare (6, 7), and transient adaptation (8, 9). Relatively little has been done to apply this work to the problems of nighttime visibility with headlights, nor have field researchers, with few exceptions (10, 11, 12, 13, 14, 15), sought to interpret their results in terms of laboratory findings. In general, field researchers have not performed the detailed photometric measurements required to evaluate findings by the use of a contrast-detection model. The existing models of nighttime target-detection performance (12, 14, 16) are limited to a narrow range of conditions to which they apply.

The objective of the research reported in this paper was to determine whether a model based on existing laboratory data can be either directly applied or refined to predict the driver's seeing distances to various stand-up and road surface targets under night driving conditions.

PREDICTING SEEING DISTANCE

Blackwell Model

For an alerted observer, the detection of targets under night-vision conditions is governed by the adaptation level, the brightness contrast between the target and its background, the size of the target, and the duration of the target exposure. Figure 1 (3) shows the relation among these variables in the vision laboratory. Log contrast threshold (the contrast required for 50 percent probability of detection) is plotted as a function of log adaptation brightness for various target sizes. The data in Figure 1 were obtained with a target exposure duration of $^1/_{30}$ s, which Blackwell stated is appropriate for night driving. Other exposure durations give rise to similar families of curves. Contrast is defined as

$$C = (B_T - B_B)/(B_B + B_V) = (B_T - B_B)/B_A \quad (1)$$

where

B_T = target brightness,
B_B = background brightness,
B_V = veiling brightness produced by glare, and
B_A = adaptation brightness.

The expression for B_V is given by Fry (17) and is included later as equation 6. In the absence of glare, the adaptation brightness is the background brightness.

The target at a given distance should be visible if the contrast C, as computed from equation 1, is greater than the contrast threshold $\hat{C}$, as given by the Blackwell

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curves, corresponding to the target size at that distance and at adaptation brightness B_A. Target size is defined as the angular subtense of the diameter of a circle having the same area as the target.

A mathematical model was developed to fit the Blackwell data presented in Figure 1. The contrast threshold $\hat{C}$ defined by the model is as follows:

$$\log_{10} \hat{C} = b_0 + b_1 \cdot \log_{10} B_A + b_2 \cdot (\log_{10} B_A)^2 \quad (2)$$

where

$b_0 = 7.4935 - 6.97678 \cdot \Theta + 0.544938 \cdot \Theta^2$,
$b_1 = 0.55315 + 0.021675 \cdot \Theta + 0.0003125 \cdot \Theta^2$,
$b_2 = 0.07721 + 0.00558 \cdot \Theta + 0.000175 \cdot \Theta^2$,
$\Theta = \log_2$ (target size in minutes), and
$B_A = B_B + B_V$ (adaptation brightness in candelas per square meter).

Ford Model

The Ford seeing-distance model is based on Blackwell's (3) brightness contrast thresholds and incorporates the above expressions. However, the seeing-distance predictions made by the Ford model are based on target, background, and veiling brightness values as shown in Figure 2. The computations are as follows:

$$B_T = R_T [(I_1/D_1^2) + (I_2/D_2^2)] + B_{AT} \quad \text{(target brightness at point P)} \quad (3)$$

$$B_B = R_1 \cdot (I_1/\hat{D}_1^2) + R_2 \cdot (I_2/\hat{D}_2^2) + R_3 \cdot (I_3/\hat{D}_3^2) + R_4 \cdot (I_4/\hat{D}_4^2) + B_{AP}$$
$$\text{if target background is pavement or shoulder} \quad (4)$$

$$= B_{AS} \quad \text{if target background is sky} \quad (5)$$

$$B_V = 10\pi \sum_{i=3}^{4} \{(E_i \cos\Theta_i)/[(\Theta_i + 1.5)\Theta_i]\} \quad (6)$$

$$C = K_M \times K_A \times [(B_T - B_B)/(B_B + B_V)] \quad (7)$$

where

R_T = target reflectance,
I_1 = combined candelas of left head lamp of observer vehicle directed at point P on target,
I_2 = combined candelas of right head lamp of observer vehicle directed at point P on target,
I_3 = combined candelas of left head lamps of glare vehicle directed at target background,
I_4 = combined candelas of right head lamps of glare vehicle directed at target background,
D_1 = distance of left head lamp of observer vehicle from target,
D_2 = distance of right head lamp of observer vehicle from target,
$\hat{D}_1$ = distance of left head lamp of observer vehicle from point P^1,
$\hat{D}_2$ = distance of right head lamp of observer vehicle from point P^1,
$\hat{D}_3$ = distance of left head lamp of glare vehicle from point P^1,
$\hat{D}_4$ = distance of right head lamp of glare vehicle from point P^1,
B_{AT} = ambient brightness of target,
R_1 = retroreflectance of target background when viewed from point 'O' under left head-lamp illumination,
R_2 = retroreflectance of target background when viewed from point 'O' under right head lamp illumination,
R_3 = forward reflectance of target background P^1 when viewed from point 'O' under left head-lamp illumination of glare vehicle,
R_4 = forward reflectance of target background when viewed from point 'O' under right head-lamp illumination of glare vehicle,
B_{AP} = ambient brightness of pavement,
B_{AS} = ambient brightness of sky,
E_i = illumination from i th glare head lamp at point 'O',
Θ_i = angle in degrees between i th glare of head lamp and point P from point 'O' (i = 3, glare of left head lamp; and i = 4, glare of right head lamp),
K_M = contrast multiplier to account for effects of target complexity and transient adaptation,
A = driver age in years, and
K_A = contrast multiplier to account for degradation in driver's visual detection performance
= $-0.3796 + 0.134398A - 0.0044422A^2 + 5.50484 \times 10^{-5}A^3$ [this expression is derived by fitting Blackwell (24) data presented for adaptation levels between 0.34 to 0.0034 cd/m^2].

Seeing distance is determined by computing actual and threshold contrast by converging on a distance and using an iterative procedure until the threshold is reached. Preliminary studies at the Ford Motor Company suggested that reasonably accurate predictions of seeing distance could be made on the basis of the Blackwell formulations. Accordingly, a study was undertaken to obtain seeing-distance data under known photometric conditions to (a) validate the Blackwell formulations by computing seeing distance directly from measured brightness data and (b) exercise the Ford model by computing the brightness data needed for the Blackwell formulations from head-lamp characteristics and environmental parameters.

SEEING-DISTANCE TESTS

Under actual highway conditions, alertness, attention, and other subtle factors play an important role in seeing-distance performance. However, since the purpose of the present investigation was to model those aspects of performance mediated by lighting conditions, the research was conducted with alerted drivers on a closed road.

Test Site

The three-lane 4-km (2.5-mile) concrete straightaway on the Ford Motor Company's Proving Ground at Romeo, Michigan, was used as a test site. The lanes are 3.66 m (12 ft) wide, and the shoulders on either side are grass. This test facility is unique in two important respects. First, since the proving ground is located in rural countryside, the sky and pavement ambient brightness levels were below 0.017 cd/m^2 (0.005 ft-L) and remained fairly constant during the data collection sessions. The data were collected between 9:30 p.m. and 4:00 a.m. in the fall of 1974. Second, the condition and appearance of the pavement, shoulder, and more distant background are uniform.

Test Vehicle

The test car was a 1973 Ford LTD fitted with a regulated voltage power supply to ensure constant head-lamp intensity. The head lamps on the test car were wired to produce the following three beam patterns: (a) low beam (L) produced by two conventional, type 2, 146-mm (5¾-in) diameter low-beam lamps (same as those available on vehicles produced in the United States after mid-1972

with the four-lamp headlighting system); (b) high beam (H) produced by two 146-mm ($5^3/_4$-in) diameter type 5 government-proposed (21) high-beam lamps (no filler lamps were used with these high-beam lamps); and (c) low plus high beam (L + H) produced by the two low-beam lamps in addition to the high-beam lamps. The type 5 high-beam lamps produce about 2.5 to 3.5 times the intensity of the current type 1 high-beam lamps. The above lamp conditions were selected to cover a wide range of illumination levels and to produce different levels of far and near (foreground) illumination. The purpose of the L + H condition was to determine the effect of a bright foreground on the detection of distant targets.

Figure 1. Threshold contrast as a function of background brightness for various angular target sizes.

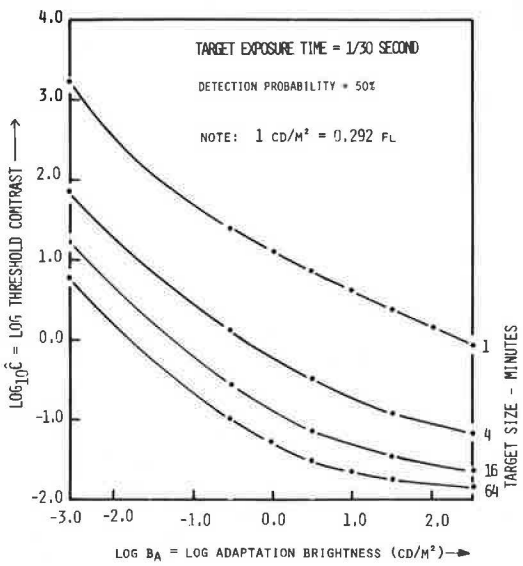
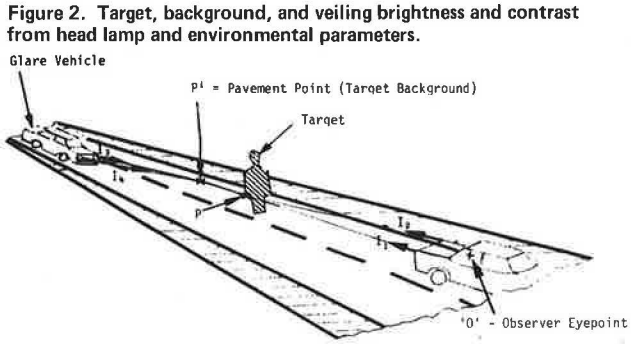


Figure 2. Target, background, and veiling brightness and contrast from head lamp and environmental parameters.



