# Loss of Visibility Distance Caused by Automobile Windshields at Night

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The Technical literature was reviewed with respect to the loss of visibility distance caused by automobile windshields or other optical filters. A series of nighttime luminance measurements in the field provided baseline data for a visibility distance computer model that was developed to investigate nighttime visibility of diffusely reflective targets under low-beam illumination conditions seen through automobile windshields having different transmittances. The computer model offers three alternative luminance contrast threshold models: (*a*) Adrian's target visibility algorithm, (*b*) PCDETECT, and (*c*) Blackwell's 1946 contrast threshold data. The new model, which is based on Blackwell's 1946 data, considers the effects of age and observation time and determines the actual contrast from the target luminance, which depends on the target reflectance, the selected headlamps, and the current observation distance. Percent visibility distance loss graphs, as a function of the initial visibility distance $D_0$ (using no windshield) were established. A tentative field factor of 2.28 for the Blackwell data was determined. The obtained percent visibility distance loss data were compared with those published earlier by Haber in 1955. This comparison indicates that the percent distance loss functions shown by Haber are misleading and wrong because they are proposed to apply for a target with a constant mean linear dimension of 91.4 cm (3 ft) over the entire initial visibility distance range. Furthermore, the data presented by Haber are conservative and too high. On the basis of the results of this investigation, it would appear to be of benefit to further validate the results in the field and to review the appropriateness of established minimum luminous transmittance standards.

Visibility considerations are highly important in the driving task, as most of the information a driver needs for keeping the vehicle on the road, to drive through curves, to stop at intersections and so forth, is acquired visually. The visual information that is acquired from outside the vehicle must typically pass through the automobile windshield, which may act like an optical filter. Target visibility ahead of an automobile mainly depends on the transmittance characteristics of the windshield, the reflectance properties and linear dimensions of the target, the observer's visual performance, and to a large degree the intensity distribution of the headlamps. The investigation described here examines the loss of visibility distance caused by automobile windshields at night.

## REVIEW OF TECHNICAL LITERATURE

Roper (*1*) and Heath and Finch (*2*) conducted nighttime visibility distance experiments to assess the effects of tinted windshields on visibility distance. Roper used square targets with a side length of 40.64 cm (16 in) and the same uniform reflectance of $R = 0.075$. The experiment was conducted using (*a*) a clear safety plate windshield with a transmittance of $T = 0.883$ and (*b*) a tinted windshield with a transmittance of $T = 0.73$. Initial target visibility distances ranging from 76 to 123 m (250 to 400 ft) were established with the clear safety plate windshield. The tinted windshield resulted in a visibility distance loss of about 5 percent. Heath and Finch (*2*) used targets of different sizes, shapes, and reflectances. Heath and Finch found a reduction in visibility distances of up to 22 percent caused by tinted windshields. On the basis of the results of their study, they concluded that it does not appear to be feasible to assign an overall percent loss value to account for the difference in transmittance between two windshields. However, Heath and Finch pointed out that tinted windshields may significantly reduce the visibility distance.

Haber (*3*) attempted to theoretically analyze the effects of various tinted media on the percent loss of the initial visibility distance $D_0$ (no windshield) for a target having a mean linear dimension of 91.4 cm (3 ft) and a reflectance of $R = 0.15$ under low-beam illumination conditions. Haber used the data from Roper (*1*) and Heat and Finch (*2*) to validate, by extrapolation, the loss percentage of visibility distance as a function of the initial visibility distance $D_0$. However, Haber's approach to extrapolate and validate his percent loss curves into ranges below 61 m (200 ft) and beyond 137 m (450 ft) without having one single field data point available appears to be questionable. The method used by Haber (*3*) to obtain the visibility distance appears to be incorrect and provides visibility distances that are too short. Haber presented percent loss curves for a target having a constant mean linear dimension of 91.4 cm (3 ft) and a constant reflectance. Under illumination from a pair of headlamps having a constant intensity, such a setup will provide 1 percent loss point rather than a functional relationship. To obtain losses of a magnitude given by Haber (*3*) and subsequently published previously (*4*), it would be necessary to shrink the target to a mere 3 cm (0.1 ft) when using a tinted windshield with a transmittance of $T = 0.359$. Such a small target no longer represents a pedestrian and would not likely have to be considered as a major or important road hazard for the establishment of minimum transmittance standards.

Waetjen et al. (*5*) investigated the influence of windshields with different transmittances under various angles of inclination. It was found by the researchers that the windshield angle of inclination only marginally influenced the transmittance $T = f(\text{angle})$. However, at large angles more and more light was found to be reflected specularly off the windshield. Therefore, it was expected that large angles and tinted windshields would provide the shortest legibility distances [they used a Landholt ring with a stroke width of 8.7 cm (3.42 in.) as the target]. The researchers found legibility distances (mean, and standard deviation) of (*a*) 32.2 ± 5.5 m (105.64 ± 18.04 ft) when no windshield was used and (*b*) 26.9 ± 5.1 m (88.25 ± 16.73 ft) for the tinted windshield at the maximum angle of inclination of 70 degrees. This would result in an average loss percent

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legibility distance of 16.45 percent because of a transmittance of $T$ (70 degrees) $= 0.6$. Waetjen et al. concluded, on the basis of their findings, that tinted windshields reduce driver visibility such that they might impose a road hazard, especially if the target is a pedestrian. However, it is unclear why the legibility of a Landholt ring with a stroke width of 8.7 cm (3.42 in.) is brought into relationship to the detection of a pedestrian. A Landholt ring with a gap size of 8.7 cm (3.42 in.) and a height of 43.5 cm (17.12 in.) certainly does not represent a pedestrian.

Freedman et al. (*6*) investigated the visibility of targets, seen through automobile rear windows, of various transmittances using six slide projectors to subsequently present five common roadway objects on screens located about 3 m (9.84 ft) to the rear and side-rear of a simulated vehicle. The results indicate that the probability of detecting the target strongly depends on the target type. Older subjects generally showed a considerably smaller probability of detection. All age groups appeared to have more difficulties detecting the seated child and the bicyclist. On the basis of their findings, Freedman et al. (*6*) concluded that the safety of backing maneuvers may be significantly reduced for all drivers in cars having rear windows with a transmittance of less than $T = 0.35$. These findings appear to be reasonable, considering the typically low illumination of targets in the rear visual search zone of an automobile. It should be noted, however, that the objective of the current study is the visibility of targets in the search zone ahead of an automobile.

Derkum (*7*) conducted a dynamic perception laboratory experiment under simulated nighttime low-beam illumination conditions to determine the minimum permissible transmittance level for automobile windshields. The lowest transmittance without significant decrease in visibility was determined as 68 percent when no glare source was present and 63 percent when glare was present.

Kessler (*8*) investigated the degradation of driver visibility under consideration of the light-scattering properties of worn optical media. Theoretical models that were based on the physics of light scattering were developed. Kessler pointed out that the negative influence of scattered light should be considered in driver visibility.

Hazlett and Allen (*9*) investigated the effects of pedestrian clothing, reflectorization, and driver intoxication on the ability to detect pedestrians at night. The obtained visibility distances for grey, nonreflectorized pedestrians were short. Reflectorization dramatically increased the visibility distances.

Shinar (*10*) studied the nighttime pedestrian visibility, considering the influence of driver expectancy and pedestrian clothing. It was found that the visibility distance increased with expectancy. It was also found that pedestrian reflectorization significantly influenced visibility.

Strickland et al. (*11*) investigated the effects of hyperopia, myopia, and increased optical scatter on the detection of roadway obstacles under low-beam and high-beam illumination conditions. Visibility impairments were found with ametropia and increased optical scatter. High beams appeared to be helpful in improving visibility.

