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Railroad-Highway Crossings, Visibility, and Human Factors

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Contents

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

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

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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*Mr. McMahan was with the Ford Motor Company when this research was performed.

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:

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

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:

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

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

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

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

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

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 ($5\frac{3}{4}$-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.

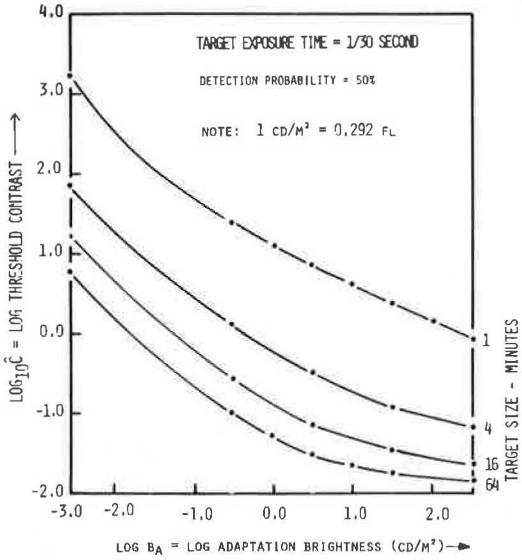
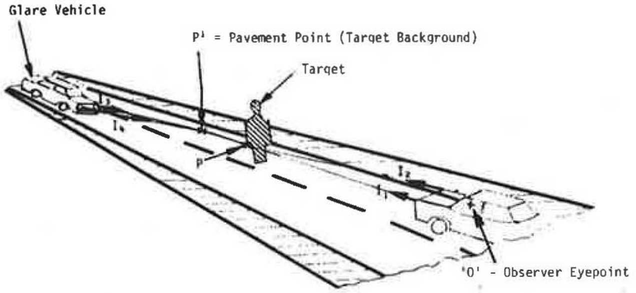


Figure 2. Target, background, and veiling brightness and contrast from head lamp and environmental parameters.



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

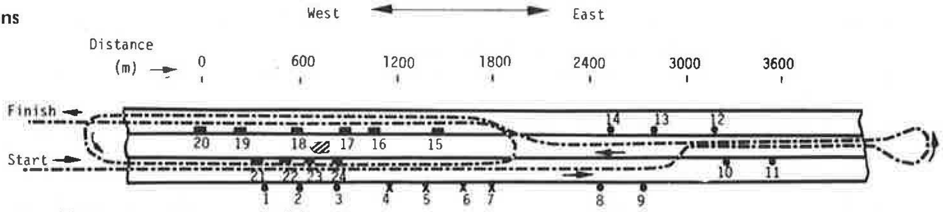
The reflectance of the pavement and shoulder on the test site was measured by using the Pritchard photometer and a photocell. The reflectance at any point on a surface is defined as the ratio of luminance in candelas per square meter (measured by the photometer) to the illumination in luxes (measured 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.

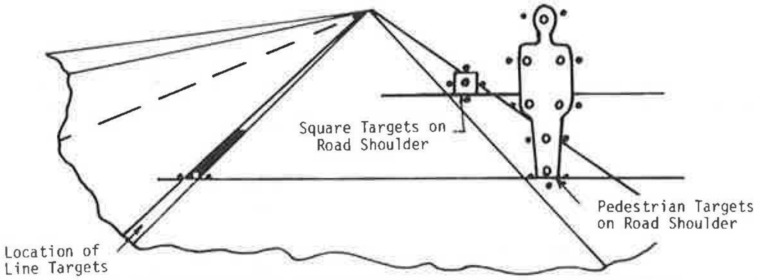
The means and standard deviations of the field-observed seeing distances presented in this section were, therefore, obtained by pooling the seeing distances of the 12 subjects for each target-background condition (as given in Table 1) under each beam pattern.

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



Note: ▨ is the glare vehicle. 1 m = 3.28 ft.

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



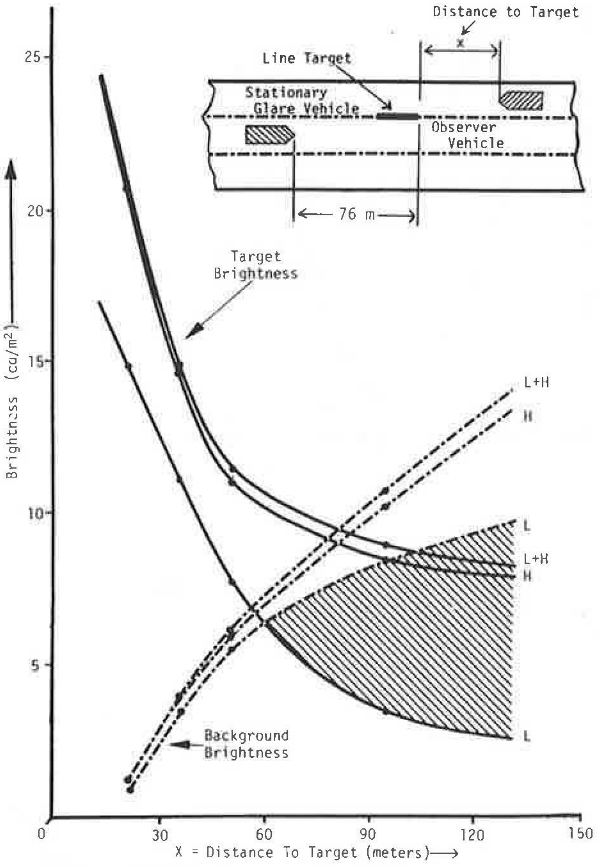
o Indicates location of photometer aim used for target brightness measurement

• Indicates location of photometer aim used for background brightness measurement

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.



Note: 1 cd/m^2 = 0.292 fL 1 m = 3.28 ft

Detection With No Opposing Glare

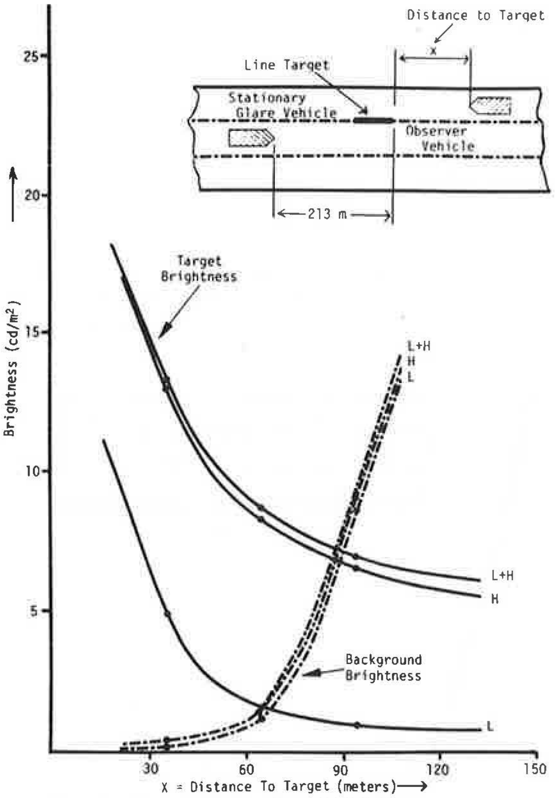
Pedestrian Targets

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

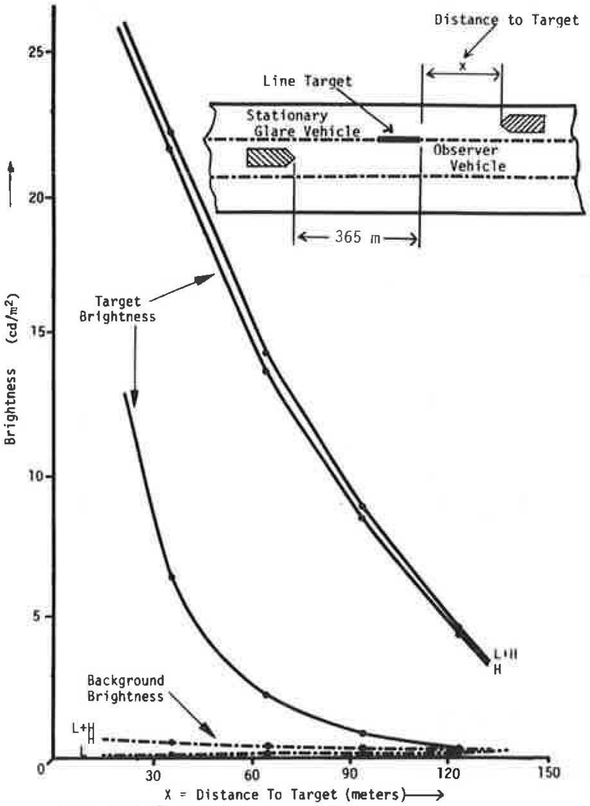
Figure 13 shows the mean values of the field-observed seeing distances with one and two standard deviation limits for the three types of line targets for the three different beam patterns. When the Blackwell model was used to predict the average seeing distance to the line targets, the predicted seeing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