Targets

Three types of targets were used: (a) 1.82-m (6-ft) pedestrian silhouettes, (b) 0.3-m (1-ft) squares, and (c) pavement delineation markings. The pedestrian targets were all located on the right edge of the travel lane; the background was the concrete road surface in some trials and the grassy shoulder in others, depending on which lane was used as the travel lane (Table 1). Three different reflectances were used for the pedestrian targets: 8, 15, and 25 percent. The square targets were all located on the right shoulder of the road. The target reflectance values ranged from 6 to 90 percent.

Reflectorized pavement marking tape [102 mm (4 in) wide] and nonreflectorized tape [102 mm and 203 mm (4 and 8 in) wide] in 15.24-m (50-ft) lengths served as the delineation or line targets. All the line targets were located on the left boundary of the travel lane.

A 1973 Mercury sedan equipped with standard head lamps, i.e., two type 2 (No. 4000) and two type 1 (No. 4001), served as the glare vehicle. The glare vehicle was stationary and positioned in the center of the left adjacent lane with its high beams on. Only the 8 percent reflectance, shoulder-mounted pedestrian targets and the reflectorized delineation markings were studied under glare conditions. Table 1 gives distances between the targets and the glare vehicle. The 24 targets were distributed along the 4-km (2.5-mile) length of the straightaway. The test subjects drove a route that exposed them to each target at least once on a given lap. The target locations and the test car path that constituted a lap are shown in Figure 3.

Test Procedure

Twelve subjects, whose vision was corrected to 20/30 or better and who ranged in age between 25 to 48 years, participated in the experiment. Each subject made eight laps around the route in two sessions. In the first lap the

Table 1. Target-detection conditions.

Target Type	Target No.[a]	Target Reflectance (%)	Target Background	Target Location[b] (m)	Target Distance of Glare Vehicle[c] (m)
Pedestrian	1	8	Shoulder	+2.13	335
	2	8	Shoulder	+2.13	122
	3	8	Shoulder	+2.13	-122
	8, 9	8	Shoulder	+2.13	No glare
	10, 11	8	Concrete	+2.13	No glare
	12	25	Concrete	+2.13	No glare
	13	8	Concrete	+2.13	No glare
	14	15	Concrete	+2.13	No glare
Line targets	15, 16, and 19	Reflectorized	Concrete	-1.83	No glare
	21	Reflectorized	Concrete	-1.83	365
	22	Reflectorized	Concrete	-1.83	213
	23	Reflectorized	Concrete	-1.83	76
	24	Reflectorized	Concrete	-1.83	-122
	17, 20	Nonreflectorized	Concrete	-1.83	No glare
Line target	18	Nonreflectorized	Concrete	-1.83	No glare
Square targets	4	89.7	Shoulder	+2.13	No glare
	5	6.6	Shoulder	+2.13	No glare
	6	27.3	Shoulder	+2.13	No glare
	7	11.2	Shoulder	+2.13	No glare

Note: 1 m = 3.28 ft.

[a]Figure 3 shows target locations.
[b]Plus indicates right and minus indicates left of the centerline of the travel lane.
[c]Plus indicates distance in front and minus indicates distance behind the glare vehicle.

subject drove at a slower speed and was shown each of the targets. In the second lap the subject was pilot-tested for target and track familiarization. In the last three laps of the first session, data were collected under a different beam pattern in each lap (Table 2). The subject was allowed to rest for about 40 min after completing the first session. In the second session, the subject made three more laps using the three beam patterns in reverse order (Table 2). The counterbalanced experiment design used in this study also served to remove the effects on seeing distances of changes in vehicle attitude (primarily due to decrease in gas tank weight) during the two data collection sessions.

The target-detection distance was measured by a fifth wheel with a digital distance counter. The subject was provided with a push button that started the digital counter, and the experimenter operated the other push button to stop the counter. During all the trials the subject was asked to use the speed control, and thus a constant 72.4-km/h (45-mph) speed was maintained. To ensure that the subject was fully alerted, the experimenter reminded the subject to watch for each target by giving him information about the target type and its expected location (i.e., left or right) a few hundred meters before the expected detection. The subject's task was to push the button as soon as he could detect the target. The experimenter then switched the counter off at the instant that the subject passed the target. The displayed distance on the counter was recorded by the experimenter.

PHOTOMETRY

Brightness Measurements

A Pritchard photometer with a 2-min aperture was mounted inside the vehicle at the driver's eye point. Target and background brightness measurements were made for one of each type of target under each headlight and glare condition with the test car positioned 60, 120, 180, 240, and 305 m (200, 400, 600, 800, and 1000 ft) from the target. Measurements were made at several locations on and around the target as shown in Figure 4. At far distances where the width of a single line target subtended less than a 2-min angle, several of the line targets were placed side by side to fill the field of the Pritchard aperture with the target material. When the target and background brightness were measured in the presence of the glare vehicle, direct illumination from the glare head lamps on the Pritchard objective was baffled to avoid errors due to stray light effects.

Road surface and delineation brightness data for the glare vehicle target distances of 76, 213, and 365 m (250, 700, and 1200 ft) are shown respectively in Figures 5, 6, and 7. When the target is 76 m (250 ft) ahead of the glare vehicle (Figure 5), the brightness of the road-surface background decreases as the test car approaches because the reflectance of the road surface decreases as the angle of reflectance of the light from the opposing glare lamps increases. The brightness of the reflective line targets, on the other hand, is produced largely by the test vehicle lamps and increases as the distance closes. Thus, the contrast changes from negative to positive during the approach. The area in Figure 5 covered by diagonal lines shows the region where, under low beams, the background is brighter than the target. At a target-glare vehicle separation of 213 m (700 ft), the brightness relations are much the same (Figure 6). At 365 m (1200 ft), the glare lamps are contributing little to the pavement brightness (Figure 7). The three figures show data for three different targets and pavement areas and therefore cannot be directly compared.

Similar target and background brightness curves for the pedestrian and square targets were obtained by averaging the brightness values obtained at each distance at different locations on the target and its background.

Veiling brightness was measured by using a Fry integrator lens in front of the Pritchard photometer objective. The Fry lens is constructed to yield the same B_v value as would be obtained by summing the B_v computed by Fry's formula from several sources. For these measurements, the photometer was placed at distances from 7.5 to 670 m (25 to 2200 ft) from the glare vehicle, and readings were taken by aiming the photometer 15, 30, 60, 120, and 365 m (50, 100, 200, 400, and 1200 ft) in front of the test vehicle at the same left and right lateral locations as the target. Figures 8 and 9 show the veiling brightness data measures respectively for the pedestrian targets on the right side and the line targets on the left side as a function of the observation distance and distance to the glare vehicle.

Reflectance Measurement

The reflectance of the pavement and shoulder on the test site was measured by using the Pritchard photometer and a photocell. The reflectance at any point on a surface is defined as the ratio of luminance in candelas per square meter (measured by the photometer) to the illumination in luxes (measured by the photocell). Reflectance is dependent on the relative location of the point on the surface, the observer, and the light source. Both the retroreflectance and the forward reflectance were measured. The reflectance is defined as retroreflectance when the light source and observer are on the same side as the point of interest on the surface and as forward reflectance when the observer and the light source are on opposite sides of the point of interest. Figures 10 and 11 show the retroreflectance and forward-reflectance characteristics of the test surfaces. Forward-reflectance measurements were made at observer-source separation distances of 60, 120, and 240 m (200, 400, and 800 ft) to cover a range of combinations of the incident, reflected, and horizontal angle. (The reflectance data were obtained in summer of 1973, a year earlier than the other data were collected.) Farber and Bhise (18) give more details of the reflectance measurement procedure.

RESULTS

All Blackwell and Ford model predictions were made by considering contrast thresholds of 99 percent detection probability, because practically no false detections were observed in the field tests. The problem of determining the accuracy of seeing-distance predictions was approached by comparing the average field-observed and predicted performances of the 12 subjects as a "group" rather than as individuals. In addition to providing analytic simplicity and improved statistical validity from the counterbalanced experiment design (Table 2), such an approach was justified because no statistically significant interactions between (a) subject and target-background conditions and (b) subject and beam patterns were found. The above result is important since it shows that performance differences between individuals are due solely to differences in their basic visual capabilities. Such differences can be largely accounted for by applying contrast multipliers (14, 24) to adjust contrast thresholds. Therefore, it can be stated that, if the visual performance of a group of subjects can be predicted, the visual performance of an individual can also be predicted by using the same model with a different contrast multiplier.

The means and standard deviations of the field-observed seeing distances presented in this section were, therefore, obtained by pooling the seeing distances of the 12 subjects for each target-background condition (as given in Table 1) under each beam pattern.