Austin et al. (*12*) studied pedestrian visibility under standard headlamp illumination. On the basis of their analysis, they proposed applicable retroreflective treatments as safety countermeasures.

Zwahlen (*13*) developed a geometric model to analyze reflectorized targets along a tangent-curve and curve-tangent section of a highway. The model demonstrated that unknown or unexpected reflectorized targets may initially appear at moderately large peripheral angles up to 15 degrees away from the foveal fixation point or line of sight. On the basis of a peripheral detection field study, it was found that the detection distance at a peripheral detection angle of 10 degrees was only about one-half of the foveal detection distance.

## OBJECTIVES

On the basis of information mentioned earlier, the objectives of this study were as follows:

1. To examine each step in Haber's theoretical visibility distance analysis;
2. To conduct exploratory field luminance measurements involving targets of different reflectances;
3. To develop an independent visibility distance prediction software package written in the C-language, providing the user with the following three luminance contrast threshold models:
   (*a*) Adrian's target visibility algorithm (*14*),
   (*b*) PCDETECT (*15*) algorithm, and
   (*c*) Two-dimensional, 3rd-order polynomial Lagrangian interpolation (*16*) of Blackwell's 1946 contrast threshold data (*17*) (positive contrast, 6 sec exposure time);
4. To compare the outputs of the newly developed visibility model with the findings of Haber (*3*);
5. To conduct a small target visibility field experiment under low-beam nighttime driving conditions to obtain a tentative field factor. This field factor is required to account for the average performance of a normal observer in a driving situation; and
6. To provide visibility distances and percent loss curves as a function of the initial visibility distance $D_0$, as they can be expected by a typical headlamp pair (6054 headlamps in a 1981 VW Rabbit).

## EXPLORATORY FIELD LUMINANCE MEASUREMENTS

### Objective and Method

The exploratory field luminance measurements were required to provide a basis of reliable target and background luminances, measured on eight different nonretroreflective targets under low-beam illumination conditions at night. The measured luminances were used to validate the algorithms during the development of the visibility distance software package. Note that no glare source was present. A spray-painted black plywood board, a spray-painted reddish dark brown plywood board, a spray-painted blue plywood board, a spray-painted dark yellow-beige plywood board, a spray-painted dark green plywood board, dark brown clothing attached to plywood board, light blue (jeans) clothing attached to plywood board, and a plain plywood board served as targets.

Figure 1*C* illustrates the target setup. The targets 0.6096 × 0.6096 m (1 × 1 ft) were installed 0.3048 m (1 ft) above the pavement. Luminance values were obtained at the positions marked 0 to 5, as indicated in Figure 1*C*, using a Pritchart photometer model 1980*A*, which was located as close to the vehicle as possible (see Figure 1*A* and *B*.) The photometer aperture was selected such that the measured area was about 60 percent of the target area. Note that the photometer was not measuring through the automobile windshield and provided therefore the luminance values that were needed to determine the initial seeing distance $D_0$.

Figure 1*A* shows the setup of the targets and experimental car on the runway of an old, unused airport in Athens, Ohio. Each one of

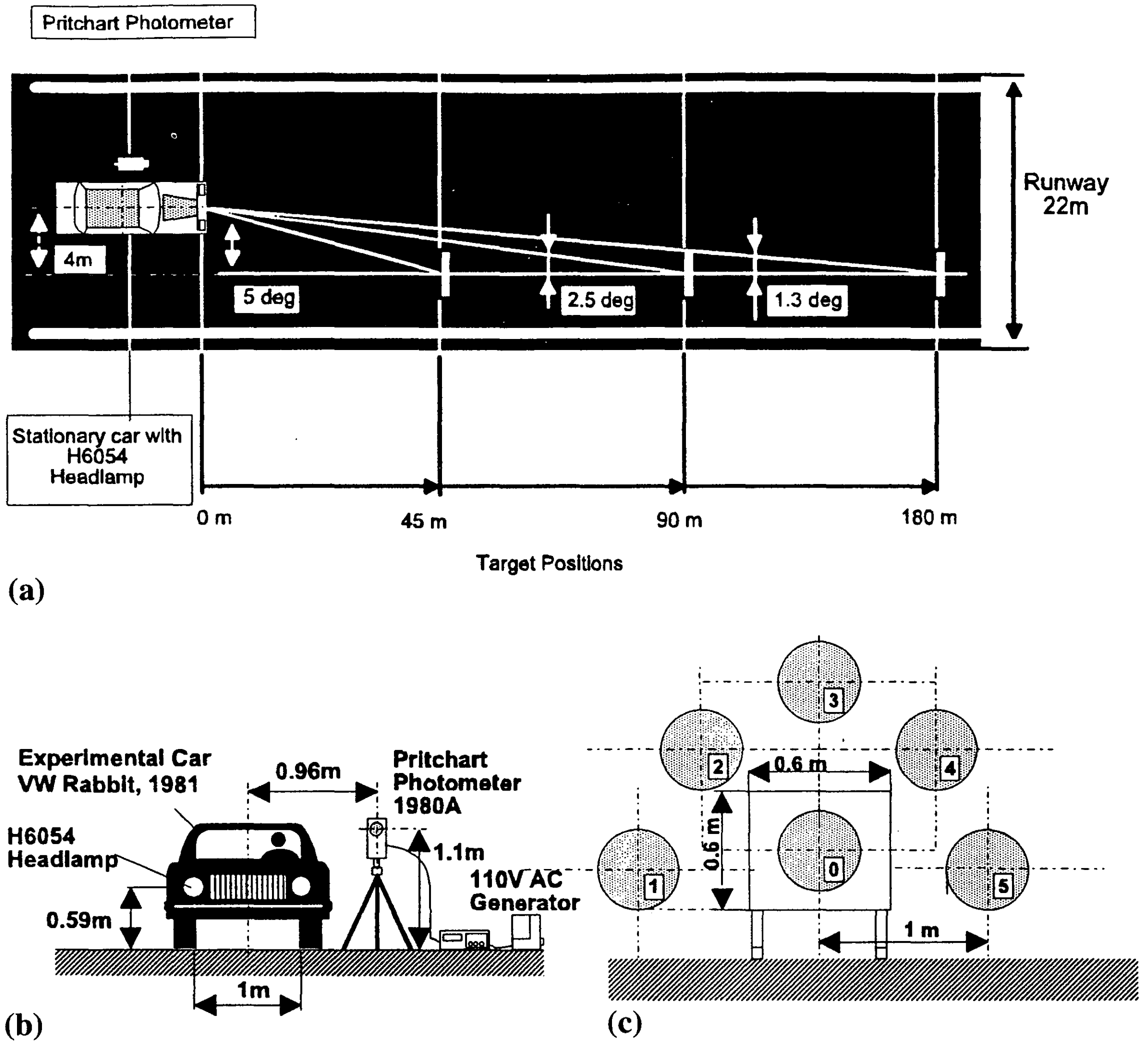


FIGURE 1 Layout of experimental site (*a*) setup of the experimental vehicle (*b*); and Pritchart photometer measurement positions (*c*).