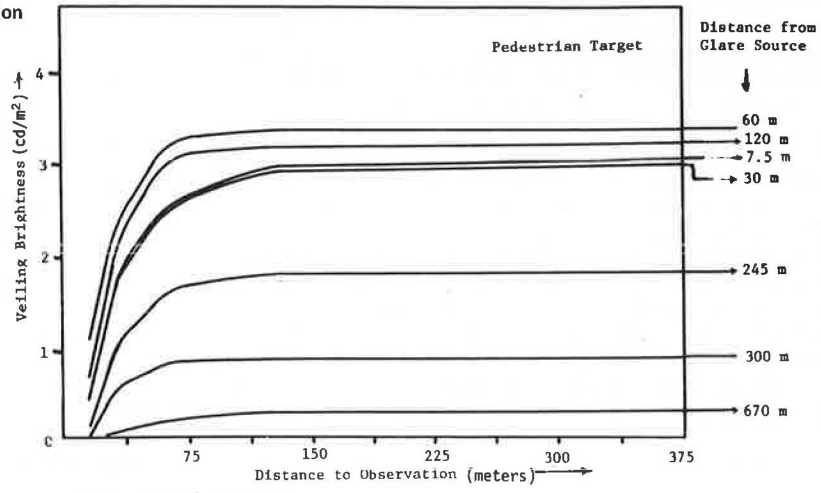
Note: 1 cd/m² = 0.292 fL 1 m = 3.28 feet

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



Note: 1 cd/m² = 0.292 fL, 1 m = 3.28 ft

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



Note: 1 cd/m² = 0.292 fL
1 m = 3.28 feet

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

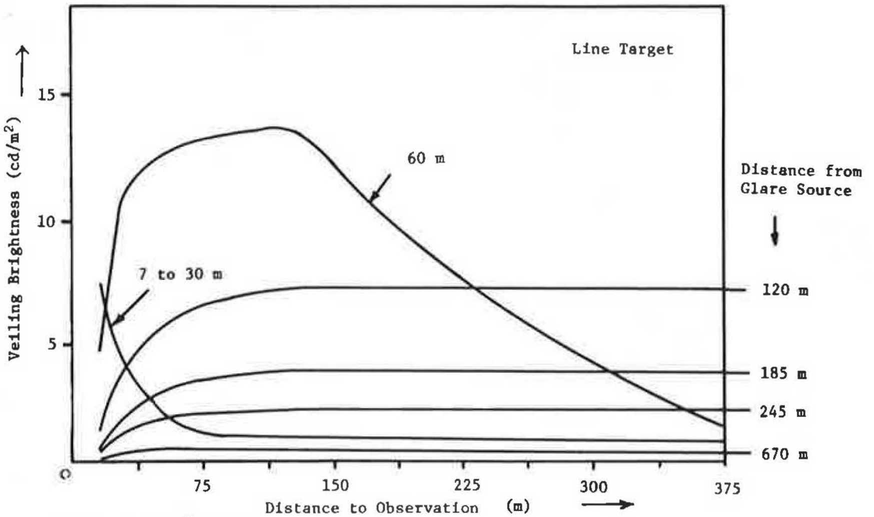
Figure 14 shows field-observed seeing distance to the four 1-ft square targets and the seeing distances predicted by the Blackwell and Ford models. Since the background reflectance of these targets increased rapidly with distance (Figure 10) for the low-reflectance targets (i.e., 6.6 and 11.2 percent 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

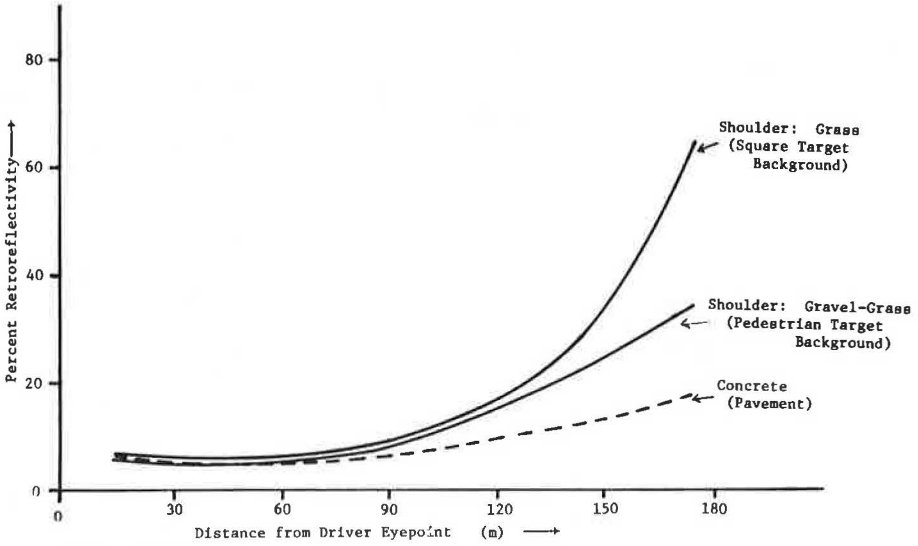
Figure 15 shows the field-observed and model-predicted seeing distances to the pedestrian targets located on the right shoulder and at different distances from the glare source. The veiling brightness used in the Blackwell model was measured directly by using the Fry integrator lens. However, since the 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.



Note: 1 cd/m^2 = 0.292 fL, 1 m = 3.28 ft

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



Note: 1 m = 3.28 ft

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

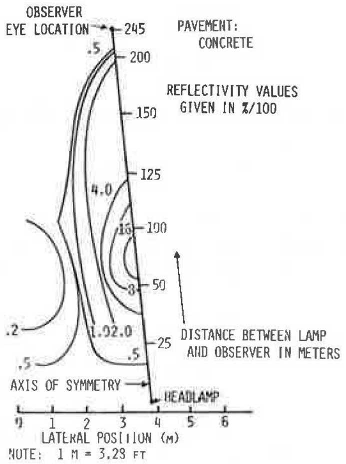


Figure 12. Comparison of field-observed and predicted seeing distance to pedestrian targets.

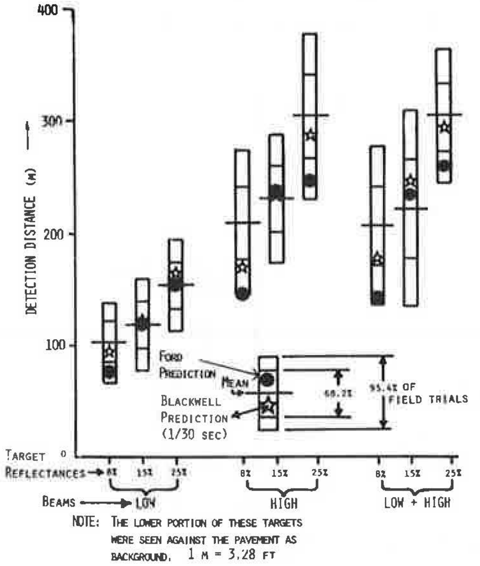


Figure 13. Comparison of field-observed and predicted seeing distances to line targets.

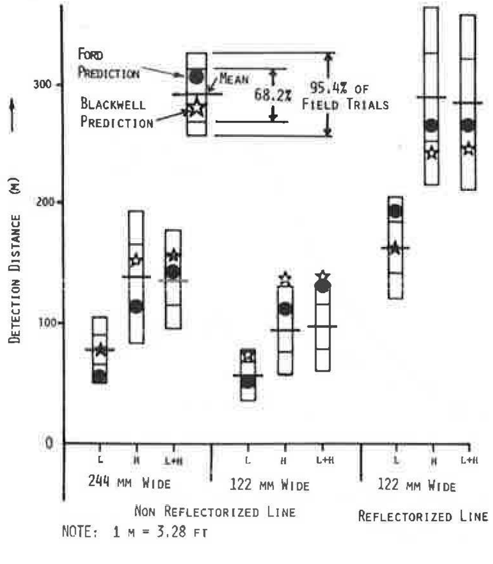


Figure 14. Comparison of field-observed and predicted seeing distances to square targets.