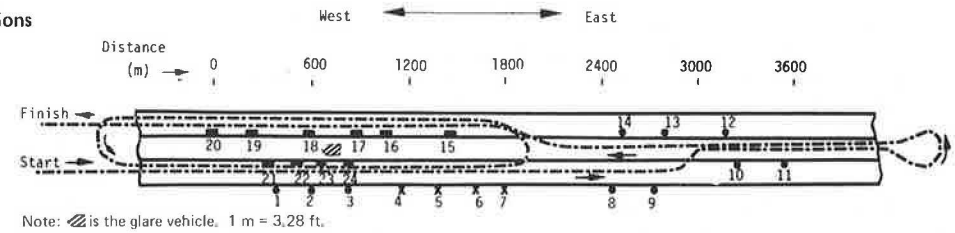


Figure 3. Track layout showing locations of targets and glare vehicle.

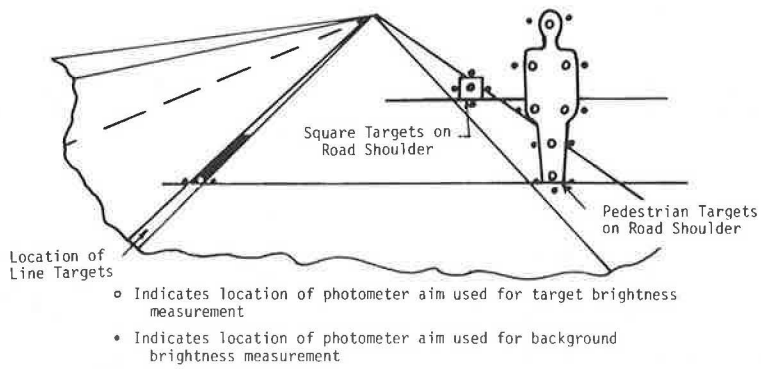


Figure 4. Target setups used for target and background brightness measurements.

Table 2. Head-lamp beam pattern in subject testing sequence.

	Session 1			Session 2		
Subject	Lap 1	Lap 2	Lap 3	Lap 1	Lap 2	Lap 3
1	L	H	L + H	L + H	H	L
2	L + H	L	H	H	L	L + H
3	H	L + H	L	L	L + H	H
4	L	L + H	H	H	L + H	L
5	L + H	H	L	L	H	L + H
6	H	L	L + H	L + H	L	H
7	L + H	L	H	H	L	L + H
8	H	L + H	L	L	L + H	H
9	L	H	L + H	L + H	H	L
10	L + H	H	L	L	H	L + H
11	L	L + H	H	H	L + H	L
12	H	L	L + H	L + H	L	H

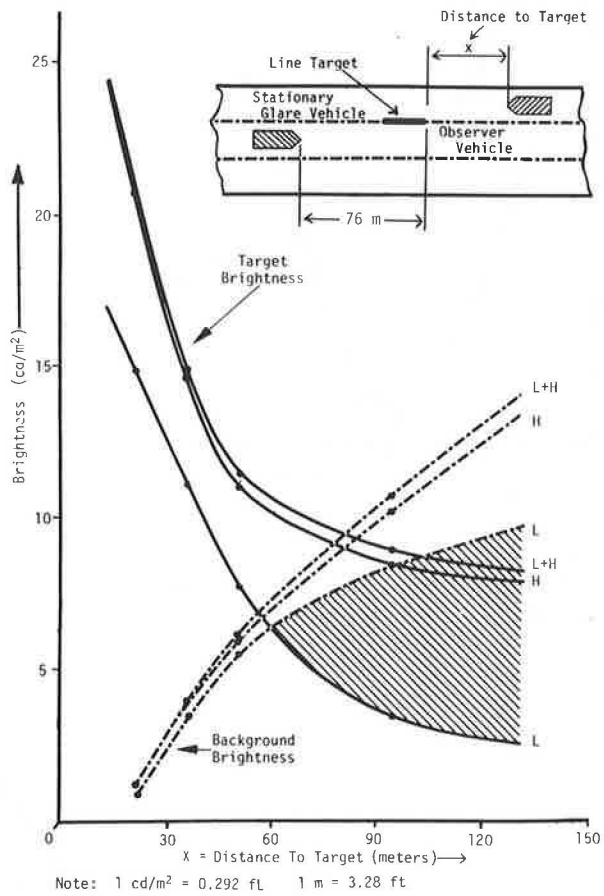


Figure 5. Brightness of background and line targets as a function of observer distance from target located 76 m from glare vehicle.

Detection With No Opposing Glare

Pedestrian Targets

Figure 12 shows the means and limits of one and two standard deviations of seeing distances observed for the 8, 15, and 25 percent reflectance pedestrian targets. These targets (targets 12, 13, and 14 in Figure 1) were purposely placed in the middle lane to provide concrete as the background for their lower portion. The average detection performance of 12 subjects was predicted by using the Blackwell formulation (based on directly measured brightness values) and the Ford model (based on completed brightness values). The Blackwell predicted seeing distances for the pedestrian targets for each condition are shown in Figure 12 by stars for the Blackwell formulation (no age correction factor is used in obtaining the Blackwell predictions), and by large black dots for the Ford model. The relative differences between the field-observed mean and seeing distances predicted by the models for each pedestrian target condition shown in Figure 12 are, in general, well within the two standard deviation limits around the field-observed mean corresponding to each target condition.

Line Targets

Figure 13 shows the mean values of the field-observed seeing distances with one and two standard deviation limits for the three types of line targets for the three different beam patterns. When the Blackwell model was used to predict the average seeing distance to the line targets, the predicted seeing distances were 30 to 60 percent lower. Considering this finding, along with the

previous finding that the seeing distances to the pedestrian targets could be predicted by using the Blackwell thresholds obtained under $^1/_{30}$-s exposure, it appears that the difficulty of detecting a line target is less than that of detecting a pedestrian target. Therefore, additional model runs with different contrast multipliers (K_M) to the Blackwell threshold contrast were made to determine the value of a contrast multiplier that would predict the field-observed seeing distances to the most line target types under the three different beam patterns. The resultant contrast multiplier was 0.2. This means that, when the target contrast C exceeds $0.2\hat{C}$, the line target could be detected. Multiplying the Blackwell $^1/_{30}$-s exposure contrast thresholds ($\hat{C}$) by 0.02 is equivalent to lowering the threshold curves in Figure 1 by approximately 0.7 log-contrast units. The set of contrast threshold curves thus obtained closely resembles the contrast threshold data obtained by Blackwell (3) for $^1/_{30}$-s exposure. The Blackwell contrast thresholds decrease with increase in target exposure.

Figure 6. Brightness of background and line targets as a function of observer distance from target located 213 m from glare vehicle.

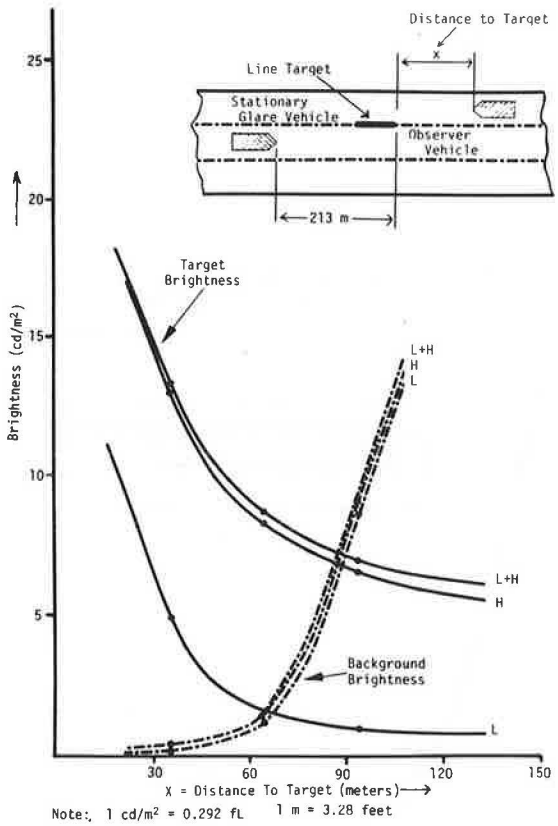


Figure 7. Brightness of background and line targets as a function of observer distance from target located 365 m from glare vehicle.