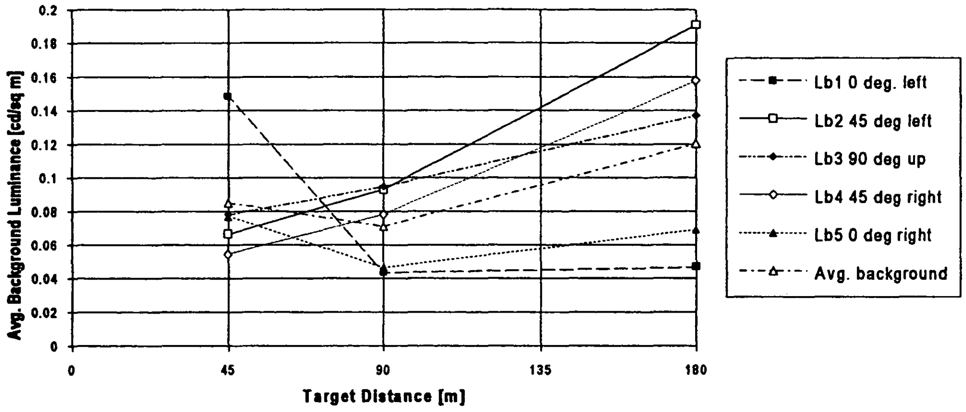
the eight targets was measured at a distance of 45, 90, and 180 m away from the car. The setup of the experimental vehicle is shown in Figure 1*B*.

### Experimental Results and Conclusions

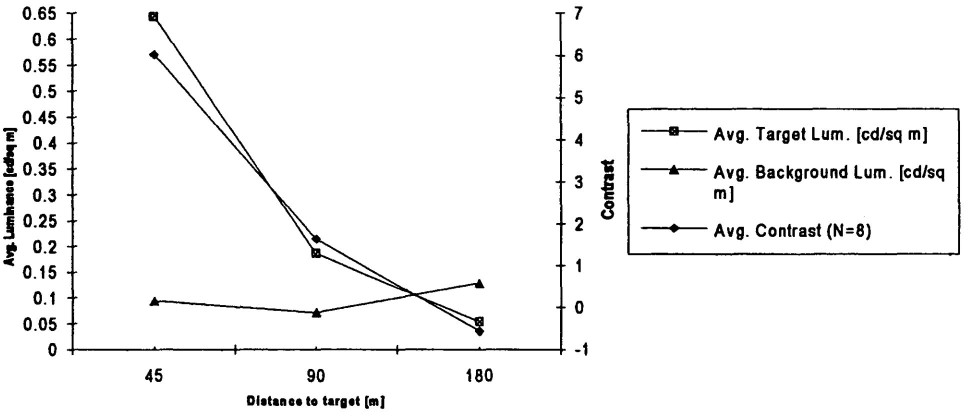
From Figure 2*A*, it appears that most background luminances are fairly close to one another regardless of the measurement location. At close distances (45 m), however, there seems to be an increase in background luminance to the left of the target. An analysis of variance on the background luminance values was used to determine whether it is adequate to take an average background luminance over all five measurement locations for further model development and validation. Because $F_{\alpha}=0.05$ $v_1=2$ $v_2=10 > F_0$, one fails to reject $H_0$, and therefore it is adequate to use an average taken over all five measurement locations as background luminance. Figure 2*B* shows the target luminance, the background luminance, and the contrast for the eight nonretroreflective targets as a function of the target distance. The exact values can be found in Tables 1–3. From these results it can be seen that the average background luminance lies within the range of 0.0939 and 0.1288 cd/m$^2$, that is, the background luminance remains almost constant over the entire range of the target distances used in the experiment. The target luminance, on the other hand, ranges from 0.0535 to 0.644 cd/m$^2$, that is, the target luminance increases considerably for smaller target distances. The resulting actual average contrast drops from 6.02 for a target distance of 45 m to −0.558 for a target distance of 180 m.

## EXPLORATORY TARGET DETECTION FIELD EXPERIMENT

A small visibility distance field experiment was conducted to determine a field factor (contrast multiplier) that must be used to account for average observers under nighttime driving conditions. The experiment was conducted on the runway of the old, unused airport in Athens, Ohio. A blue spray-painted target 60.96 × 60.96 cm (2 × 2 ft) with a reflectance of $R = 0.155$ was placed at the right edge of the runway. Two women with an average age of 22.5 years



A. Average Background Luminance At Different Measurement Locations For All Non-Retroreflective Targets (N=8) As A Function Of Target Distance



B. Average Target Luminance, Average Background Luminance and Average Contrast (N=8) As A Function of Target Distance

FIGURE 2 Average background and target luminances for all nonretroreflective targets ($N=8$) as a function of target distance.

TABLE 1 Target Luminances Averaged over Five Different Measurement Positions of Eight Nonretroreflective Targets Under Low-Beam Illumination at Night

| | | Target Luminance [cd/sq m] | | | | | |
|---|---|---|---|---|---|---|---|
| | | 45m | | 90m | | 180m | |
| Target Number | Material and Color | Avg | Std.Dev | Avg | Std.Dev | Avg | Std.Dev |
| 1 | S.P.Black | 0.1371 | 2.40E-04 | 0.0408 | 1.03E-04 | 0.0243 | 2.40E-04 |
| 2 | S.P. Reddish Dark Brown | 0.5413 | 6.85E-04 | 0.1206 | 3.43E-04 | 0.0449 | 2.06E-03 |
| 3 | S.P. Blue | 0.7778 | 6.17E-03 | 0.2957 | 1.37E-03 | 0.0658 | 6.85E-04 |
| 4 | S.P. Dark Yellow Beige | 0.7915 | 1.71E-03 | 0.1912 | 6.85E-04 | 0.0589 | 2.40E-04 |
| 5 | S.P. Dark Green | 0.6990 | 4.11E-02 | 0.2837 | 2.06E-03 | 0.0617 | 3.43E-04 |
| 6 | Dark Brown Clothing | 0.1018 | 3.43E-04 | 0.0305 | 3.43E-04 | 0.0185 | 1.03E-03 |
| 7 | Light Blue Clothing | 0.6030 | 2.40E-03 | 0.1552 | 1.37E-03 | 0.0521 | 2.06E-03 |
| 8 | Plain Plywood | 1.5007 | 1.95E-02 | 0.3700 | 6.85E-04 | 0.1021 | 6.85E-04 |
| Average | | 0.6440 | | 0.1860 | | 0.0535 | |

**TABLE 2 Background Luminances Averaged over Five Different Measurement Positions of Eight Nonretroreflective Targets Under Low-Beam Illumination At Night**

| | | Background Luminance [cd/sq m] | | | | | |
|---|---|---|---|---|---|---|---|
| | | 45m | | 90m | | 180m | |
| Target Number | Material and Color | Avg | Std.Dev | Avg | Std.Dev | Avg | Std.Dev |
| 1 | S.P.Black | 0.0634 | 8.84E-03 | 0.0829 | 3.40E-02 | 0.1593 | 7.95E-02 |
| 2 | S.P. Reddish Dark Brown | 0.0822 | 3.84E-02 | 0.0805 | 2.96E-02 | 0.1333 | 5.24E-02 |
| 3 | S.P. Blue | 0.0850 | 3.67E-02 | 0.0819 | 2.98E-02 | 0.1466 | 8.70E-02 |
| 4 | S.P. Dark Yellow Beige | 0.0815 | 3.04E-02 | 0.0829 | 3.28E-02 | 0.1124 | 7.67E-02 |
| 5 | S.P. Dark Green | 0.0874 | 4.69E-02 | 0.0692 | 3.03E-02 | 0.1566 | 1.55E-01 |
| 6 | Dark Brown Clothing | 0.0939 | 5.52E-02 | 0.0541 | 1.45E-02 | 0.1110 | 7.67E-02 |
| 7 | Light Blue Clothing | 0.1624 | 4.25E-02 | 0.0517 | 1.63E-02 | 0.1151 | 5.07E-02 |
| 8 | Plain Plywood | 0.0949 | 4.28E-02 | 0.0665 | 2.30E-02 | 0.0963 | 3.77E-02 |
| | Average | 0.0938 | | 0.0712 | | 0.1288 | |

were used as subjects in this experiment. The experimental vehicle was a 1981 VW Rabbit with 6054 headlamps (low beams) and a windshield transmittance of $T = 0.72$. Because of the limited runway length, the subjects had to wear dark sunglasses ($T = 0.0568$) to provide useful visibility distances. Earlier attempts to use sunglasses with a greater transmittance failed because the subjects were often able to detect the target from the beginning of the runway [distance > 400 m (1,312 ft)]. Overall, the transmittance was $T_{tot} = 0.72 \cdot 0.0568 = 0.040896$. Each subject performed five runs. After each run the target was moved to another location along the right edge of the runway to avoid learning. Subject order and target location were completely randomized.