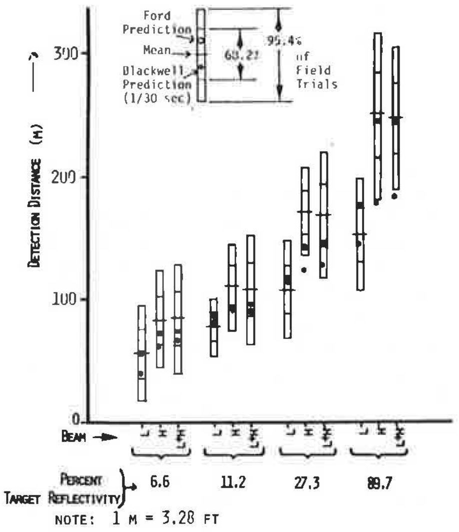
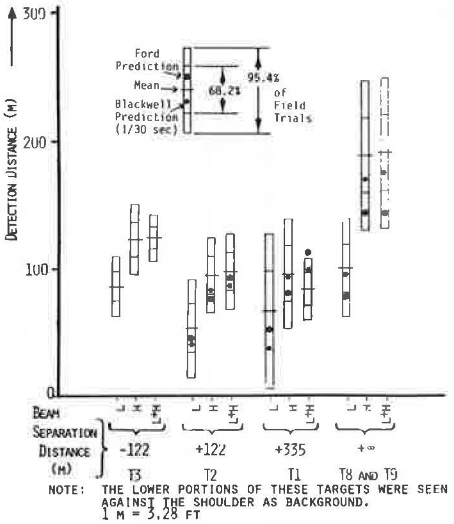


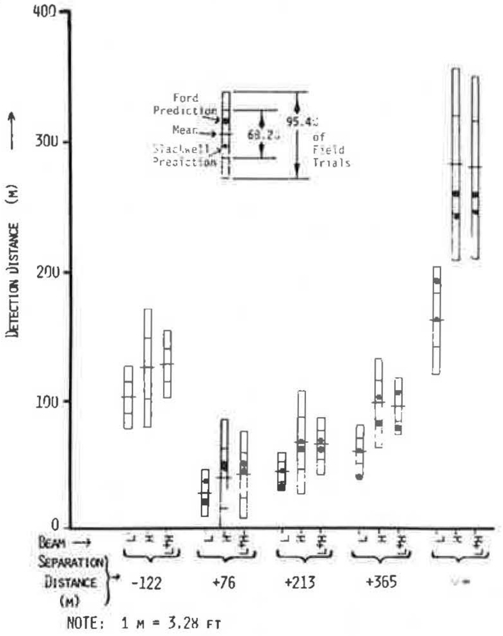
Figure 15. Comparison of field-observed and predicted detection distances to pedestrian targets under glare.



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.

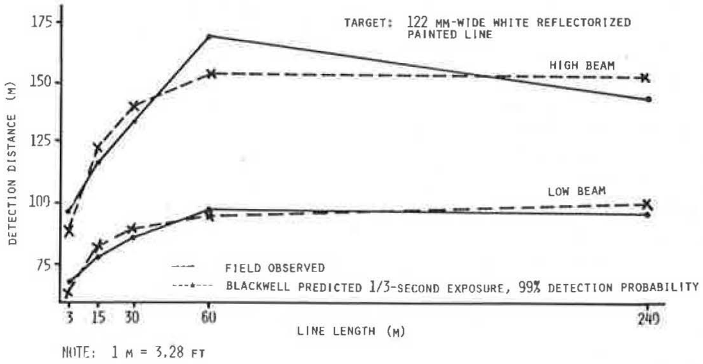
Authors' Closure

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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Luminance and Contrast for Sign Legibility and Color Recognition

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A laboratory study of sign legibility has shown that a contrast of between 30 and 50 percent is required to maintain 75th percentile legibility. Legibility distance increased gradually with greater contrast to about 80 percent; above a luminance ratio of 5 to 1, legibility did not increase greatly. As ambient levels increased, legibility distance increased linearly with the logarithm of either the letter or the sign luminance, whichever was greater. Five color combinations were measured. This report gives additional results on color recognition and applies the effects of luminance and contrast to legibility distance for 11 color combinations, after corrections were made for letter and stroke width. A method for estimating legibility was developed for black and white letter and sign combinations. The effects of luminance and contrast on color recognition at five ambient levels showed the need to increase luminance and contrast as ambient levels increase. Laboratory luminance data, confirmed by two sets of outdoor measurements, furnished a basis for determining the luminance ratios used in the legibility estimates. A basis for estimating glance legibility distance in relation to ordinary legibility (long viewing time) is suggested.

Results have been previously reported of a study of luminance and contrast effects on legibility of certain highway sign color combinations (1). The study included legibility measurements for five color combinations in the laboratory and for two color combinations in the outdoors.

This paper reports laboratory color recognition results for luminance and contrast measurements of colored targets not included in the previous report (1). It provides estimates of luminance requirements for color recognition and legibility of color combinations. Since data and corrections were used from the earlier report, a brief review is included.

Colored slides were projected in a darkroom laboratory. Each slide carried a series of small target signs. Neutral overlays were used to reduce the luminance of colored materials in the simulated signs, and the signs were then photographed. Average luminance of the slide background was varied to furnish different ambient levels simulating rural, suburban, and brightly lighted city conditions. Two series of target signs in seven colors and two series of target signs carrying a capital letter C or O with different orientations were presented on the slides. Legend and sign luminance in each series varied systematically. Letter width was four-fifths of the letter height, and stroke width was one-fifth of the letter height. Laboratory subjects totaled 150 male and female college students. After adapting to darkroom conditions, the subject called out the color or letter orientation in each series of signs. Each subject, without knowledge of results, viewed a total of 51 slides, which included 8 to 16 target signs, in about 45 min. An experimenter recorded the calls of the subject.

In the outdoor observations, subjects viewed test signs under high- and low-beam headlights. A gray panel beside the test signs was illuminated to furnish three ambient luminances. Each test letter was a square E made of two types of reflective materials modified to provide a range of luminance and contrasts. Two color combinations were used—white on green and black on yellow. Each letter was 30.5 cm (12 in) in height and placed on a 45.7-cm (18-in) sign. Ten signs, all of one color combination, were viewed in each run. Subjects observed in groups of six while riding in a slowly approaching station wagon. Test signs were set up in a different preplanned randomized order for each run. Fifty adult male and female volunteers served as observers, and each observer recorded the orientation of the test letter.

Luminance measurements were made with a Pritchard telephotometer having a photopic correction for human visual sensitivity. The laboratory test signs were projected on the screen and measured from the position of the observer's eye for each of the five studies of ambient levels. Luminances of outdoor test signs and sign materials were measured under headlights from distances of 60.9 and 152.4 m (200 and 500 ft).

Three methods of calculating the contrast between sign and background or between legend and sign were used.

1. Percentage of contrast:

$$(L_1 - L_2)/L_1 \times 100 \quad (1)$$

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where

L_1 = the higher luminance and
L_2 = the lower luminance (letter luminance in the case of white letters and sign luminance in the case of black letters).

2. Luminance ratio (LR):

$$L_1/L_2 \quad (2)$$

3. Contrast as used by Blackwell (2):

$$\Delta L/L_2 = (L_1 - L_2)/L_2 \quad (3)$$

L_1 and L_2 can be easily calculated from LR. It is convenient that $\Delta L/L_2 = LR - 1$.

LABORATORY PROCEDURE

For a given ambient level, a contrast of between 30 and 50 percent (2 to 1 luminance ratio) proved to be the minimum contrast below which 75th percentile legibility was lost. Above that contrast level, legibility distance increased gradually on the average to above 80 percent contrast (5 to 1 luminance ratio). Above that luminance ratio, legibility did not increase greatly.

As the ambient level increased and data points were averaged for different luminance ratios, the legibility distance (D_L) increased linearly with the logarithm of luminance (letter luminance for white letters and sign luminance for black letters on white or yellow signs). The slope of the average trend line was steeper for higher contrast color combinations and flatter for color combinations of lower contrast. This resulted in a fan-shaped set of trend lines.

OUTDOOR PROCEDURE

The outdoor legibility distances under high-beam headlights also showed a linear trend of average and 85th percentile legibility when plotted against logarithm of luminance. These trend lines for the white on green and black on white were essentially similar to the laboratory trend lines for equivalent legibility distances. Legibility distances under low-beam headlights, however, were greater than had been expected from laboratory results. Under both headlight conditions, the lower luminance material gave shorter legibility distances than the higher luminance material.

The longer than expected legibility distances under lower luminance (low-beam headlights) were attributed to the effects of unlimited viewing time rather than the short viewing time allowed in the laboratory method. Therefore, it appeared that short-time glance legibility, which is important for automobile driving, requires high luminance. Greater legibility (in the laboratory) at high luminance for black letters on yellow than for white letters on green was attributed to a spreading effect of light in the eye. This hypothesis was confirmed in the outdoor observations by comparing the height of test letters of wider and narrower strokes (7 to 1 versus 5 to 1 ratios of height to stroke widths).

COLOR RECOGNITION RESULTS

Before interpreting and applying the legibility results to the new sign and legend color combinations, it is necessary to examine in some detail the results of the color recognition study. Proper color recognition is important because color coding is used to indicate the type of sign and message. The luminance values of the colored target signs furnished data for estimating legibility.

Two series of colored target signs were used to determine the sign luminance needed for color recognition that was 75 percent correct. Table 1 gives the sign luminance required for each of the five background luminances for 75 percent correct color recognition. It also gives the luminance ratios of the sign to background-luminance level. The zone beyond which colors were confused (less than 75 percent correct color recognition by the 30 subjects in each of the five studies) was determined by a visual comparison of graphic tabulations of the results for each sign color and luminance level.