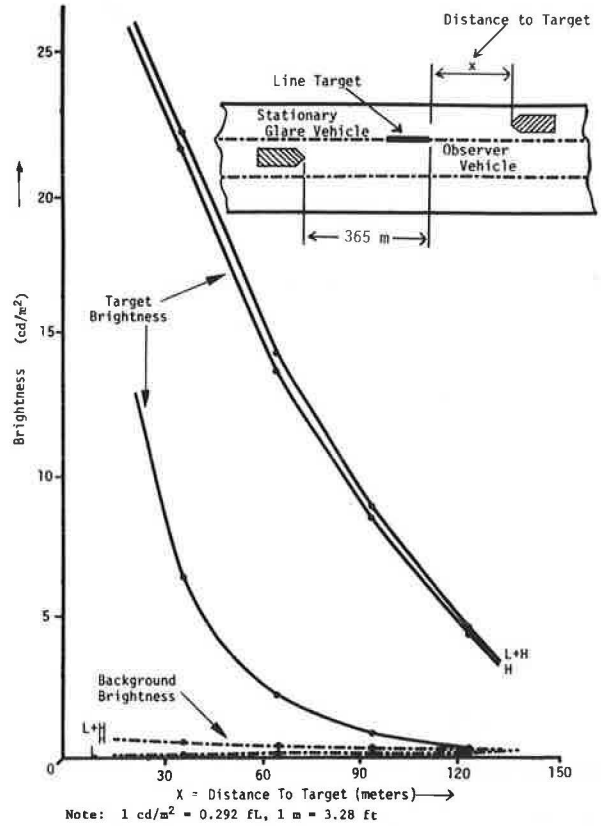
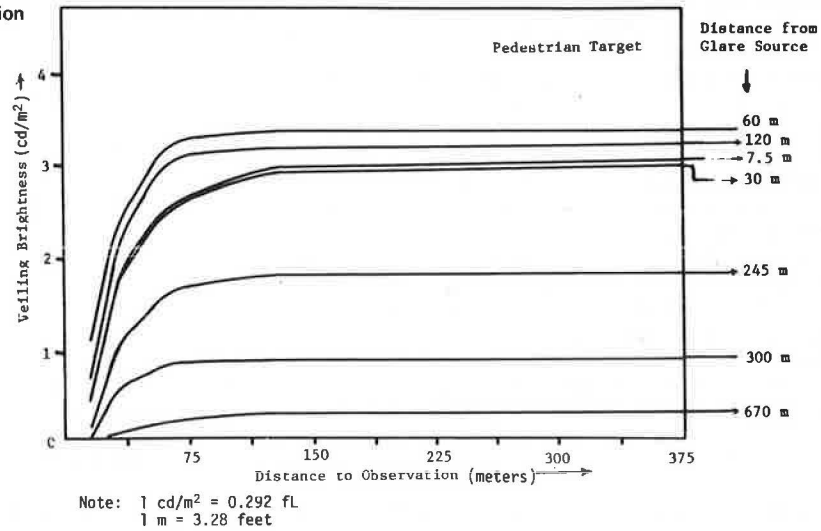


Figure 8. Veiling brightness as a function of observation distance to pedestrian targets and distance from glare source.



The Blackwell seeing distances indicated by stars in Figure 13 are, therefore, predicted by applying the 0.2 contrast multiplier factor. The Ford model predictions shown in Figure 13 are also made by applying the same contrast multiplier.

Square Targets

Figure 14 shows field-observed seeing distance to the four 1-ft square targets and the seeing distances predicted by the Blackwell and Ford models. Since the background reflectance of these targets increased rapidly with distance (Figure 10) for the low-reflectance targets (i.e., 6.6 and 11.2 percent reflectance targets) under the high and high plus low beams, the contrast changes from negative to positive, and the Ford model predicted multiple detection distances. At greater distances the low-reflectance targets appear darker than the background. As the distance between the target and the driver decreases, a point of null contrast is reached and later, at shorter distances, the targets appear brighter than the background. For example, the 6.6 percent reflectance target under the high beam was found to be visible between 0 to 68 m (0 to 225 ft) when it appeared brighter than the background and between 91 to 236 m (300 to 775 ft) when it appeared darker than the background. The field data, however, show that most detections occurred when the target was brighter than the background. The relative target visibility, defined as a ratio of the actual contrast to the required contrast, computed as a function of distance by the Ford model, is consistent with this finding. The average relative target visibility was higher under the positive contrast conditions that occurred at the shorter distances than the negative contrast conditions that occurred at longer distances.

Detection Under Opposing Vehicle Glare

Pedestrian Targets

Figure 15 shows the field-observed and model-predicted seeing distances to the pedestrian targets located on the right shoulder and at different distances from the glare source. The veiling brightness used in the Blackwell model was measured directly by using the Fry integrator lens. However, since the Fisher and Christie (6) formulation of the veiling brightness takes into account the driver age, the Ford model predictions were initially

Figure 9. Veiling brightness as a function of observation distance to line targets and distance from glare source.

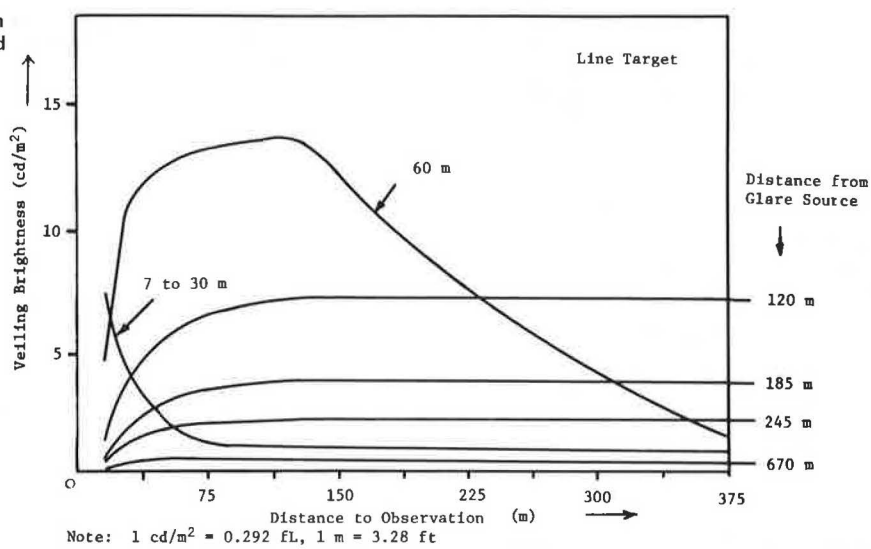


Figure 10. Retroreflectivity coefficients of test track surfaces as a function of distance.

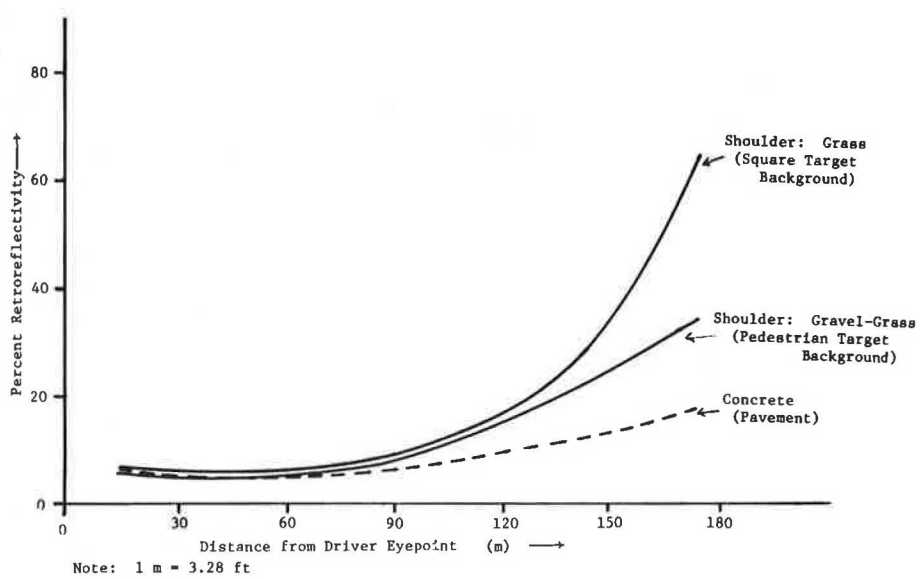


Figure 11. Contours of constant forward reflectivity based on separation of observer and glare lamp.

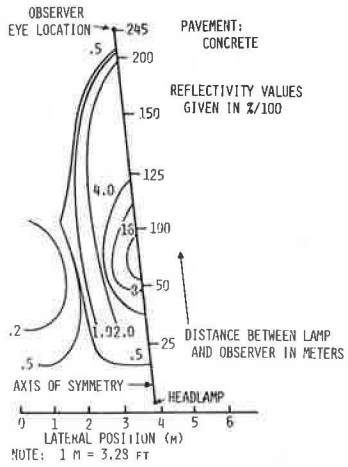


Figure 12. Comparison of field-observed and predicted seeing distance to pedestrian targets.

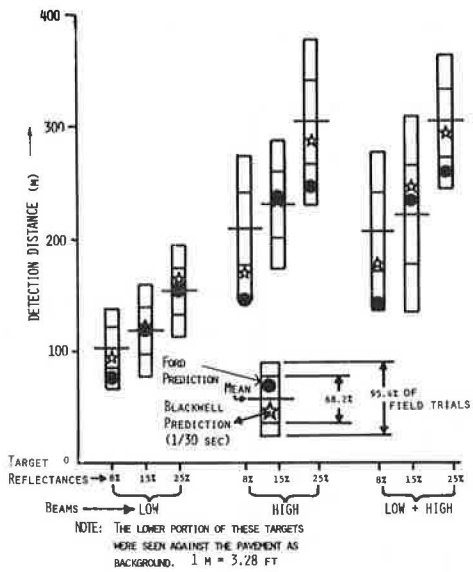


Figure 13. Comparison of field-observed and predicted seeing distances to line targets.