The average visibility distance was 104 m (342 ft) with a standard deviation of 16.6 m (54 ft). This data point was used to obtain a field factor (contrast multiplier) of 2.28, which must be applied to Blackwell's threshold contrast values (*17*), during the computation of $C_{th}$ in the computer model.

## DEVELOPMENT OF A VISIBILITY DISTANCE PREDICTION SOFTWARE PACKAGE

### Introduction

The visibility distance of a target as seen through an automobile windscreen or other similar optical filters with different transmittances can be determined by using representative human visual threshold contrast data (*17*). Threshold contrast data provide a better basis for visual task performance studies than can be obtained using visual acuity measures (*18*). Visual acuity can be compensated in most cases with corrective glasses or lenses, whereas the threshold contrast function cannot be influenced.

The underlying algorithm of the program is based on the fact that a target is just visible at a given distance if the threshold contrast $C_{th}$ and the actual contrast $C_{act}$ are the same. For simplicity it is assumed that a driver's eyes are at the same longitudinal position as the headlamps. If no optical filter is present in the visual path from the headlamps to the target to the observer, one can determine the initial visibility distance $D_0$ as described by Haber (*3*). Now assume that an optical filter is inserted into the visual path of the observer. This reduces the light that reaches the retina of the observer, leaving the actual contrast $C_{act}$ unaffected but increasing the threshold contrast $C_{th}$ according to Blackwell's data (*17*) or that of other threshold contrast models, or both (*14,15*).

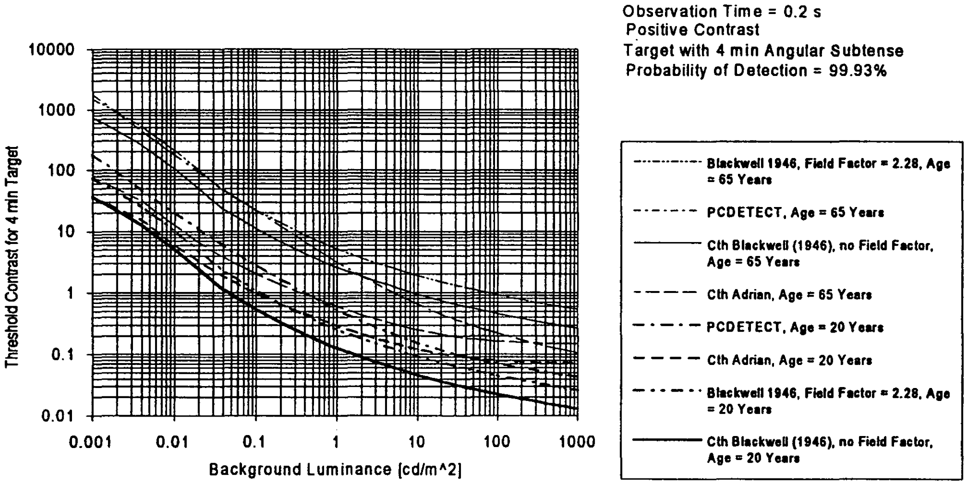
The visibility distance algorithm varies the distance of the observer and the headlamps to the target until $C_{th}$ and $C_{act}$ are equal. The same approach was also used by the Ford Motor PCDETECT (*15*) program. However, the CIE 19/2.1 (*19*) threshold contrast model used in PCDETECT does not appear to be in close accordance with the most comprehensive source of threshold contrast data as provided by Blackwell (*17*). In his experiment Blackwell (*17*) attempted to determine the threshold contrast of the human eye by conducting a large-scale experiment involving 19 subjects for an

**TABLE 3 Contrasts Averaged over Five Different Measurement Positions of Eight Nonretroreflective Targets Under Low-Beam Illumination at Night**

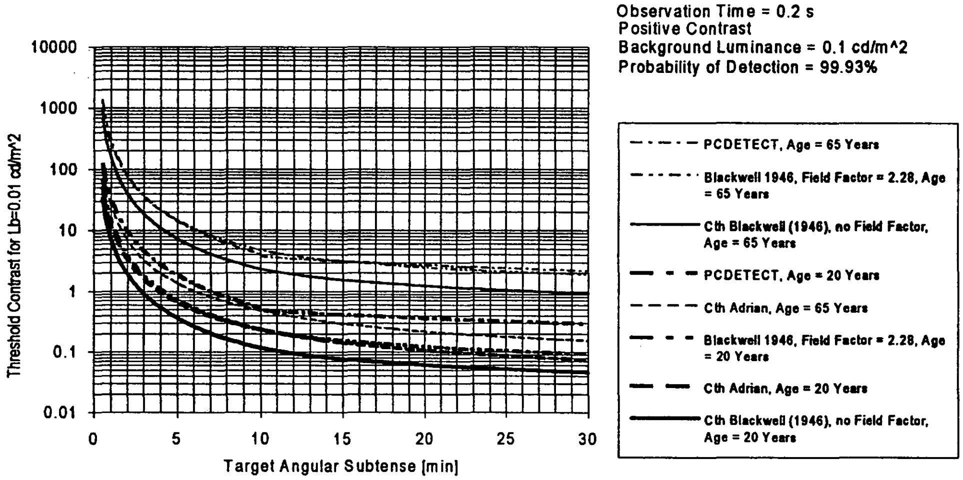
| | | Actual Contrast | | |
|---|---|---|---|---|
| Target Number | Material and Color | 45m | 90m | 180m |
| 1 | S.P.Black | 1.16 | -0.51 | -0.85 |
| 2 | S.P. Reddish Dark Brown | 5.58 | 0.50 | -0.66 |
| 3 | S.P. Blue | 8.15 | 2.61 | -0.55 |
| 4 | S.P. Dark Yellow Beige | 8.70 | 1.31 | -0.48 |
| 5 | S.P. Dark Green | 7 | 3.10 | -0.61 |
| 6 | Dark Brown Clothing | 0.084 | -0.44 | -0.83 |
| 7 | Light Blue Clothing | 2.71 | 2 | -0.55 |
| 8 | Plain Plywood | 14.81 | 4.57 | 0.06 |
| | Average | 6.028 | 1.64 | -0.56 |

extended period of up to 2.5 years. The subjects had to report whether they could detect a projected circular spot of a given angular subtense and a given luminance on a screen with a given background luminance as seen from about 60 ft away. Young women, aged 19 to 26, served as subjects with a visual acuity for both eyes of about 20/20. Stimulus size, stimulus brightness, and the background luminance were systematically changed. The subjects provided more than 2 million responses, some 450,000 of which were statistically evaluated.

On the basis of the statistical quality of Blackwell's experiment (*17*) it appears reasonable to use his data for the development of a visibility distance prediction software package. PCDETECT (*15*) on the other hand uses the CIE 19/2.1 (*19*) model because it is analytically derived from the vision theory and can therefore easily be implemented using a programming language. The PCDETECT model appears to produce threshold contrasts that are different (see Figure 3) from those that Blackwell (*17*) found in his experiments.