Since the background luminance increased from study to study, higher sign luminance for each of the seven colors in this part of the experiment was required for color recognition (Table 1). For a given background level, green and blue were recognized at a lower luminance than were white, yellow, and orange. The larger red signs were recognized at luminance similar to that for yellow and orange, but the smallest red signs were recognized at lower luminances.

The luminance ratio of sign to background was somewhat higher for the darkest ambient luminance than for the four studies with higher ambient luminances. Conversely, with a few exceptions, the luminance ratio was lower for signs viewed against higher ambient luminances.

Since brown was often confused with other colors (red and orange especially), a 75 percent correct performance was not obtained. Red and orange were confused with each other to a considerable extent. The smallest red signs were correctly recognized at low luminance levels. This relation was contrary to relations established for the other colors.

Discussion of Color Recognition Results

Although color recognition was achieved at low luminance levels against a low ambient background, the luminance ratio of sign to background was higher for the lower luminance levels than for the higher luminance levels. For the higher luminance levels, the sign-to-background luminance ratio was between 4 and 5 to 1 for green and blue and from 10 to 20 to 1 for red, orange, yellow, and white. These ratios were similar for the four higher luminance levels (within the variation to be expected of the type of subjective judgment inherent in this type of experiment).

At the highest ambient level—15.25 cd/m^2 (4.45 ft-L)—orange, red, yellow, and white may have suffered from a gold tone in the projection of the dark background slides on the high-gain screen. The fact that green and blue were most easily recognizable at low luminance levels can be expected from the known sensitivity of the human eye for these wavelengths under dark-adaptive conditions.

Application of Color Recognition Results to Highway Signs

From the results given in Table 1, it may be concluded that up to the medium background level of study 5—1.54 cd/m^2 (0.449 ft-L)—a luminance of 8.57 to 30.8 cd/m^2 (2.5 to 9.0 ft-L) will give satisfactory color recognition for all colors. This medium background would simulate a lighted suburban condition. For the higher brightness backgrounds, the luminance required for satisfactory color recognition is between 34.3 and 102.8 cd/m^2 (10 and 30 ft-L), with some possible exceptions. These luminances make possible signs of sufficient contrast for legibility in both darker and medium levels of luminance.

The range of 82.2 to 343. cd/m^2 (24 to 100 ft-L) required for color recognition against the highest luminance background would cause no problem of satisfactory contrast for legibility with white letters on green or blue signs or for black letters on signs of other colors. There might be a problem if white letters are used on red or brown signs. Since brown signs were confused at all luminance levels, this indicates that brown is not a good color to use for a sign when to distinguish it from a red or orange sign is critical to transmitting meaning.

OBSERVED LEGIBILITY AND LUMINANCE OF COLOR COMBINATIONS

As previously mentioned, the equivalent legibility distance (calculated from visual angle) for 75 percent correct responses in the laboratory when plotted against the logarithm of luminance resulted in a family of straight lines. Since square letters were used for the outdoor legibility observations and stroke-width comparisons in the previous studies, it seemed best to make estimates for square letters in this study. From the previous daylight studies, it is known that legibility distance increases with letter width if letter height is constant. Accordingly, our laboratory legibilities were corrected for square-letter width (laboratory letter width was four-fifths the letter height), resulting in the average trend lines shown in Figure 1. The trend line for black on yellow in the laboratory fitted the outdoor black on yellow 85th percentile fairly well, but the white-on-green line indicated lower legibility distances than those obtained from the outdoor observations. These comparisons were made with the higher luminance under high-beam conditions.

There was a possibility that by averaging all data points (all contrasts), the legibility trend lines might be unduly influenced by aberrant data points. Therefore, the higher data points of the legibility versus luminance plots were averaged to produce trend lines; the legibility points that appeared to be too low were omitted. The average trend lines appeared to fit the outdoor data equally well. Since the average is more conservative, the average trends were used for estimating legibility of the different color combinations and contrasts.

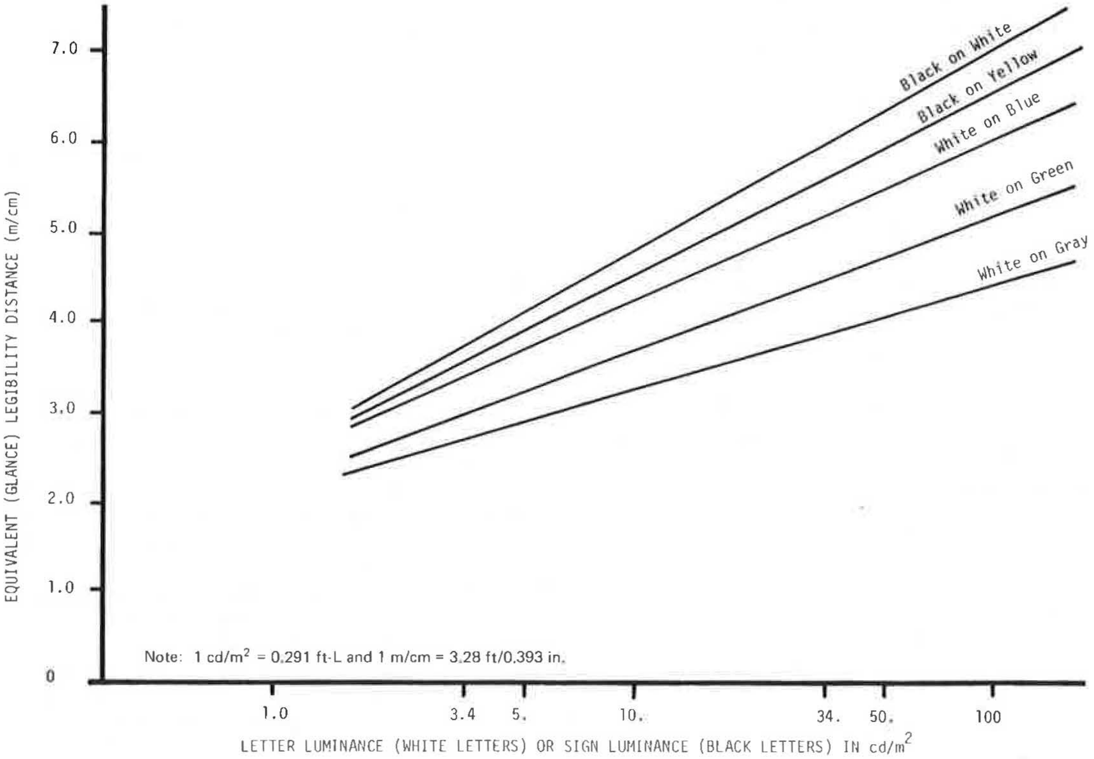
Table 1. Summary of color recognition and luminance.

Study Number	Average Ambient Background Luminance (cd/m²)	Color													
		White		Yellow		Orange		Red		Brown		Green		Blue	
		(cd/m²)[a]	LR[b]	(cd/m²)[a]	LR[b]	(cd/m²)[a]	LR[b]	(cd/m²)[a]	LR[b]	(cd/m²)[a]	LR[b]	(cd/m²)[a]	LR[b]	(cd/m²)[a]	LR[b]
1	0.127	2.98	23.5	6.17	48.6	3.22	25.4	2.12	16.7	>2.40	—	1.71	13.5	1.30	10.6
2	0.466	7.26	15.6	9.49	20.3	11.0	23.6	7.26	15.6	>8.22	—	2.91	6.3	1.13	2.4
5	1.54	26.24	17.1	20.9	13.6	32.4	21.1	11.1	7.3	>37.7	—	8.91	5.8	8.57	5.6
4	7.30	87.36	12.0	217.6	30.0	113	15.5	95.9	13.1	>109	—	34.3	4.7	41.1	5.6
3	15.25	274	18.0	274	18.0	479	31.5	343	22.5	>363	—	115	7.5	83.9	5.5

Note: 1 cd/m² = 0.291 ft-L.

[a] Luminance. [b] Luminance ratio.

Figure 1. Average legibility for color combinations.



Note: 1 cd/m² = 0.291 ft-L and 1 m/cm = 3.28 ft/0.393 in.

DISCUSSION AND APPLICATION OF STROKE-WIDTH EFFECTS

The stroke width used in the laboratory study (stroke width equal to one-fifth of the letter height) is similar to that of the modified series E and F of the U.S. standard alphabets. Our laboratory results suggested that the effect of spreading of light in the eye from the higher luminance white letters tended to reduce legibility of the white letter on a darker sign. A reverse effect would be expected with black letters on a light sign. The outdoor results that compared legibility of four narrow-stroke letters with that of four wider stroke letters confirmed that hypothesis. The narrower stroke width of the narrow square letters used outdoors was one-seventh of the letter height, which is similar to that of some of the narrower stroke U.S. standard capital letters.

The increased legibility under high luminance of narrow-stroke white letters on a dark sign and the reduced legibility of black letters with a narrower stroke width are consistent with experimental results reported by others (1, 2, 3). Also, Anderton and Cole (4) used a red annulus on a speed sign and compared a standard, a wide, and a narrow stroke width. The narrow stroke width caused the red annulus to become washed out. This gave a shorter legibility distance for the narrow-stroke red-on-white combination, an effect similar to that with our black-on-white narrow stroke width.