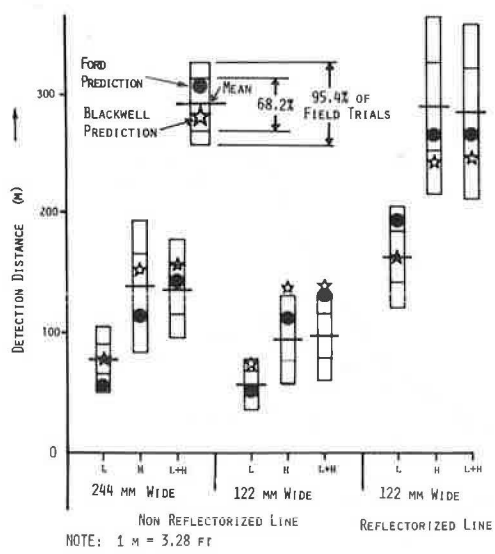


Figure 14. Comparison of field-observed and predicted seeing distances to square targets.

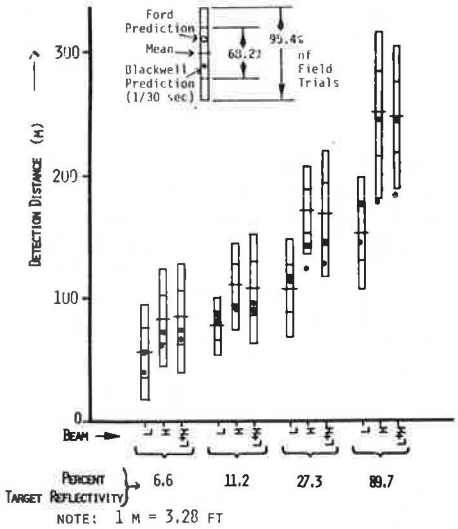
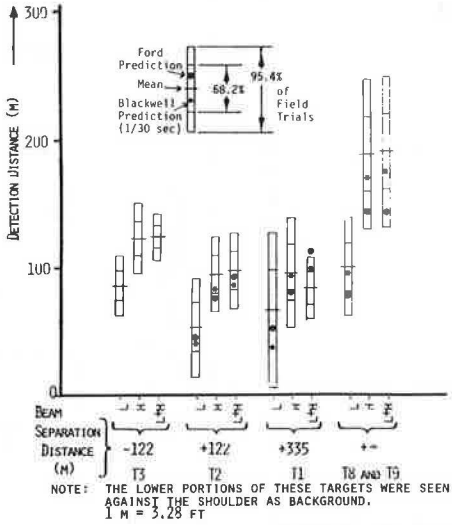


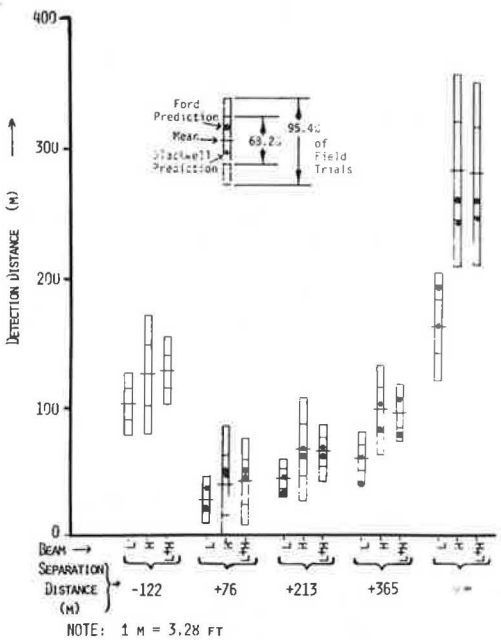
Figure 15. Comparison of field-observed and predicted detection distances to pedestrian targets under glare.



made to test its applicability. The seeing distances predicted by using the Fisher and Christie expression were found to be considerably less than those based on the Fry expression because the Fisher and Christie veiling brightness values were about 150 to 900 percent of those obtained by the Fry formula. The Fry formulation was, therefore, retained in the Ford model for all seeing-distance predictions made under the presence of the disability glare. Thus, the veiling brightness used in the Ford model was not functionally related to the driver age.

Figure 15 shows that, for the pedestrian targets at 120 and 335 m (400 and 1100 ft) in front of the glare source, all except one Blackwell and one Ford prediction were within one standard deviation of the mean field-observed seeing distances. Both the Blackwell and Ford predictions shown in the figure were obtained by using the Blackwell $1/30$-s exposure data. The standard deviations of field-observed seeing distances obtained under the low

Figure 16. Comparison of field-observed and predicted detection distances to reflectorized line targets under glare.



beam and under the opposing glare were much larger than the standard deviation obtained at corresponding distances under the high beam. This fact could probably be explained by considering the simultaneous spatially separated informational demands on the driver of maintaining lateral control and detecting a target with low potential visibility.

The seeing distance to the target placed 120 m (400 ft) behind the glare vehicle was not predicted. It was felt that, in spite of the instructions to watch for the target, the subjects either did not or could not begin to search for the target before passing of the glare vehicle.

Line Targets

Figure 16 shows similar data for the 122-mm (4-in) wide and 15.24-m (50-ft) long reflectorized line targets. Initial predictions made by using the Blackwell model with $\frac{1}{3}$-s exposure data (i.e., $\frac{1}{30}$s with 0.2 contrast multiplier) and veiling brightness as computed by the Fry formula gave seeing distances that were much higher than those observed under the field tests. This was thought to be due to two reasons: The line targets were located on the left side of the driver, and thus the glare angles subtended between the target and the closest glare head lamp were smaller than 0.75 deg. The Fry formula is not applicable to angles smaller than 0.75 deg. It is extremely difficult to evaluate effects of disability glare at glare angles less than 0.75 deg because the nonvoluntary tendency of the human eye movements, which is commonly referred to as glare reflex, becomes especially predominant at such small glare angles. This further affects adaptation of the eyes and thus the detection thresholds.

Therefore, to account for the combined effects of smaller glare angles on veiling brightness estimation and transient adaptation, several Blackwell model predictions were made with different contrast multipliers. Blackwell predictions made with a contrast multiplier of 28.18 on $\frac{1}{3}$-s exposure Blackwell data (i.e., by addition of 1.45 log contrast units) or with a contrast multiplier of 5.62 on $\frac{1}{30}$-s exposure Blackwell data (i.e., by addition of 0.75 log contrast units) were in close agreement with the field-observed data. A contrast multiplier of 28.18 on the line target detection (with $\frac{1}{3}$-s exposure) was also incorporated in the Ford model, and the predictions thus obtained are shown in Figure 16.

Effect of Foreground Illumination

One of the reasons for employing the high (H) and low plus high (L + H) beam patterns was to determine the effect of foreground (i.e., near) brightness on the detection distant targets. Four separate analyses of variance conducted on combinations of two target types (i.e., 8 percent reflectorized pedestrian versus reflectorized line) and two glare levels (i.e., glare versus no glare) showed that seeing distances obtained under the high beam as compared to those obtained under low plus high beam were not statistically different (at significance probability ≤ 0.10) under the four conditions. This result does not support the decrement in seeing distances observed by Hull and others (20) by adding low beam illumination to the high beams. The data shown in Figure 16, however, suggest that the variability in seeing distances obtained under glare of the line targets under the low plus high beam is smaller compared to the variability under the high beam. The seeing-distance data obtained under glare for the pedestrian targets, however, failed to show such an effect.

DISCUSSION OF RESULTS

The absolute difference between the predicted (Blackwell) and mean seeing distances when averaged for the 51 test conditions (17 target-background-glare conditions and three beam patterns) was 19.2 m (63 ft) or about 13 percent of the mean seeing distances. The corresponding figures for the Ford model predictions were 20.7 m (68 ft) or about 14 percent. Expressed as a percentage of the mean, the standard deviation for the individual test conditions when pooled over all test conditions was 20 percent. The basic variability in the field seeing-distance measurement obtained from the standard deviation of intrasubject variations (i.e., the seeing-distance variation for a single subject over repeated detections averaged for all the test situations) was 13.53 m (44.4 ft), or about 10 percent. These results clearly demonstrate the applicability of fundamental contrast threshold data to the night-driving situation. Nevertheless, further research is certainly warranted to improve and extend the seeing-distance prediction capability. Particular issues are discussed below.

In this research the problem of nonhomogeneous target and background brightness found under head-lamp illumination was considered in the Blackwell model simply by using the photometered values of both target and background brightness as a function of distance. The Ford model actually computed these brightness functions from nonuniform characteristics of the background reflectance and the head-lamp intensity. In the Blackwell model, the predictions were made by computing contrast by averaging the brightness on and around the target. In the Ford model, the predictions were made by computing contrast at the base of small targets, such as the square targets beyond 76 m (250 ft) and the line targets (i.e., targets with glare angles smaller than 15 min); for the pedestrian targets, the contrast was obtained by averaging brightness on and around the pedestrian's shoulder and foot level. The prediction accuracy obtained in this research by using such simple contrast computation procedures was probably because the targets employed were relatively simple and had a low degree of nonhomogeneity. The extension of these models to real-world targets with

high complexity and nonhomogeneity would require further investigations; possibly Morris' proposal (22) of dividing target area in several parts and determining the visibility of total target on the basis of visibility of different parts could be used. The real driving situation is still more complicated by the extreme mobility of the eye fixation point, and this is particularly important under opposed glare driving situations where large abrupt changes in foveal adaptation occur.