A : Threshold contrast comparison over a selected range of background luminances, for a target angular subtense of 4 min, observer age 20 years and 65 years, and a probability of detection of 99.93 %



B : Threshold contrast comparison over a selected range of target angular subtenses, for a background luminance of 0.1 $\frac{cd}{m^2}$, observer age 20 years and 65 years, and a probability of detection of 99.93 %

**FIGURE 3** **Comparison between Adrian's threshold contrast model (*14*), PCDETECT (*15*), and the newly developed threshold contrast model based on data from Blackwell (*17*) with and without field factor.**

## THRESHOLD CONTRAST ALGORITHMS

### *Precise Two-Dimensional Third-Order Polynomial Langrangian Interpolation (16) Using Blackwell's Data (17) as Tabular Points*

Any point between the cells of Blackwell's tabulated threshold contrast data can be found with

$$C_{\mathrm{th}}\,(\alpha,\mathrm{L}_b) = \sum_{r=i}^{i+n} \sum_{s=j}^{j+n} \left( \prod_{\substack{k=i \\ k \neq r}}^{i+n} \frac{\alpha - \alpha_k}{\alpha_r - \alpha_k} \right) \cdot \left( \prod_{\substack{l=j \\ l \neq s}}^{i+n} \frac{L_b - L_{bk}}{L_{bs} - L_{bk}} \right) \tag{1}$$

where $n$ is the order of the polynomial (order 3 seems to be sufficient). The interpolation in the newly developed computer model is based on Equation 1, implemented with Neville's algorithm (*16*) using 16 tabulated threshold contrast points around the point of interpolation. Using this method, it is possible to interpolate Blackwell's data (*17*) with a maximum relative error of, at the most, 5 percent for background luminances ranging from $3.4262 \times 10^{-5}$ to 3426.2 cd/m$^2$ and target angular subtenses ranging from 0.595 to 360 min of arc. Thanks to the high precision of the interpolation method it is possible to compare the visibility distances that can be obtained by using the PCDETECT (*15*) model and by using Adrian's model (*14*) with the visibility distances obtained by using Blackwell's data (*17*) adjusted with a field factor of 2.28.

### *Adrian's Threshold Contrast Model*

Adrian (*14*) describes a threshold luminance model based on the luminous flux function ($\Phi$) characteristic for the Ricco process

$$\Delta L_{\alpha \to 0} = \Phi(L_b)\,\alpha^{-2} \tag{2}$$

and the luminance function ($L$) characteristic for Weber's law

$$\Delta L_{\alpha \to \infty} = L(L_b) \tag{3}$$

where $\alpha$ is the visual angle subtended by the target.

Adrian describes the threshold luminance function over the entire range of $\alpha$ as

$$\Delta L = k\left(\frac{\sqrt{\Phi}}{\alpha} + \sqrt{L}\right)^2 \tag{4}$$

Adrian gives the flux and luminous functions as follows

- On the basis of data from Adrian (*20*), for higher luminance levels of $L_b \geq 0.6$ cd/m$^2$

$$\sqrt{\Phi} = \log(4.1925 \cdot \mathrm{L}_b{}^{0.1556}) + 0.1684 \cdot L_b{}^{0.5867} \tag{5}$$

$$\sqrt{L} = 0.05946 \cdot \mathrm{L}_b{}^{0.466} \tag{6}$$

- On the basis of data from Aulhorn (*21*) for very low luminance levels of $L_b \leq 0.00418$ cd/m$^2$

$$\sqrt{\Phi} = 10^{\,0.028+0.173 \cdot \log(L_b)} \tag{7}$$

$$\sqrt{\mathrm{L}} = 10^{-0.891+0.5275 \cdot \log(L_b)+0.0227 \cdot (\log(L_b)^2\,)} \tag{8}$$

- On the basis of Blackwell (*17*) for medium luminance levels of $0.00418\ \mathrm{cd/m^2} \leq \mathrm{L}_b \leq 0.6\ \mathrm{cd/m^2}$

$$\sqrt{\Phi} = 10^{-0.072+0.3372 \cdot \log(L_b)+0.0866 \cdot (\log(L_b))2} \tag{9}$$

$$\sqrt{\mathrm{L}} = 10^{-1.256+0.319 \cdot \log(L_b)} \tag{10}$$

To account for an observation time $t$ of less than 2 sec, Adrian (*14*) uses the following relationship:

$$\Delta \mathrm{L}_t = \Delta \mathrm{L}_{t\,=\,2s} \cdot \frac{a(\alpha, L_b) + t}{t} \tag{11}$$

where

$$a(\alpha,L_b) = \frac{\sqrt{a(\alpha^2 + a(L_b)^2}}{2.1} \tag{12}$$

and

$$a(\alpha) = 0.36 - 0.0972 \times \left\{ \frac{[\log(\alpha) + 0.523]^2}{[\log(\alpha) + 0.523]^2 - 2.513\,[\log(\alpha) + 0.523] + 2.7895} \right\} \tag{13}$$

$$a\,(L_b) = 0.355 - 0.1217 \times \left\{ \frac{[\log(L_b) + 6]^2}{[\log(L_b) + 6]^2 - 10.4\,[\log(L_b) + 6] + 52.28} \right\} \tag{14}$$

In Adrian's model, the influence of observer age is given as follows:

$$23 < \mathrm{Age} < 64 \qquad AF = \frac{(\mathrm{Age} - 19)^2}{2160} + 0.99$$

$$65 < \mathrm{Age} < 75 \qquad AF = \frac{(\mathrm{Age} - 56.6)^2}{116.3} + 1.43 \tag{15}$$

According to Adrian (*14*) the probability of detection is 99.93 percent. The contrast threshold is then given by inserting Equations 5 through 11 into 4 and dividing the threshold luminance difference by the background luminance

$$C_{\mathrm{th}} = \frac{2.6}{L_b}\left[\left(\frac{\sqrt{\Phi}}{\alpha} + \sqrt{L}\right)^2 \cdot \frac{a(\alpha,\mathrm{L}_b) + t}{t} \cdot AF\right] \tag{16}$$

The model, as illustrated, should be used for positive contrasts only because Adrian's contrast polarity factor $F_{cp}$ was not considered here. Adrian found a relatively strong contrast polarity effect, whereas a close investigation of Blackwell's data (*17*) reveals almost no contrast effect.

### *PCDETECT Model*

The PCDETECT threshold contrast algorithm (*15*) is based on the CIE 19/2.1 (*19*) model. Unlike in the earlier model DETECT, which was based on the empirical data from Blackwell, the programmers decided to use a slightly modified version of the analytical CIE 19/2.1 model. The threshold contrast in PCDETECT is given by

$$C_{\text{th}} = cx \cdot \frac{0.0923}{n} \cdot \left[\left(\frac{S}{t \cdot L_e}\right)^{0.4} + 1\right]^{2.5} \tag{17}$$

where the background luminance and the veiling luminance are used to express the effective background luminance present

$$L_e = L_b + B_v \tag{18}$$

and

$$n = \left[\left(\frac{S}{100 \cdot t}\right)^{0.4} + 1\right]^{2.5} \tag{19}$$

and $cx$ is a size factor introduced by the developers of PCDETECT

$$\begin{array}{ll} d \leq 10 \text{ min} & cx = 3 \cdot (0.37)^{\log_2 d} \\ d > 10 \text{ min} & cx = 0.106 - 0.0006d \end{array} \tag{20}$$

This factor seems to cause an irregularity in the threshold contrast function at a target visual angle of 10 min (see Figure 3*B*).