On the average, the legibility distance for the narrow stroke increased about 10 percent for the white letters and decreased a similar amount for the black letters. Thus, a stroke width one-sixth of the letter height would be the best compromise, for practical purposes, if the same stroke width is to be used for both color combinations.

Accordingly, the laboratory trends were corrected for stroke width before estimating relative legibility distances of color combinations. Figure 2 shows the average trend lines corrected for a stroke width of one-sixth of the letter height. This correction results in a logical series of trend lines in which black on white is highest and white on blue and black on yellow are relatively close together. The correction for one-seventh of the letter height yielded a series of trend lines for the color combinations that was not as logical. Therefore, the one-sixth letter height correction was used for estimating the relative legibilities of the different color combinations.

To estimate the legibility trend lines for colors other than those described above, the luminances and luminance ratios for all the colors are needed. The open colors (i.e., without the neutral overlays used to reduce luminance) of the target signs used in the laboratory procedure furnished the needed data. Measurements of actual traffic signs in and around East Lansing, Michigan, were examined; the luminances of these signs were similar to those in the laboratory for intermediate levels of background luminance. Furthermore, shoulder-mounted sign luminances measured by Woltman and Youngblood (5) at 182.8 m (600 ft), using high and low beams, indicated that the laboratory mid-range luminance levels were in the same range as outdoor measurements.

ESTIMATED LEGIBILITY OF OTHER COLOR COMBINATIONS

Legibility levels and the trend-line slopes for the five color combinations in the previous report showed a relation to luminance ratio for each color combination. For a given luminance, a maximum and a minimum range of legibility can be obtained. By assuming that the luminance ratios from study 2 were representative, estimates of legibility distance were made for each color combination measured in the previous report and also for the new color combinations. Maximum and minimum legibility distances were determined from the average trend lines that had been corrected for square-letter width and for a stroke width one-sixth of the letter height as shown in Figure 2. After correction for this stroke width, white on black and black on white were assumed to give the same legibility distance. Based on these trend lines, maximum and minimum legibility distance values for 34.2 and 3.4 cd/m^2 (10 and 1.0 ft-L) were recorded. The difference between maximum and minimum legibility distance was proportioned according to luminance ratio to give ΔD_L. This amount was then subtracted from the maximum legibility distance to give the estimated legibility distance for the color at that luminance.

These calculations, using values for square letters, resulted in the trend lines shown in Figure 3. For series D letters, legibility distance would be four-fifths the values derived. It should be remembered that these estimates are for the glance legibility and for the colored materials measured in the laboratory. If there is a high negative contrast (white and yellow signs with black letters of very low luminance), it will be necessary to assume a luminance for black that is one-twentieth of the white-sign luminance.

The procedure for estimating legibility in terms of factors involving luminance ratios of legend to sign is based on reductions from maximum legibility distance (2). For an observer with 85th percentile visual acuity, 6.6 m/cm (55 ft/in) of letter height is a reasonable maximum, since 7.2 m/cm (60 ft/in) with a stroke width of one-fifth of the letter height corresponds roughly to normal acuity of 1.0 min of arc. The trend lines should not be used beyond such maximum values. These maximum values were also confirmed by the outdoor legibilities. The luminances of the projected target signs, even though they were carefully measured with a Pritchard photometer, were more variable than is desirable. Therefore, average trends and intermediate-level luminance ratios that were generally similar to our measurements outdoors were chosen for the estimates.

GLANCE LEGIBILITY IN LABORATORY AND FULL-SCALE LEGIBILITY RESULTS

As previously mentioned, the outdoor observations confirmed the laboratory results for high-luminance 85th percentile legibility distances. Distances were similar to the laboratory (equivalent) legibility distance values and to the luminance relationships for high luminance (high-beam headlights) for both standard- and high-luminance sign materials. However, for low-luminance (low-beam headlights) legibility distance, the outdoor full-scale observations gave longer legibility distances than the laboratory results would predict for both materials.

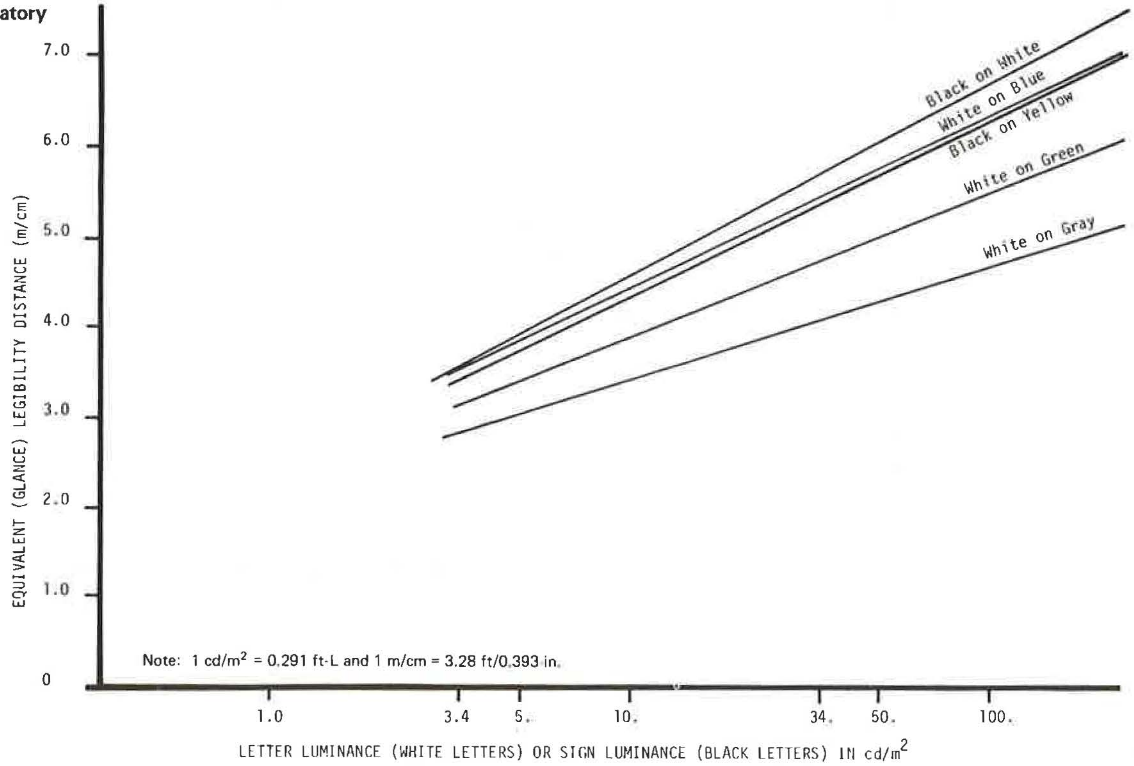
The laboratory measurements involved glance legibility because the observation time was limited and the subjects were required to call out letter orientation as each group of test signs was shown. For full-scale outdoor observations, the observation time was not limited. Each subject recorded his or her observations and looked at the signs when desired.

The laboratory trend lines fitted the outdoor high-luminance trend lines quite well. Previous studies by Forbes (5) and Hurd (6) have shown glance legibility to to give shorter legibility distances under high luminance (outdoor, daylight) conditions. This indicates that legibility under these conditions is a more difficult visual task. Therefore, it is reasonable to assume that glance legibility would require higher luminance under night viewing conditions. This interpretation conforms qualitatively with the finding that shorter exposure gives a steeper curve of visual performance plotted against the logarithm of luminance (2). This led to the use of a 0.2-s exposure in measuring the effectiveness of illumination for visual tasks.

ORDINARY AND GLANCE LEGIBILITY REQUIREMENTS

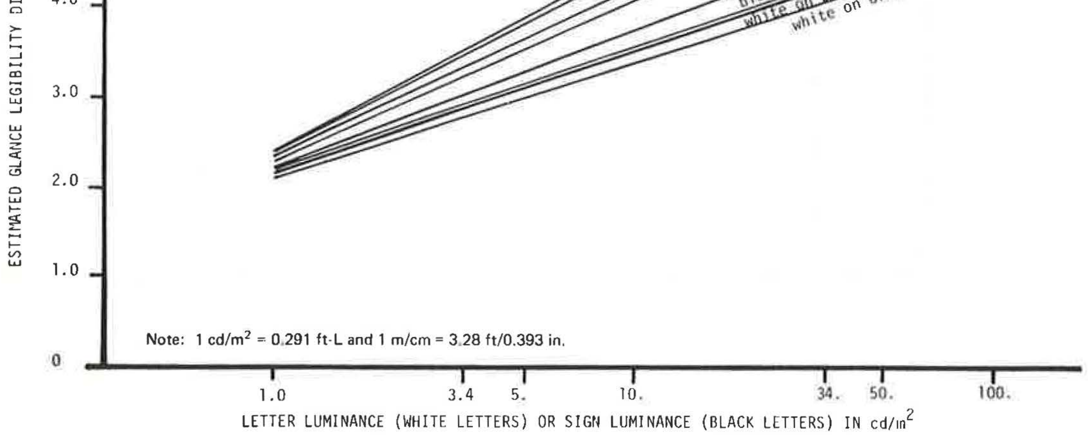
Because the results of the laboratory procedure were used, the estimates are for glance legibility of the different color combinations. Ordinary (long) legibility and glance legibility relations were examined in outdoor observation data and trend lines (7). By assuming that the high luminance trends represent glance legibility and

Figure 2. Laboratory legibility and luminance.