The extensive laboratory research available in the literature has shown that the target detection thresholds can be adjusted by using the simple concept of a contrast multiplier to account for factors such as target shape, uncertainty in temporal and spatial aspects of target appearance, transient adaptation, and driver alertness (9, 10, 19, 23). Our field research has developed a few contrast multipliers to account for situations such as the detection of delineation targets and detection of targets under opposed glare encounters with glare angles smaller than 0.75 deg. Further investigation of these and many other factors is needed to validate and extend the applicability of the laboratory findings to include a variety of targets found under the night-driving environment. Some such issues are currently being explored to improve the prediction capability of the Ford model.

CONCLUSIONS

1. The laboratory brightness contrast detection threshold data obtained under $1/30$-s exposure by Blackwell (3) are applicable in predicting seeing distances of alerted drivers to vertical targets under night-driving situations.
2. The Blackwell (3) data are also applicable in predicting seeing distance to horizontal, i.e., road surface, targets. The detection thresholds to delineation lines are, however, lower as compared to the threshold for stand-up targets.
3. The Blackwell (3) model along with Fry's (17) veiling glare formula to account for disability glare can predict seeing distances to targets under opposed glare situations when the glare angles are larger than 0.75 deg.
4. For glare angles smaller than 0.75 deg, a contrast multiplier of about 30 appears appropriate for seeing-distance prediction under high-beam situations.
5. The seeing distance to targets under any headlighting beam can be analytically predicted with sufficiently good accuracy from the following: (a) headlamp characteristics, e.g., isocandle patterns of each lamp, lamp aim, cleanliness or transmission of the lamp lens, and location of lamps; (b) photometric and geometric characteristics of the roadway, e.g., pavement and shoulder reflectance, and ambient brightness conditions; (c) driver characteristics, e.g., age and eye height; (d) target characteristics, e.g., size, shape, and reflectance properties; and (e) laboratory brightness contrast threshold data, veiling glare formulation, and contrast multipliers to account for factors such as target complexity and transient adaptation.

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Discussion

R. J. Donohue, General Motors Corporation

Although many field studies, predictions, and computer computations have been made through the years to evaluate the performance of forward illumination systems on motor vehicles, a new comprehensive approach to predicting target distances is always welcome. Having participated in the "midnight shift" of headlight evaluation many times and having digested numerous accounts of performance evaluations of headlight systems, I welcome the opportunity to discuss the recent research of Bhise, McMahan, and Farber.

This work is an attempt to apply the basic laboratory detection data of Blackwell and combine it with other pertinent factors to produce a predictive model for three basic targets: a gray square, a pedestrian target, and line stripes on the road. The authors take an approach in which the drivers are alerted to the approximate location and type of the approaching target. Consequently, the driver's eye is used as a photosensor and recognition instrument, and the study does not determine driver behavioral characteristics while viewing or searching for roadside objects. This approach is appropriate for attempting to define the maximum capability of drivers with respect to the target, the background, and the candidate forward lighting systems and perhaps will place an upper bound on the performance of those illumination systems.

TEST CONDITIONS

The head lamps chosen were a "standard" low beam and an "improved" high beam. An analysis of the data would benefit from a better definition of the headlight beam patterns, particularly the high beams for which only a range of peak intensity is quoted. Also, the type of high beam used on the glare vehicle is not identified.

The test subjects chosen range in age from 25 to 48, but no "older" subjects were used. Since the effect of age on visual capability is a factor included in the Ford model, a comparison of measured versus predicted seeing distances as a function of age, particularly under glare conditions, would be interesting.

Finally, I presume that the high beam was chosen as a glare source for centerline detection to provide a worst case situation. However, it would appear that in actual driving conditions opposing vehicles should have low beams on rather than high beams and drivers would be looking for a right lane edge or edge marking rather than into the glare at the center stripe. I would hope that subsequent tests would include the right edge stripe visibility.

PEDESTRIAN TARGETS

The detection distances for three reflectances of the pedestrian targets for the low, high, and low plus high beams show that the Ford prediction values are within two standard deviations of the average measured detection distances, and, as a matter of fact, the Blackwell and Ford predictions are fairly accurate for the low beam. However, considerable disparity exists between the Blackwell and Ford predictions for high and combined low plus high beams. On the scale chosen to describe the results, the relation between the Blackwell, Ford, and average measured seeing distances and the reflectance values is almost linear. For high beam and low plus high beam, the Blackwell predictions and the measured values remain linear with reflectance while the Ford predictions are much smaller than either the 15 or 25 percent reflectivity values. It would be interesting to see the mathematical rationale for the two discrepancies.

LINE TARGETS

Unfortunately the predictive equations and data used for the pedestrian targets did not apply to the line targets. A new contrast multiplier was empirically determined in order to apply both the Ford and the Blackwell models to these detection distances. The following would influence the ability to predict the stripe distance: The stripe is located on a horizontal plane about 0.6 m (2 ft) below the head-lamp axis. Consequently, because of the small angle of light incidence and small angle of driver view, the directional reflectivity of stripe and background is critical and may be difficult to measure accurately. Also, any pitch of the moving vehicle could cause large variations of the amount of road surface exposed to higher intensity light. For example, an upward pitch angle of less than 0.1 deg could move a headlight intensity point 15 m (50 ft) down the road. However, without a knowledge of the vibration characteristics of the test vehicle on the road used, it is difficult to assess this effect. I presume that the center of the road is defined by a crack or tar strip. If this is the case, perhaps the driver's eyes can be "led" to the line target since the road center division defines the lateral position of the line and since the line is an extension of the road center division.

SQUARE TARGETS

The Blackwell predictions are fairly accurate for both low and high reflectivity square targets. The prediction by the Ford model, however, of a much greater detection distance with high beam plus low beam than with high beam alone puzzles me. It would be interesting to determine the reason for the discrepancy of prediction versus experimental data. The predictive values of the high reflectivity square are also of interest. The Ford model predicts values for high beam and low plus high beam well above those detected, while the Blackwell model predicts values below those detected. It would appear that some of the reasons for the anomaly between the two models might be extracted from a closer examination of the analysis of these data.

TARGETS UNDER OPPOSING VEHICLE GLARE

In this series of experiments, the predictions are fairly close to the mean detection distances for a glare vehicle 122 m (400 ft) behind the target with fair prediction but increased scatter for the detection distances with the glare vehicle 335 m (1100 ft) behind the target. The authors state that the anomalously large spread in seeing distances with low beam under glare conditions is

caused by the separated demand on the driver of maintaining lateral control and detecting a target with low potential visibility. This obviously has some effect on the results, but it would appear that the driver would be looking at the right side of the road anyway (where the pedestrian target is located) and would be maintaining his lateral control from that side of the road. Perhaps the spread is due to the glare effects on the different drivers. I think a replot of the detection values separately by drivers over their three individual runs might clear up this question.

LINE TARGETS UNDER GLARE CONDITIONS

The last comment with respect to the pedestrian targets under glare also can apply to the line targets under glare. For example, it appears from the large spread of the data that some subjects had a more difficult time observing the line with a high beam than with a low beam; in other words, the spread of detection distances with high beam is considerably greater than that with low beam and even extends to zero on the ordinate. It would be interesting to have observed the eye movement characteristics and the general glare sensitivity of those test subjects. The need to readjust empirically the contrast multipliers indicates that the Ford model to date cannot account for varying conditions without resorting to redefinition of the application of the laboratory data to the field data.

SUMMARY

It is interesting to note that the large seeing distances available to the "alerted driver" are somewhat consistent with values obtained by Hemion at Southwest Research Institute, are slightly larger than seeing distances that we have measured at the General Motors Proving Ground, and are considerably greater than the values measured and computed by the Highway Safety Research Institute (HSRI). Hemion's measurements, of course, were made in the clearer air of southwest Texas. Our measurements were made in the Midwest, where clarity of vision at night is not so great as that in San Antonio. Finally, the values measured by HSRI represent the identification of a specific characteristic of the target and could be interpreted as lower bound values on the performance of the head lamp. Therefore, the predictive technique developed by the Ford researchers presents an opportunity to compute upper bound values on performance since they compare with the alerted-driver measured values. The reason for the wide spread of values obtained for the nonreflective and reflective delineator lines, particularly with the glare vehicle approaching, would be worth determining. Is the variance in seeing distances caused by differences in drivers, or are there large variations between successive data for the same driver? Also, what are the effects, if any, of head-lamp aim, vehicle attitude, and road surface conditions? Since, most likely, the driver under this set of circumstances would be looking to the right edge of the road for his lateral guidance and since the contrast presented by the edge of the road or by an edge line is the most critical information transmitted back to the driver by the head-lamp illumination, the visibility of the right edge marking should also be measured.

I am particularly pleased to see the application of the contrast ratio of objects to head-lamp performance measures. Contrast ratio defines the perceivability of illuminated objects by the driver; without an adequate contrast ratio, no amount of head-lamp illumination will make an object visible. We cannot overemphasize the importance of keeping this relation among driver, vehicle, and environment in focus when applying performance measures to automobile forward lighting.

Roger H. Hemion, Southwest Research Institute

The authors of this paper are to be congratulated for their development of a headlight performance predictor that, although not simple, takes into consideration all of those factors that seem to have been covered by assumptions in the past. I am particularly pleased to see that the illumination falling on the target is considered by analyzing the beam-pattern characteristics rather than by calculating total lamp output or its maximum beam candlepower. Thus, a true resolution of the light falling on the target and on the roadway and shoulder areas can be developed. The importance of this has been recognized in this approach. I have only a few minor points to raise, but feel they should be considered, particularly in view of the inclusion of the many other effects necessary to completely define analysis by the authors.