The *S*-parameter in Equation 19 is a function of the target size $d$ and the observer age in $s$

$$S = 10^{\,0.5900 - 0.6235 \log(d) - s} \tag{21}$$

where $s$ is given by

$$\begin{array}{ll} 20 \leq \text{Age} \leq 44 & s = 0 \\ 45 \leq \text{Age} \leq 64 & s = 0.00406 \cdot (\text{Age} - 44) \\ 65 \leq \text{Age} \leq 80 & s = 0.0812 + 0.00667 \cdot (\text{Age} - 64) \end{array} \tag{22}$$

the function for $t$ in Equation 17 is given by

$$\begin{array}{ll} 20 \leq \text{Age} \leq 30 & t = 1 \\ 31 \leq \text{Age} \leq 44 & t = 10^{-0.01053 \cdot (\text{Age} - 30)} \\ 45 \leq \text{Age} \leq 64 & t = 10^{-0.1474 - 0.0134 \cdot (\text{Age} - 44)} \\ 65 \leq \text{Age} \leq 80 & t = 10^{-0.4154 - 0.0175 \cdot (\text{Age} - 64)} \end{array} \tag{23}$$

Another age-related factor is the contrast multiplier $m_1$

$$\begin{array}{ll} 20 \leq \text{Age} \leq 42 & m_1 = 1 + 0.00795 \cdot (\text{Age} - 20) \\ 43 \leq \text{Age} \leq 64 & m_1 = 1.175 + 0.0289 \cdot (\text{Age} - 42) \\ 65 \leq \text{Age} \leq 80 & m_1 = 1.811 + 0.1873 \cdot (\text{Age} - 64) \end{array} \tag{24}$$

To account for the increased variability of the threshold contrast for older observers and to apply the threshold contrast function at any probability of detection, PCDETECT uses

$$\begin{array}{ll} \text{Age} \leq 35 & \sigma_{\log} = 0.124 + 0.001133 \cdot \text{Age} \\ \text{Age} > 35 & \sigma_{\log} = 0.064 + 0.002850 \cdot \text{Age} \end{array} \tag{25}$$

and a factor $cf$ to correct the log standard deviation in Equation 25 to account for the influence of the background luminance on the variability of the threshold contrast:

$$\begin{array}{ll} \log L_b \leq -0.5 & cf = 1.0875 - 0.065 \cdot \log(L_b) \\ \log L_b > -0.5 & cf = 1.012 - 0.216 \cdot \log(L_b) \end{array} \tag{26}$$

Equation 27 is used to correct the standard deviation given in Equation 25 as follows:

$$\sigma_{\log C_{\text{th}}} = \sigma_{\log} \cdot cf \tag{27}$$

A contrast multiplier is introduced to allow evaluation of the threshold contrast function at any given probability of detection

$$\log(\text{cmp}) = Z_p \cdot \sigma_{\log C_{\text{th}}} \tag{28}$$

where $Z$ is the standardized normal variable associated with the desired probability $P$. The threshold contrast function $C_{\text{th}}$ can be obtained by inserting equations 18 to 23 into Equation 17 and by applying the multipliers given in Equations 24 and 28 as follows:

$$C_{\text{th}} = cx \cdot m_1 \cdot cmp \cdot \frac{0.0923}{n} \cdot \left[\left(\frac{S}{t \cdot L_e}\right)^{0.4} + 1\right]^{2.5} \tag{29}$$

## Comparison and Discussion Of Threshold Contrast Models

The three previously described threshold contrast models were implemented in a computer program using the C-language. The computer program was used to plot the threshold contrast curves indicated in Figure 3*A* and *B*. Figure 3*A* illustrates the comparison of the three threshold contrast models for a background luminance range of 0.001 (cd/m$^2$) qe $L_b \leq 1000$ (cd/m$^2$), a positive contrast target having a constant angular subtense of a 4-min arc, an observation time of 0.2 sec, and a probability of detection of 99.93 percent. As indicated in Figure 3*A*, the lowest threshold contrasts were obtained from Blackwell's 1946 data (*17*), which is no surprise, considering that the involved subjects were young women who were highly skilled observers. A previously described exploratory target visibility field experiment was conducted under automobile low-beam illumination conditions to provide a field factor (contrast multiplier) for Blackwell's 1946 data. A field factor of 2.28 seemed to be adequate to account for average observers under such conditions. The adjusted Blackwell threshold contrast values shown in Figure 3*A* have the same overall shape as the original data from that work (*17*) but are higher in magnitude, indicating that normal observers would provide shorter visibility distances. Adrian's model (*14*) provides threshold contrast values that seem to match Blackwell's data (*17*) relatively closely for background luminances below 0.01 cd/m$^2$. For higher luminances, Figure 3*A* shows that Adrian's model (*14*) deviates more and more from Blackwell's data (*17*). This may be attributed to the fact that the model uses the three independent threshold contrast data bases from Adrian (*20*), Aulhorn (*21*), and Blackwell (*17*), as a function of the background luminance. From Figure 3*A* it is also evident that the age function in Adrian's model (*14*) does not seem to adequately account for observer age. PCDETECT, on the other hand, provides threshold contrast values that are considerably higher in magnitude than the adjusted Blackwell data (field factor = 2.28). This would indicate that PCDETECT generally provides visibility distances that are somewhat shorter.

Figure 3*B* illustrates the comparison of the three threshold contrast models for an angular subtense ranging from 0.5 min $\leq \alpha \leq 30$ min, a positive contrast target, a background luminance of 0.1 (cd/m$^2$), which is the approximate average background luminance obtained in the field measurements, an observation time of 0.2 sec, and a probability of detection of 99.93 percent. As seen in Figure 3*B*, the lowest threshold contrast values are obtained for Blackwell's 1946 data (*17*). Under the given conditions, it seems that Adrian's model (*14*) and the adjusted Blackwell data (field factor = 2.28) produce similar threshold contrasts. PCDETECT, on the other hand, provides threshold contrast values that are significantly higher than both Adrian's data and Blackwell's adjusted data. From Figure 3*B* it can be seen that PCDETECT has an irregularity in its threshold contrast function at a visual angle of 10 min of arc. This may be attributed to the size factor $cx$ in Equation 20. For visual angles greater than 10 min of arc the PCDETECT model produces threshold contrast values that are considerably higher than the ones obtained from Adrian's model (*14*) and both the adjusted and unadjusted data from Blackwell (*17*). From the comparison of the algorithms it can be concluded that only the adjusted Blackwell threshold contrast values appear to be adequate for use in visibility distance models where extended ranges of both the angular subtense and the background luminance may be present and normal observers are considered. Adrian's model (*14*) seems to provide adequate results for background luminances below 0.1 (cd/m$^2$), given that young observers are used. Adrian's age function appears to be too gentle for older observers. PCDETECT generally provides threshold contrasts that are too high when compared with those of the other models. This may lead to rather short visibility distances. The PCDETECT model should be used carefully, with a lot of caution, for visual angles above 10 min of arc.

## EXAMINATION OF LOSS IN DRIVER VISIBILITY CAUSED BY TINTED OPTICAL MEDIA

### Visibility Distance Prediction Software Package

The newly developed visibility distance software package, based on Blackwell's threshold contrast data (*17*), adjusted with a field factor of 2.28 was used for a critical examination of the statements made in Haber's paper (*3*). The program was implemented in the C-language and is executable on IBM (or compatible) personal computer running under MS DOS 5.0 or newer. The user must provide the target reflectance, the physical target size (size corresponds to the size of a Blackwell disk), the background luminance that will be kept constant over all iterations, the optical filter transmittance in percent, the observer age, the observation time, the probability of detection (50, 90, 95, and 99.93 percent, and the headlamp type (Haber lamp A, Haber lamp B, Taurus low beam, Taurus high beam, 6054 low beam)

Using this input, the program determines the Blackwell threshold contrast (*17*) adjusted with a field factor of 2.28, by applying the two-dimensional third-order polynomial Langrangian interpolation given in Equation 1. The actual contrast is determined from the target luminance, which depends on the target reflectance, the selected headlamp data (two low-beam headlamps), and the current observation distance, and from the background luminance, which has been found to remain almost constant over the entire visibility range. If the actual contrast $C_{act}$ is greater or equal to the threshold contrast $C_{th}$, then the target is still visible and can be moved farther away one step. The step size is reduced by 50 percent in case a threshold crossing from visible to invisible or vice versa has occurred. The iteration process continues as long as the step size is greater than 1 cm. When this final condition is reached the program returns the current distance $D$ as the visibility distance under the entered conditions. The implemented solver-algorithm basically determines the point where the actual contrast function $C_{act} = f(D)$ intersects the threshold contrast function $C_{th} = f(D)$.