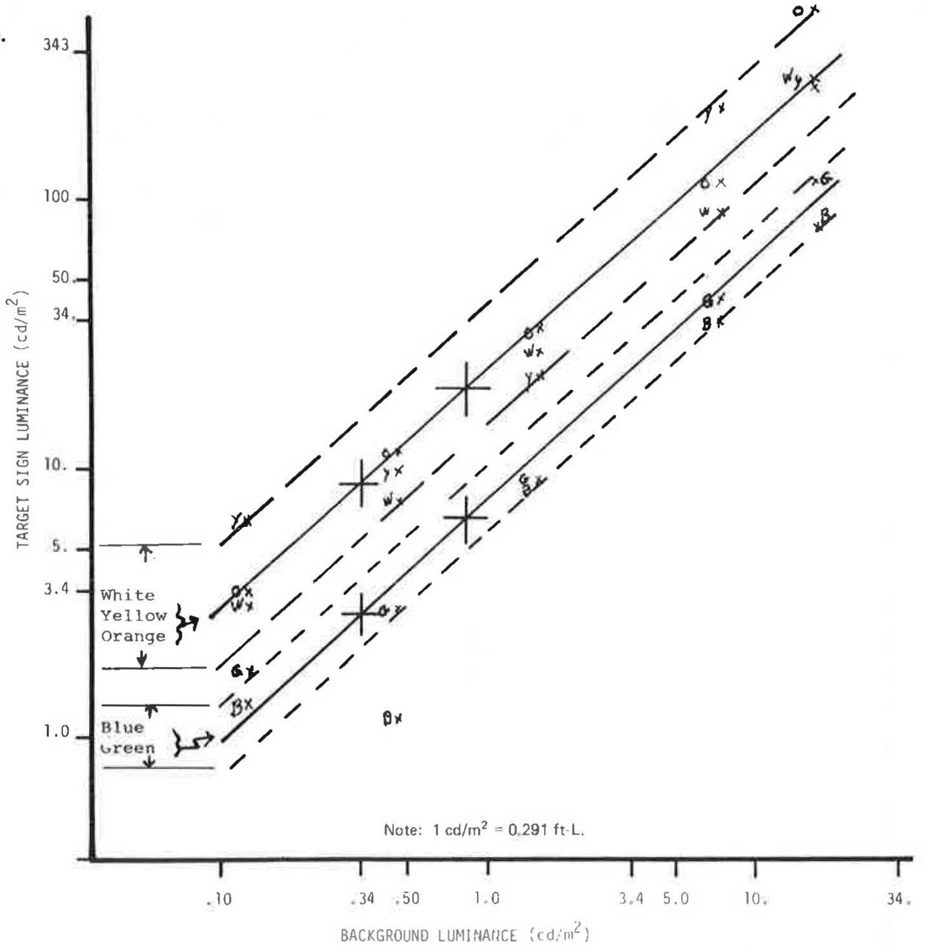
Note: 1 cd/m² = 0.291 ft-L and 1 m/cm = 3.28 ft/0.393 in.

Figure 3. Legibility estimates for laboratory color combinations.



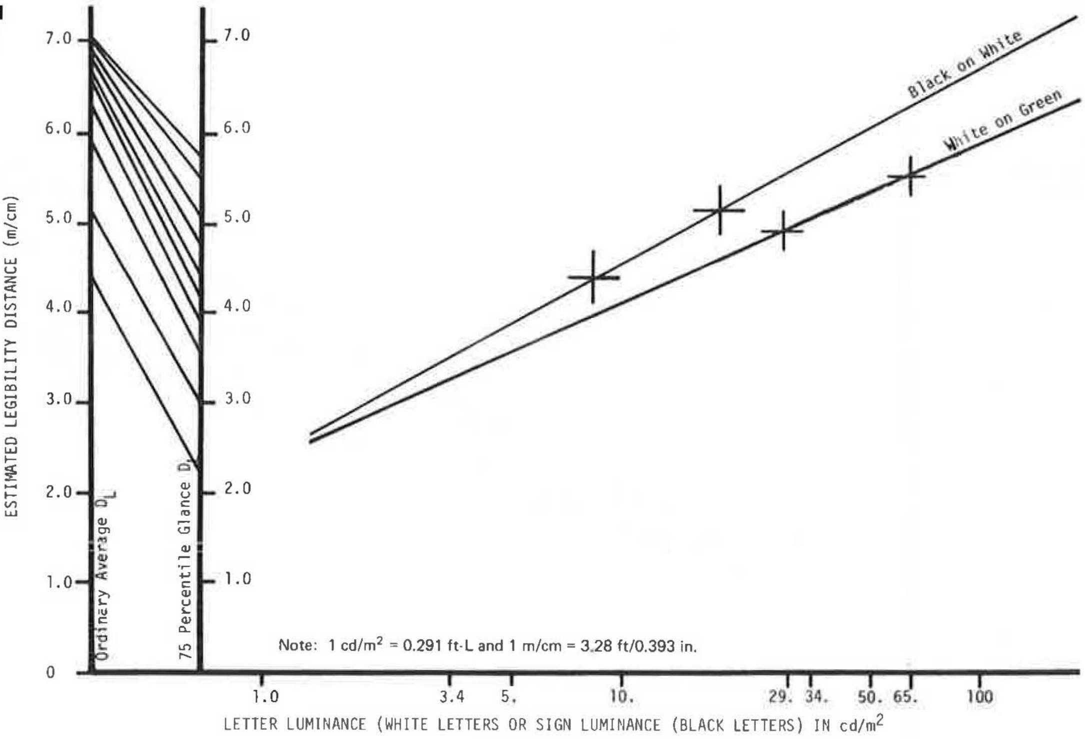
Note: 1 cd/m² = 0.291 ft-L and 1 m/cm = 3.28 ft/0.393 in.

Figure 4. Sign and background luminance.



Note: 1 cd/m^2 = 0.291 ft-L.

Figure 5. Estimated glance and ordinary legibility.



Note: 1 cd/m^2 = 0.291 ft-L and 1 m/cm = 3.28 ft/0.393 in.

low luminance represents ordinary legibility, the relations of glance legibilities to those obtained with long target exposure can be roughly estimated as follows:

$$D_L = 1.5 \times D_{L(\text{glance})} \tag{4}$$

The maximum legibility distance is 6.6 m/cm (55 ft/in).

Since the measurements for legibility distance were based on 75 percent correct responses of subjects in the laboratory, the 85th percentile responses obtained outdoors were more comparable than average distances as a check of the laboratory results. Legibility estimates were made in terms of the 75th percentile values determined in the laboratory. The 75th and 85th percentile values are ordinarily similar and are most applicable since they provide for most drivers. In comparing these values with average values obtained in other studies, however, it should be remembered that our outdoor observations showed average legibility distances to be about 1.2 m/cm (10 ft/in) of letter height greater than the 85th percentile values or from 15 to 20 percent greater for maximum values of D_L.

In the outdoor observations, the use of a single test letter with four possible orientations is similar to the use of scrambled letters under the same conditions. Previous studies have shown that familiar words and syllables are read (in daylight) at 7.2 to 8.4 m/cm (60 to 70 ft/in) and scrambled letters are read at about 6 m/cm (50 ft/in).

The legibility versus logarithmic luminance value lines of Figure 2 were calculated from the value lines of Figure 1 that averaged observations across the five backgrounds. As would be expected, the range of observed data points in the five studies overlapped. The background average luminances for each study are given in Table 1.

APPLICABILITY OF LEGIBILITY ESTIMATES

The calculated trend lines of Figure 3 approximate legibility distances for our colored materials, which are similar to those in traffic signs. The following example illustrates an estimation method that can be used for different sign color combinations if appropriate measurements of background, letter, and sign luminance (corrected for human color recognition) are available.

The legibility distances observed and those estimated are based on luminance and the luminance ratio between sign and legend. These quantities vary for highway signs according to the mounting position (by the roadside or overhead) and whether headlight beams are low or high. However, if luminance measurements for these conditions are available or can be made, the estimates from this procedure should be applicable.

The following is the method for relating glance and ordinary legibility estimates to background, sign, and letter luminance and to color recognition. The color recognition results shown in Table 1 and the equivalent legibility of color combinations shown in Figure 3 must be used together for adequate application. Figure 4 shows a plot of two color groupings that require similar luminance and contrast for color recognition. Sign luminance is plotted against the background luminance from Table 1. The white, yellow, and orange values give the upper band and the blue and green values give the lower band on the graph.