The first point involves the additional detection distance resulting from the reaction delay of the observer between the time he actually sees the target and the initiation of the electronic circuit, stopwatch, or other mechanism that measures the detection distance. Our measurements of reaction times of observers for "push-button" operation show normal time of 0.20 to 0.40 s for an alerted response. If this is not considered, at 72 km/h (45 mph), the test speed used here, this would mean an undermeasurement of 4 to 8 m (13 to 26 ft). For an unalerted observer, a reaction time in excess of 1 s would not be unusual. In some of the measurements with the alerted observers used in this study, this could mean a difference approaching one standard deviation and in any case is an effect that can and should be compensated for.

The authors' statement relative to the lack of observation of a decrement in detection distance of L + H lighting over H lighting alone when no opposing glare vehicle is present is not borne out by their data. Except for the 102-mm (4-in), nonreflectorized line in Figure 13, the 6.6 percent reflective square target in Figure 14, and the pedestrian target in Figure 15, the mean observed detection distances, as plotted, for L + H are lower than for H alone when the opposing glare vehicle is not present (Figures 12, 13, and 14 and the $+\infty$ values in Figure 16). Certainly, we would agree that the disability veiling effect of increased foreground lighting resulting from the addition of the low beams would be insignificant and undetectable when an opposing glare vehicle is present. The effect we observed in our studies does appear to be present here as well, although not to the same degree, owing undoubtedly to the differences in the head lamps used. Logically, such an effect as this would seem to be consistent, inasmuch as greater foreground lighting should produce more disability veiling.

Further, the statement relative to the search for the pedestrian target not being possible until passing the glare vehicle when it was 122 m (400 ft) in front of the target is not supported by Figure 15. This figure shows mean detection distances of more than 122 m (400 ft) for the H and L + H lighting modes, which means that more than half of the observations must have been beyond 122 m (400 ft). This cannot, therefore, be accepted as justification for not attempting to predict the detection distance, as was stated.

Adel A. Ayad, Structures and Materials Laboratory, National Research Council of Canada

A seeing-distance model can provide correlations with real-world experiments if the photometric input data are valid for the real world and the obstacle and background luminance values are used in a consistent manner with respect to the observer's performance data and the correlation conditions. Accordingly, in obstacle detection studies, such as undertaken by the authors, two different types of data are required: purely physical (or engineering) data and psychophysiological (or human performance) data.

With regard to the first type of data, most certainly no possible disagreement among different researchers should arise. However, this is only possible if all independent variables affecting scene luminance are properly isolated and correctly measured. Although there is little disagreement with the engineering independent variables listed by the authors, we would have liked to see a clear reference to the differences that may arise between calculated data and the values that exist in situ, especially for the following variables:

1. Variables affecting the photometric characteristics of the test and glare vehicles, i.e. head-lamp isocandelas, head-lamp aim, and operating voltages and roll and pitch of vehicles; and
2. Physical characteristics of the targets and surrounds, i.e., target sizes and retroreflectance properties, and retroreflectance and forward reflectance properties of pavement and surrounds.

Considering these variables, unless stringent experimental quality control procedures are used together with an adequate methodology for the measurement process, it can be difficult to correlate calculated values by using laboratory measurements with field-measured values.

An example of the type of inconsistencies that arise between calculated and measured luminance values as a consequence of weak quality control procedures is evident in the authors' final results (Figure 12 through 16). In this case, predicted seeing distances obtained from the Blackwell model are shown together with the values obtained from the Ford model. The former model uses field-measured luminance values, and the latter uses calculated luminance values from head-lamp isocandelas. Since both models use the same observer performance data, they should lead to identical results if the calculated luminance data were consistent with the measured data. However, in the authors' case they do not!

This inconsistency is partially due to the fact that the isocandela maps used were not the ones for the vehicle head lamps used in the field. However, even if the proper isocandelas for the lamps were known, knowledge of the operating conditions in the field (i.e., vertical aim and voltage) is still necessary to establish the current values for the variables in order to achieve correlation between the calculated and field-measured luminances and illuminances. In particular, the question of vertical aim is particularly crucial since it can be shown that, for a typical low beam, vertical aim changes of $\pm\frac{1}{4}$ deg may lead to changes in illuminance of more than 100 percent (25). It should be stressed that $\frac{1}{4}$-deg changes in aim are typical of variations in vehicle pitch as affected by loading, tire pressures, and pavement waviness.

Another source of inconsistency will arise in the luminance data. This can be inferred by examining the reflectance data used by the authors. In this case, the pavement and surround data obtained in the field a year earlier are used concurrently with nominal target reflectance values, and this might lead to inconsistencies in the luminance difference values ΔL, which are necessary for the calculation of detection distances. For example, the pavement retroreflectance values given in Figure 10 increase by more than 300 percent over 152 m (500 ft), and the corresponding surrounds values increase by 1400 percent over the same distance. This phenomenon is likely to be due to atmospheric backscattering, which affects the whole visual scene, i.e., pavement and target obstacles alike (2).

There are indications that this question has been overlooked and that the pavement and background reflectance values, B, have not been corrected for atmospheric backscattering. As a consequence, the calculated luminance values, obtained by multiplying B with the appropriate values of illuminance, are not consistent with the target luminance values obtained by using nominal target retroreflectance values (8, 15, and 25 percent), which by definition are not affected by atmosphere since they are laboratory values. It should be understood that the corresponding effect on the luminance difference values can be quite large.

In concluding, there is no a priori disagreement with the use of a computer model to derive detection distances in visibility studies nor with the photographic technique used to record scene luminance in the Ford study. The latter technique, pioneered at the National Research Council of Canada, has proved to be a useful tool for the understanding of many phenomenological aspects related to the night-driving problem (26); the powerful data manipulation aspects associated with the use of a computer have been previously recognized by the International Commission on Illumination (27, 28). However, the results of any calculation are only as valid as the input data used with respect to their correlation with the real world.

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Many variables need to be considered in an attempt to develop and evaluate motor vehicle headlighting systems. Unless a sufficient variety of conditions are used for head-lamp evaluation, inappropriate conclusions may likely be drawn as to the most desirable type of head-lamp photometric characteristics when meeting another vehicle or when driving without opposing traffic. For these reasons, it has been recognized that a head-lamp performance evaluation technique that does not rely only

on field testing would be highly desirable. Among the early pioneers in this effort were Jehu and De Boer (11, 25). These researchers were keenly aware of the need to compare the predictions made by their analytical methods with results from field-test situations. More recently, an extensive research program was undertaken by Mortimer and others (27) at the University of Michigan, who used the basic technique described by Jehu (11) and expanded it in a number of important ways. Besides developing an analytical model, these researchers carried out extensive field tests using numerous and different headlamp beams and road geometric situations to provide a large bulk of experimental data against which to compare the findings of their model for validation purposes.

The authors have used an alternative approach by employing the basic data that evolved in the studies conducted by Blackwell (3) concerned with contrast thresholds. There are certain important advantages to be potentially gained by that approach since it would allow the evaluation of a variety of different types of targets, if they can be described adequately in terms of their reflectance, size, location, and the photometric properties of their backgrounds. A disadvantage of the approach is that Blackwell's data were collected in laboratory test situations and used clearly specified types of targets and clean backgrounds. Nonetheless, it is believed that the basic approach involved in using Blackwell's data should ultimately be successful. However, in reviewing the data presented by the authors, I feel that they have not yet reached that stage of development where their model can be safely applied to practical situations.

One reason for this may lie in the nature of their field-testing method, which appears to lack the reliability needed for consistent measurement of visibility distances. This is largely due to the type of target used and the task required of the subjects. The subjects indicated when they could just detect the presence of a target as they approach it in a simulation of a night-driving situation. In such tests, subjects frequently report targets in places where none in fact exists, highlighting a problem with a detection task of this type. Guessing and other temporal variables are difficult to control in such situations, and this subject has been the center of discussion in the basic psychophysical measurement literature. Such targets are also sometimes seen in reverse contrast, which adds additional complications to the validation process.

Based on these considerations, but also on a significant amount of work carried out specifically with the intention of deriving a suitable test target for use in headlighting research and model verification, I feel that an identification target would be more desirable and would provide greater consistency in the data.

A high degree of repeatability is necessary in the field test if this is to be used as a baseline against which the output of an analytical model is to be verified. The large variation in the authors' data suggests that the consistency in the test procedure may be inadequate. Certainly, there is a fairly large discrepancy between the predictions made by their model and the field test result, a discrepancy that is considered by this reviewer too large for practical utility, although general trends in the field test data are certainly obtained.

In addition, the authors have reported the results of tests using only three head-lamp beams under three test conditions against which to compare the predictions made by their model. Before their model could be considered to have general usefulness, it would be necessary to demonstrate that it cannot only provide a reasonably good comparison with field test data but also do so in a wide variety of relevant night-driving conditions. Only in this way can the model be evaluated to see how it responds to a gamut of driving conditions involving variations in road geometry, head-lamp location and aim, photometric distribution, effects of glare from an approaching vehicle, and various target locations to the right or left of the roadway. Clearly, more extensive field-test data are required.