### Examination of Statements Made by Haber (1)

Figure 4*A* illustrates how a target placed at the initial visibility distance $D_0$ (target just visible without optical filter), ahead of the observer in an automobile, produces a given luminance contrast $C_{act1}$ between the target and the background under low-beam illumination. The actual contrast $C_{act1}$ at the initial visibility distance $D_0$ is then equal to the threshold contrast $C_{th1}$ from Blackwell (*17*), adjusted by a field factor of 2.28, because the target is just visible at a given probability of detection. Inserting an optical filter of a given transmittance $T < 1$ at the initial distance $D_0$ does not change the actual contrast $C_{act1}$. However, because the background luminance $L_b$ is reduced by the optical filter, the threshold contrast $C_{th}$ is increased according to the adjusted Blackwell data. The target therefore becomes invisible at the current distance because of insertion of a tinted optical filter. The target can be made visible again by moving the automobile (with the observer) closer to the location of the target (or vice versa). This changes the angular subtense $\alpha$ and the target luminance $L_t$ and to some degree the background luminance $L_b$. Therefore, moving the observer in the automobile and the target closer together also changes the actual contrast $C_{act}$ and the threshold contrast $C_{th}$. As indicated in Figure 4*A*, the target becomes visible again when $C_{th2} \leq C_{act2}$. In his analysis, Haber (*3*) incorrectly stated that this will occur at the same contrast level as the initial contrasts $C_{th}1 = C_{act}1$. This would require the background luminance $L_b$ to vary synchronously with the target luminance $L_t$, which is extremely unlikely. The previously described exploratory field luminance measurements have clearly indicated that the background luminance $L_b$ remains almost constant over the visibility range, causing the actual contrast $C_{act}$ to decrease with increasing distance. This fact is also illustrated in Figure 4*A*. Under Haber's incorrect assumption (*3*) that the actual contrast $C_{act}$ does not change as a function of distance, one generally obtains a visibility distance ($D_{Haber}$) that is too short (Figure 4*A*.) This in turn leads to an unreasonably high percent loss of the visibility distance when an optical filter of a given transmittance is inserted. The correct percent loss, based on the example shown in Figure 4*A* is given by

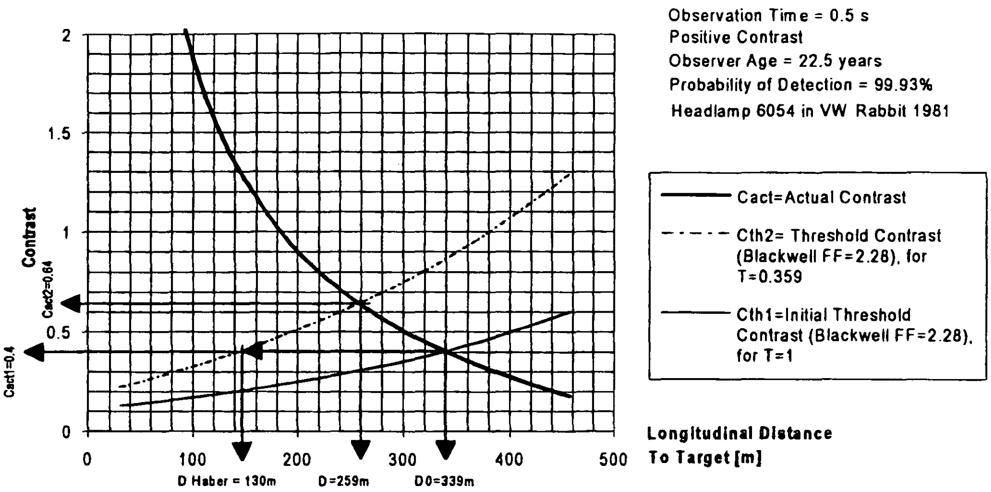
$$PL = 100 \cdot \left(1 - \frac{D}{D_0}\right) = 100 \cdot \left(1 - \frac{259m}{339m}\right) = 23.59 \text{ percent} \quad (30)$$

The incorrect percent loss in visibility distance for the example shown in Figure 4*A*, based on Haber's incorrect assumption is given by

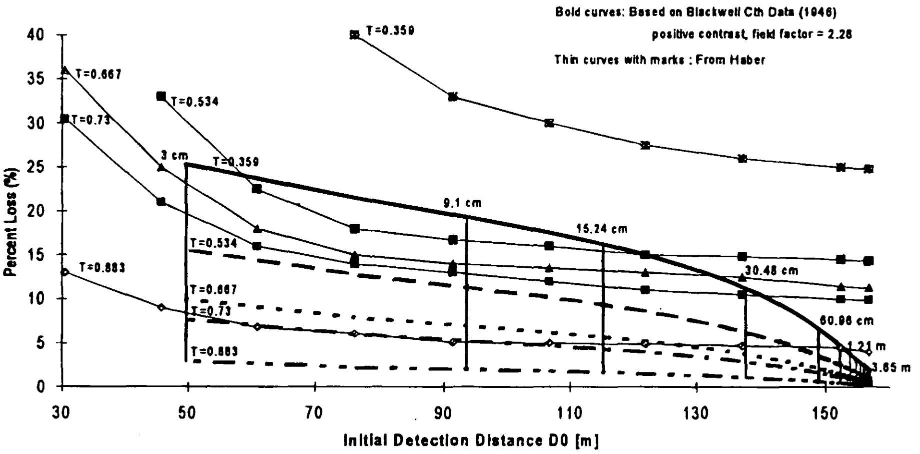
$$PL = 100 \cdot \left(1 - \frac{130m}{339m}\right) = 61.65 \text{ percent} \quad (31)$$

This would indicate that the statements made by Haber (*3*) about the reduction in driver visibility caused by tinted optical media are incorrect and misleading.

It is also evident from Figure 4*A* that a target of a given physical dimension and reflectance always provides the same average initial visibility distance $D_0$, given that the intensity of the headlamps, the filter transmittance ($T = 1$), and the ambient background luminance $L_b$ are not varied. Haber (*3*), however, presented percent loss curves for a target having a constant mean linear dimension of 91.4 cm (3 ft) over the entire distance range. These incorrect percent loss



**A: The initial distance $D_0$ in the above example is found at the point where $C_{act1}=0.4$ intersects with $C_{th1}(T=1)$. When a filter of T=0.359 is inserted, the visibility distance D is found where $C_{act2} = 0.64$ intersects with $C_{th2}(T=0.359)$. Haber (3) incorrectly proposed that D can be found at the point where $C_{th2}(T=0.359)$ intersects with $C_{act1}=0.4$. However, this would lead to unreasonably short visibility distances.**



**B: Percent loss of visibility distance curves provided by model for various filter transmittances and target sizes, and incorrect percent loss of visibility distance curves provided by Haber for a target having a constant mean linear dimension of 91.4 cm (3 ft) over the entire distance range. Target reflectance R=0.15, headlamp Haber type A, probability of detection P=99.93%, observer age = 22.5 years, exposure time T=0.5 sec.**