Figure 5 shows the estimated glance legibility trend lines for black on white and for white on green from Figure 3. Scales for estimating ordinary legibility from glance legibility data are shown on the ordinate. As previously mentioned, a very rough estimate of ordinary legibility can be obtained by multiplying the equivalent glance legibility by 1.5 with a ceiling of 6.6 to 7.2 m/cm (55 to 60 ft/in). The double ordinate gives an approximation derived by an averaging process from the trend lines (obtained from outdoor observations) that were related to glance legibility laboratory estimates from Forbes (5).

The ceiling of about 7.2 m/cm (60 ft/in) for average legibility distance is indicated by the convergence of the lines joining the two ordinate scales in Figure 5. This ceiling represents what would be expected from 20/20 vision. Greater ordinary legibility distances may be obtained by using a message familiar to subjects and by using subjects with higher acuity than normal.

To apply the combined results, the ambient luminance against which the sign will be viewed must be known. Figure 4 indicates the background luminance on the abscissa and, for the appropriate color trend line, the target sign luminance for satisfactory color recognition, on the ordinate. Figure 5 presents the sign or letter luminance on the abscissa and the equivalent glance legibility on the first ordinate. The slanting line to the left ordinate scale shows the ordinary legibility distance.

In the case of white letters on green or blue, the letter luminance must be determined from the sign luminance. The sign luminance determined from Figure 4 must be multiplied by the letter-to-sign luminance ratio (LR_{LS}). The luminance ratio for white on green used in the estimates was 11.4 (5). However, legibility levels off above 80 to 90 percent contrast; therefore, the more convenient figure $LR_{LS} = 10$ can be used. Figure 5 shows the resulting letter luminance on the abscissa and the white-on-green trend line indicates the estimates of glance and ordinary legibility distance on the ordinates. Examples of these procedures for a rural background with 0.34 cd/m^2 (0.1 ft-L) luminance follow.

1. Black-on-white sign: (a) For color recognition, read up on Figure 4 from 0.34 cd/m^2 (0.1 ft-L) to W-Y-O trend line and read across to ordinate = 8.6 cd/m^2 (2.5 ft-L) luminance for color recognition of white, yellow, or orange sign; (b) for legibility distances, read up on Figure 5 from 8.6 cd/m^2 (2.5 ft-L) to B/W trend line and read across to ordinate = 4.4 m/cm (37 ft/in) distance estimated for glance legibility or 6.6 m/cm (55 ft/in) for ordinary legibility.
2. White-on-green sign: Read up on Figure 4 from 0.34 cd/m^2 (0.1 ft-L) to G-B trend line, read across to ordinate = 2.9 cd/m^2 (0.85 ft-L) luminance for color recognition of green sign, and multiply by 10 (letter-to-sign luminance ratio) = 29.1 cd/m^2 (8.5 ft-L); read up on Figure 5 to W/G trend line from 29.1 cd/m^2 (8.5 ft-L) for letter luminance and read across to ordinate = 4.9 m/cm (41.0 ft/in) distance for glance legibility or 6.8 m/cm (57 ft/in) for ordinary legibility.

CONCLUSIONS

1. Viewed against five different ambient luminance levels, signs required increased luminance for color recognition as background luminance increased.
2. A contrast between the sign and the ambient background luminance levels of 80 percent to more than 90 percent yielded 75 percent correct color recognition under night conditions. Minimum contrast levels of at least 65 percent are recommended for maintaining a minimum level of sign visibility.
3. Legibility of the five sign color combinations at each ambient luminance level were lowest at a 50 to 60 percent contrast (legend to sign). Above an 80 percent contrast, legibility leveled off for each color combination

and ambient background level.

4. Ordinary outdoor legibility was approximately 1.5 times glance legibility for this study. It leveled off at about 7.2 m/cm (60 ft/in). A better estimate that includes the ceiling effect is given in the example of application of results. Both legibility functions increased as signs and surround luminances increased toward daytime levels.

5. Corrections for the effect of narrow versus wide strokes, for bright letters on darker backgrounds, and bright backgrounds having dark letters respectively were included in legibility estimates.

6. The method developed for estimating the glance and ordinary or static legibility of different color combinations is applicable when sign, legend, and ambient luminance values are available.

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Abridgment

Effect of Illumination on Rural At-Grade Intersection Accidents

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The at-grade intersection has been recognized as one of the more hazardous elements of the rural highway system. This is substantiated by the fact that 15 percent of fatal rural accidents and 25 percent of all rural accidents occur at intersections (1). The intersections, however, account for only a small portion of the total rural highway mileage. Further analysis of highway accident statistics reveals that the nighttime period is much more hazardous for the motorist (2, 3).

The installation of roadway lighting at rural intersections can potentially reduce the higher levels of hazard at these locations. The highway engineer, however, must weigh the benefits of lighting against other intersection safety improvements such as channelization, delineation, signalization, or geometric changes. To make such decisions, the engineer should know the probable benefits to be gained from the installation of lighting. The literature contains diverse reports regarding the benefits of roadway lighting; thus, an examination of the effect of illumination on accidents was undertaken as part of a study of warrants for rural at-grade intersection illumination in Illinois. The discussion that follows summarizes the research associated with the accident study (4, 5).

STUDY METHODOLOGY

A review of previous studies indicated that, in addition to illumination, variables such as traffic volumes, intersection geometry, traffic control devices, and channelization all have a significant effect on accidents. Thus, any research method directed toward isolating the relation between illumination and accidents has to be designed to control the effects of many important variables other than illumination.

The method of analysis used in this study compared lighted and unlighted intersections on the basis of accident experience. Initially, seven measures of accident experience were actually considered: (a) night accidents per year, (b) day accidents per year, (c) total accidents per year, (d) ratio of night accidents to total accidents per year, (e) night accident rate, (f) day accident rate, and (g) total accident rate. For the measures that indicated an accident rate, the rate was calculated on the basis of the number of accidents per million vehicles through the intersection.

While all seven measures were subsequently analyzed in the study, measures that compared day and night accidents in terms of ratios were more valid for this study. In this case, the ratio of night accidents to total accidents was used. The use of the ratio greatly reduces the possibility of error since the decision to install lighting was not randomized. The ratio measure is far less sensitive to variables such as good geometrics, which might be systematically related to illumination, than to illumination per se.

DATA COLLECTION

The data base used to measure the relation between illumination and accident experience consisted of data collected at rural at-grade intersections in Illinois. The intersections included in the sample were selected from a list of rural intersections on U.S. and Illinois state highways. For each location, information was collected that pertained to illumination conditions, physical characteristics, traffic volume data, and accident data.

For the purpose of the study, guidelines were developed to decide which rural intersections in the state would qualify as unilluminated intersections. Only the major unilluminated intersections were sampled and were identified by referring to intersection average daily traffic and geometrics, type of traffic control, and vertical and horizontal alignment. Each intersection year was used as the basic element for analysis. The final sample contained 445 intersection data years with 263 lighted intersection data years and 182 unlighted intersection data years.

The intersections in the sample were categorized according to (a) presence or absence of illumination or (b) presence or absence of channelization. Depending on how the intersection's characterization matched the two di-

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Table 1. Mean values of accident measures before and after illumination.

Measure	Before	After	Change (%)
Night accidents per year	1.96	1.67	-15
Day accidents per year	3.61	3.89	+5
Total accidents per year	5.56	5.55	-1
Night accident/total accident ratio	0.330	0.258	-22
Night accident rate	0.224	0.124	-45
Day accident rate	0.204	0.151	-26
Total accident rate	0.222	0.144	-35

chotomous factors, each intersection was placed in one of four groups. Channelization is frequently used in connection with rural intersection improvements, and illumination and channelization improvements are frequently undertaken at the same time. Because of the effect channelization has on the roadway environment, it was included as a variable in the analysis.

ANALYSIS OF RESULTS

The analysis of variance test examined the relations between the two independent variables (lighting and channelization) and the seven dependent variables (accident measures). The test also measured the effects of interactions between the independent variables. An analysis that contained computed means and levels of significance revealed all the significant relations between each of the seven dependent variables and the following combinations of independent variables:

1. The effects of lighting versus no lighting,
2. The effects of channelization versus no channelization, and
3. The interaction between the effects of lighting and channelization.

The initial test determined if there were significant differences between lighted and unlighted intersections as measured by the seven dependent variables at the 10 percent level of statistical significance. The night accident/total accident ratio, night accident rate, day accident rate, and total accident rate had significantly better accident statistics for the lighted intersections. Of these four, only the day accident rate yielded results that were unexpected; lighting reduces the day accident rate. It was concluded that the unsystematic distribution of lighting to intersections that may have unusual geometric conditions, high traffic volumes, or other peculiar characteristics could be responsible for this unusual result.