An important shortcoming in the model, in its present state, is that it does not attempt to account for transient adaptation effects, which are primarily due to changing levels of veiling glare so that visibility distances cannot be predicted during periods of visual recovery from glare sources.

I believe that the general approach used by the authors will eventually be successful, but at this time their results should be considered as tentative until more effort has been devoted to providing an effective (reliable) and comprehensive field test methodology and until it is demonstrated that the model provides an acceptable degree of error in replicating those conditions.

Authors' Closure

The authors are pleased with the interest in the paper and thank the discussants for their comments. Our closing remarks should not be construed as an attempt to evade all criticism. To the best of our knowledge, this study represents the first comprehensive attempt to demonstrate the general applicability of laboratory contrast threshold data to the problem of predicting highway seeing distances with headlights. In this we feel we have succeeded. Nevertheless, more can be done to further validate and refine the prediction model. We thus look forward to the publication of the work of Ayad and his colleagues, who are pursuing a similar line of inquiry.

The authors believe that the model in its present form can usefully be applied to the problem of predicting seeing distance to various classes of objects under a broad range of environmental conditions. We thus respectfully but firmly disagree with Mortimer's opinion that the model is not yet sufficiently developed for practical application. Mortimer cites test variability and the discrepancies between observed and predicted seeing distances as the reason for his reservations and suggests poor procedure and experimental control as the source of the problem. In particular, he takes strong exception to our use of a detection rather than an identification target. We agree with Mortimer that better experimental precision may be possible with an identification task than with the detection tasks used in the Ford study. However, the variances obtained in the Ford study are generally lower than those reported by Hemion (20), who used a detection target, and lower than or comparable to those reported by Mortimer and Olson (29), who used identification targets. In fact, the standard deviations obtained in the Ford study under unopposed conditions are not much larger than the values obtained by translating Blackwell's laboratory log-contrast threshold standard deviations into seeing distance units (3, 10, 24).

The somewhat larger standard deviations obtained under glare may be attributable to age effects as suggested by Donohue. However, better predictions were obtained by using the Fry B_v expression (7), which does not consider age, than by using the Fisher and Christie expression (6), which does. A more likely explanation is the idiosyncratic behavior of test subjects in their search patterns and tendency to fixate on the glare source and the fact that existing B_v formulations fail to deal with small angles. These factors may also account for the difficulty in pre-

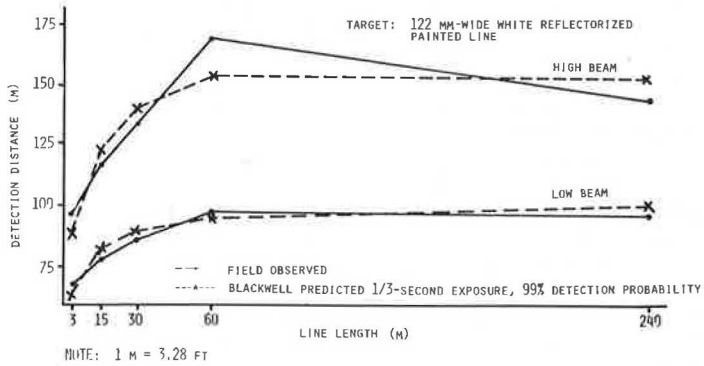

Figure 17. Comparison of field-observed and Blackwell-predicted seeing distances to painted line targets under low and high beams.

dicting seeing distances when the glare source is between the target and the observer.

The identification target favored by Mortimer is seen against an artificial background so that the contrast is uniform and fixed. When a target is seen against a real background, the contrast may vary around the perimeter and also can change with diminishing distance as the observer's vehicle approaches. Since visibility is more sensitive to contrast than to illumination, Mortimer's approach should be more precise than the Ford approach. The disadvantage of an abstract, fixed-contrast identification target is that the seeing distance depends arbitrarily on its photometric characteristics and the nature of the recognition task and thus has no meaningful real-world referent. Also, the relative performance and even the ranking of a set of head lamps can change depending on the target and background characteristics. For these reasons, the authors opted early in the program to risk the loss of some precision in favor of a model having more generality.

With regard to the accuracy of the prediction, 37 of the 51 distances predicted from Blackwell parameters (target and background luminances, target size, and veiling luminance) were at or within one standard deviation of the observed means and only four fell outside a ±2 standard deviation band. In general, the predictions conform well with the observed data: The predicted seeing distances are of the correct magnitude (generally within 15 percent of the observed value), and the relative performance under the various test conditions is preserved by the predictions. This, we feel, constitutes sufficient validation to justify application of the seeing-distance model.

Donohue questions the use of contrast multipliers to adjust the predictions. This should not be a cause for concern. Contrast multipliers have been used in the past in vision research as a simple and effective method for taking task difficulty into account (14, 19, 23).

Highly alerted observers were used because anything less would result in seeing distances with an arbitrary attention component. In our applications of the model we apply a contrast multiplier based on Roper and Howard's (30) study of alerted versus unalerted seeing distances to model the normally attentive driver.

The authors feel that the larger discrepancies between observed and predicted seeing distances arise not from any inherent weakness in the model but from the limitations of the photometry. Ayad's comments probably constitute an adequate explanation of the differences between the empirical data and the Blackwell predictions based on scene luminances. Only one target of each type and reflectance was photometered and this at only one location at the track. Variation in the reflectance gradients and therefore the luminance gradients from location to location in the road surface and grass shoulder are likely the major source of the discrepancies in the unopposed line targets and the square targets. Other sources of variation difficult to control or monitor were ambient luminance, vehicle vibration and aerodynamic pitch effects, and lateral lane position.

Figure 17 shows the results of an earlier pilot study to determine the effect of road line length on detection distances (no glare). In this study each line target and its surround were carefully photometered. The excellent correspondence between the observed seeing distances and the "Blackwell" predictions demonstrates the inherent accuracy of the model when the luminances are well known.

Both Donohue and Ayad cite the discrepancies between the Ford and Blackwell predictions. Ayad's explanation of the differences is probably correct. The Blackwell predictions are based on directly measured luminances; the Ford predictions are based on luminances computed from candlepower and reflectance. The same set of expressions is used with both models to compute seeing distance. Ayad is correct that the differences between the Ford and Blackwell points demonstrate inconsistencies between measured luminance values and the luminances predicted from candlepower and reflectance. Actually, no serious attempt was made to measure the latter parameters. As Ayad points out, we had no isocandelas for the test lamps and used the low- and high-beam isocandelas in our computer files. Thus, the Ford predictions are to be regarded as an exercise, and we had no reason to expect that they would be accurate. Nevertheless, 33 out of 51 of the predictions were at or within one standard deviation of the mean. In any event, the validity of the model rests on the Blackwell predictions, and future applications of the model in no way depend on the accuracy with which reflectance and candlepower were known at the test track. For purposes of comparing head lamps, typical values of these parameters can be measured or assumed, and the resulting seeing-distance predictions will be as valid as the Blackwell predictions from the luminances and the physical laws that translate candlepower into luminance.

We agree in principle with Ayad's comments on atmospheric backscatter effects. However, recent experiments at the test site (prompted by Ayad's comments) to determine the magnitude of atmospheric effects showed their contributions to be less than 25 percent of the measured brightnesses. Since the atmospheric backscatter effects depend on many factors (humidity, air contaminants, temperature, temperature gradients, pavement and surround surface reflectance, and illuminating beam patterns), there is no reason to believe that the magnitude of these effects observed by Ayad during his field measurements at Ottawa, approximately 320 km (200 miles) north of our test site, would be similar. Our experiments showed that on a typical clear night at Romeo,

Michigan, backscatter introduces no practical error (less than 5 percent) at distances less than 150 m (500 ft); at distances above 150 m (500 ft), the backscatter could increase luminance (or reflectivity) with increase in distance from about 5 percent at 150 m (500 ft) to about 25 percent at 300 m (1000 ft).

The observed effect of the increase in pavement and shoulder retroreflectivity with increase in distance from the point of observation, therefore, is only partly an artifact of backscatter. Finch and Marxheimer's (31) data, collected in a laboratory, also support our observation. Their data were influenced minimally by backscatter effects because of smaller measurement distances and better control over ambient conditions in the laboratory. The pavement reflectivity data presented in Figures 10 and 11 are not corrected for backscatter and therefore represent "effective" rather than "actual" reflectance properties.

However, the errors in seeing distance predictions that the backscatter effect introduces, if it is not properly accounted for, are small—at most 10 percent at distances greater than 150 m (500 ft) and less at smaller distances. Seeing-distance predictions are not so sensitive to errors in photometrics as might be thought. This is because the inverse square law results in rapidly increasing illumination at the target during the observer vehicle's approach, which tends to swamp errors in photometry [for example, 50 000 cd produces the same illumination at 83.2 m (273 ft) as 60 000 cd produces at 91.4 m (300 ft)], and because visibility varies with log contrast and luminance. Thus, increasing low-beam candlepower by 50 percent will result in only a 7 to 15 percent increase in seeing distance to the pedestrian targets. Nevertheless, it is likely that backscatter effects are responsible for some of the prediction error at the longer seeing distances. Incorporating backscatter effects would add substantially to the complexity of the model, and we are not certain that it is worth the cost. We anticipate that more information will be forthcoming from Ayad and his colleagues that will help resolve this issue.

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