**FIGURE 4 Loss of visibility distance because of tinted optical media.**

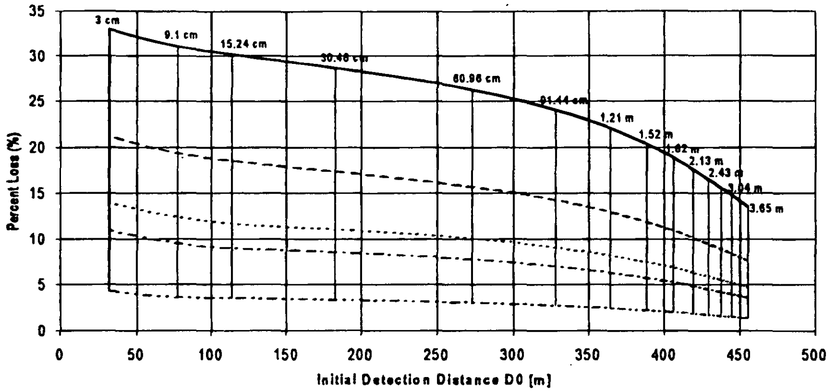
curves are shown in Figure 4*B*, superimposed on the size-dependent percent loss curves provided by the newly developed computer model. For a target having a constant mean linear dimension and a constant reflectance, Haber's curves are incorrect because at a given initial visibility distance $D_0$, there is only one given target luminance $L_t$, only one given background luminance $L_b$, and only one given angular subtense α. Therefore there is only one actual contrast $C_{act} = (L_t - L_b)/L_b$ and only one threshold contrast $C_{th}$. Figure 4*B* illustrates how Haber incorrectly assumed an entire range of $D_0$ for a single-size 91.4-cm (3-ft) target with a reflectance of $R = 0.15$. Figure 4*B* also illustrates that the magnitude of the percent loss curves from Haber's (thin lines with marks) grossly overestimates the true percent loss obtained with the computer model (bold lines). According to the computer model, a motorist can detect a 91.4-cm (3-ft) target ($R = 0.15$) at $D_0 = 157$ m (515 ft) when no windshield is used ($T = 1$). Even with a filter having a transmittance $T = 0.359$ the motorist can detect the same target at $D = 149.4$ m (490.15 ft) which is equivalent to a 4.81 percent loss. The incorrect percent loss at $D_0 = 157$ m (515 ft) given by Haber is about 25 percent. To obtain such high losses, it would be necessary to shrink the target to a mere 3 cm (0.1 ft) when using a tinted windshield with a transmittance of $T = 0.359$. Such a small target no longer represents a pedestrian and would not likely have to be considered as a road hazard for the establishment of minimum transmittance standards.

Figure 5*A* indicates the output of the computer model for various windshield transmittances and target sizes for data from the 6054 headlamps that were used in the field target visibility experiment, a constant background luminance of 0.1 cd/m$^2$, and an observer age of 22.5 years. Figure 5*B* indicates the percent loss when the observer age is increased to 65 years. By comparing Figure 5*A* with 5*B* it can be seen that the magnitude of the percent loss does not considerably change with age, but the initial visibility distances are reduced significantly. On the basis of the literature (*5,6*), further research with older drivers may be required to quantify the influence of observer age with an even-higher accuracy.

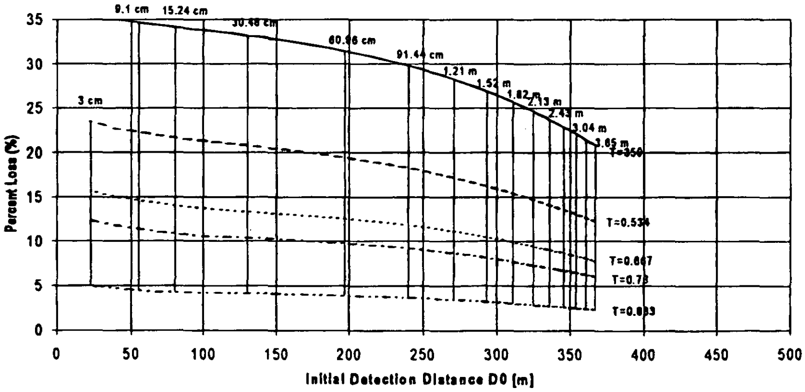
## CONCLUSIONS

The exploratory field luminance measurements indicate that the background luminance remains almost constant over the entire visibility range. The actual contrast $C_{act}$ therefore decreases as the distance to the target increases. A target visibility field experiment has indicated that even with a transmittance as low as $T=0.0408$, young subjects can detect a blue spray-painted target 60.96 × 60.96 cm (2 × 2 ft) under low-beam illumination on the average at 104 m (342 ft).

It was found that Adrian's model (*14*) provides threshold contrast values that seem to match those of Blackwell (*17*) for background luminances below 0.01 cd/m$^2$. PCDETECT (*15*) provides threshold contrast values that are considerably higher in magnitude than both the adjusted Blackwell data (field factor = 2.28) and the threshold contrast values obtained from Adrian's model (*14*). This would indicate that PCDETECT provides visibility distances that are generally somewhat too short. PCDETECT should be used with a lot of caution for visual angles above 10 min of arc. From the comparison of the algorithms it can be concluded that only the adjusted Blackwell threshold contrast values (field factor = 2.28) appear to be adequate for use in seeing distance models, where extended ranges of both the angular subtense and the background luminance may be present and normal observers are considered.



A: Percent loss visibility distance as a function of initial visibility distance $D_0$ (transmittance T=1) for various filter transmittances and target sizes. Target reflectance R=0.155, headlamps 6054 in VW Rabbit 1982, probability of detection P=99.93%, observer age = 22.5 years, exposure time T=0.5 sec.



B: Percent loss visibility distance as a function of initial visibility distance $D_0$ (transmittance T=1) for various filter transmittances and target sizes. Target reflectance R=0.155, headlamps 6054 in VW Rabbit 1982, probability of detection P=99.93%, observer age = 65 years, exposure time T=0.5 sec.

FIGURE 5 Percent loss visibility distance as a function of initial visibility distance.

The graphical method to determine the visibility distance proposed by Haber (*3*) was closely examined and appears to be ambiguous and incorrect because it assumes a constant actual contrast $C_{act}$. It was shown with a newly developed computer model that the magnitude of the percent loss visibility distance is much smaller than that stated by Haber, even for windshields with a relatively low transmittance. Haber (*3*) presented incorrect percent loss curves for a target having a constant mean linear dimension of 91.4 cm (3 ft) and a constant reflectance. It was demonstrated in this investigation that for a constant headlamp intensity, only 1 percent loss point can be obtained for one given filter transmittance. Haber's percent loss curves are therefore unclear and misleading. To obtain losses of the magnitude given by Haber (*3*) and subsequently published (*4*), however, it would be necessary to shrink the target to a mere 3 cm (0.1 ft) when using a tinted windshield with a transmittance of $T = 0.359$. Such a small target no longer represents a pedestrian and would not likely have to be considered as a major or important road hazard for the establishment of minimum transmittance standards. However, tinted windshields will reduce not only foveal but also peripheral detection distances. Therefore, despite the much smaller percent visibility distance losses found in this study when compared with Haber's (*3*) percent loss values, the authors are in no way suggesting that darker tints on windshields should be permitted or that drivers should be driving with sunglasses at night. Any changes in windshield transmission standards should be based on tradeoffs between factors such as visibility, thermal comfort (infrared deflection), and glare reduction and on additional field validation studies that include older drivers and peripheral target detection.

Further field experiments using a wider range of transmittances (less tinted optical media) would be beneficial to further validate the developed computer model. After additional validation, the output of the computer model could assist in the review of the appropriateness of the established minimum transmittance standards.

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