Table 1 gives the percentage change in accidents for the seven measures. The largest decrease in accidents is in the night accident rate, which is 45 percent lower for illuminated intersections. The 26 percent decrease in the day accident rate can again be attributed to the unsystematic distribution of lighted intersections.

Although analysis of the interactions between lighting and channelization did not prove to be significant, there were differences in the accident measures for combinations of these two variables. The mean night accident/total accident ratio for lighting and channelization conditions indicates that when both lighting and channelization are present the night accident/total accident ratio (0.238) is lower than for either lighting without channelization (0.277), channelization without lighting (0.306), or no lighting and no channelization (0.354). Thus, the simultaneous introduction of channelization and illumination at locations experiencing a high number of night accidents should be encouraged. Because of the nature of the sample, however, it is impossible to draw a conclusion regarding this interactive effect.

The above analysis illustrates the importance of isolating the effects of illumination so that the effectiveness of rural lighting programs can be measured. Only two of the seven dependent variables, night accident rate and night accident/total accident ratio, serve as potential measures of lighting effectiveness. Of these two, the night accident/total accident ratio is the most reliable because it measures changes in accident totals that are related directly to differences in visibility conditions and accounts for variations in traffic volumes. Also, this statistic is easier to compute since night traffic volume estimates are not needed.

When the data are analyzed by using the two dependent variables that can account for differences due to lighting, the beneficial effects of illumination are seen. Thus, the intersections with lighting proved to have significantly better accident statistics than those intersections without lighting. The magnitude of reduction, from 22 to 45 percent for the various measures of effectiveness, indicates that the installation of illumination improves the night driving environment and reduces hazards at locations that have experienced a high total of night accidents.

CONCLUSIONS

This study serves to further validate the general safety benefits that may be derived from the use of illumination at rural at-grade intersections. Furthermore, it substantiates the increased levels of hazard that are associated with rural at-grade intersections during the nighttime period. Based on this study, it may be concluded that

1. Night accidents are significantly reduced at rural at-grade intersections when illumination is installed (the magnitude of reduction varies with the dependent variable that measures accident experience);
2. The night accident rate and the night accident/total accident ratio are significant measures of accident experience when the influence of illumination on night accidents is considered;
3. Illumination results in a 45 percent reduction in the night accident rate and a 22 percent reduction in the night accident/total accident ratio; and
4. Other safety improvements of rural at-grade intersections may reduce both the day and night accident potential at these locations (channelization and illumination together can result in a greater combined reduction in accidents, and thus the implementation of illumination along with other improvements should be encouraged at high accident locations).

It must be recognized that the figures presented in this paper are generalized values and represent the influence of illumination. If illumination is applied to a number of intersections, these values could be expected for the composite group. However, some variation could be expected for the individual intersections since the degree of reduced visibility contributes to the cause of accidents.

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Evaluation of High-Intensity Sheeting for Overhead Highway Signs

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The purpose of this research was to determine the feasibility of using high-intensity sheeting on overhead highway signs without external illumination. The brightness of five high-intensity overhead signs without illumination was compared with that of five conventional signs with illumination. All experimentation was conducted in the field under the physical and environmental conditions experienced by the highway user. Luminance measurements were made with a telephotometer at the driver's eye position in 11 domestic automobiles. A total of 4821 luminance measurements were recorded from the travel lanes of illuminated and nonilluminated roadways. It was concluded that external lighting can be eliminated through the use of high-intensity sheeting on many overhead signs without adversely affecting the service to motorists.

The current practice in Virginia is to reflectorize and illuminate all overhead signs. Reflectorization is obtained by using enclosed-lens reflective sheeting as background and legend materials, and diffuse illumination on the sign surface is provided by lighting fixtures. Many of the lighting fixtures are fluorescent; however, the newer overhead sign installations are equipped with mercury vapor fixtures. Although overhead signs play a significant role in the safe and orderly flow of traffic, they do create problems for traffic engineers and maintenance personnel. One of these problems is external illumination. Cost is always an important factor, and the expense of the initial light installation is compounded by the great distances to the power sources and unfavorable working conditions on heavily traveled highways. The maintenance of the lighting has proved to be a regular and continuing process that requires periodic night inspections to locate malfunctioning lights, and the repairs require that equipment and workers be on the roadway. Associated with the malfunctioning illumination is the loss of sign service to motorists. Several studies have shown that the brightness of conventional signs is reduced drastically when the lighting is eliminated, and thus the level of visibility on the conventional unlighted sign is not sufficient for the average driver (1, 2, 3). Another factor is the demand for electrical energy. In view of the national program for energy self-sufficiency, every practical means of energy conservation must be explored.

Studies have concluded that the brightness of encapsulated-lens (high-intensity) sheeting is superior to that of the enclosed-lens sheeting currently used on overhead traffic signs (1, 2, 3, 4). The performance of the high-intensity sheeting shows significant promise, and the purpose of this research was to determine the feasibility of using the material on overhead highway signs without illumination. Since sign brightness standards have not been established, a comparative technique was employed whereby the brightness of high-intensity overhead signs without illumination was compared with that of conventional signs with illumination.

All experimentation was conducted in the field under physical and environmental conditions experienced by motorists. Luminance measurements were made of the legend and background materials with a telephotometer at the driver's eye position in a variety of conventional automobiles. All measurements were taken from the travel lanes. The major portion of the evaluation was performed on signs installed on nonilluminated highways; however, several experiments were conducted on signs with ambient lighting because of the trend toward illuminating highways, especially in urban areas. Human factors were incorporated into the study by requesting individuals such as police officers, engineers, and motorists to make visual comparisons of the visibility and legibility of the signs.

PHOTOMETRIC INSTRUMENTATION

Luminance measurements were made with a telephotometer that measured the amount of reflected light from the sign surface. The instrument had a transistorized photomultiplier and electrometer amplifier, independent battery power supply, 2-min angle sensing probe, and internal standardization and calibration. Although five acceptance angles were available with the instrument, the 2-min angle sensing probe was chosen since it closely approaches the 20/40 acuity eyesight required for licensing of drivers in Virginia. Furthermore, this acceptance

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angle allowed the measurement of sign letters at the legibility thresholds. The instrument was mounted on a tripod above and behind the driver's seat at the driver's eye position, and two operators were required; one aligned the optical head with the object in the field of view, and the other recorded the result.

STUDY SITES

Because of the comparative technique employed in the study, sites were selected where two or more signs were installed on the same overhead structure. At each site, one sign was refurbished with enclosed-lens sheeting (background and legend) and the adjacent sign was refurbished with high-intensity sheeting. The overlay method of sign refurbishment was used. The lighting fixtures on the conventional signs were inspected and adjustments made to those that were not in accordance with design standards. On the high-intensity signs, all fixtures were disconnected.

The first site selected was the overhead signs (Figure 1) that were located on a 4-lane Interstate highway. The approach was straight, and the downgrade was 0.76 percent. The unlighted high-intensity sign and lighted conventional sign were placed over the left and right lanes respectively. Fluorescent fixtures provided illumination on the conventional signs, and there was no ambient lighting.

Site 2 was selected because the signs (Figure 2) were placed near the crest of a vertical curve. The approach on the three-lane roadway was straight, and the upgrade was 0.59 percent. The nonilluminated high-intensity sign was erected over the right lane, and the conventional sign was placed over the center and left lanes. Illumination was provided on the conventional sign by fluorescent fixtures, and there was no ambient lighting.

To determine the effects of horizontal alignment on the brightness of overhead signs, site 3 was chosen on an exit ramp from an Interstate highway. This two-lane facility included a 3-deg curve, which is the desirable maximum curvature for most Interstate and arterial highways in Virginia. The ramp had an approximate 1.8 percent upgrade, and sign visibility was restricted to approximately 275 m (900 ft) by the geometry and topography. The conventional sign, erected over the right lane, had fluorescent illumination, and there was no other lighting in the vicinity of the signs (Figure 3).

The approach to the overhead signs at site 4 was on a 2-deg horizontal curve and a 2 percent upgrade (Figure 4). The maximum visibility of the signs, erected over an Interstate highway, was approximately 275 m (900 ft) for the left lane and 230 m (750 ft) for the right lane. As at the previous sites, the conventional sign (over the left lane) was illuminated with fluorescent fixtures, and there was no ambient lighting.

Site 5, an Interstate highway, was chosen because it was provided with roadway lighting. The signs in this area did not need refurbishing; therefore, special signs were fabricated and erected for study (Figure 5). The sign erected over the left lane (placed on the existing sign) was fabricated with conventional material, and additional illumination was provided by mercury vapor fixtures. The high-intensity sign, placed over the right lane, had no illumination except the roadway lighting. The roadway geometrics consisted of a 0.24-deg horizontal curve and an upgrade that varied from 0.83 to 1.66 percent.

TEST VEHICLES

The vehicles used for data collection were domestic passenger cars or station wagons, and all had tinted windshields (Table 1). The vehicles were equipped with photometric instruments and needed accessories. The fuel tanks were filled, and the vehicles were taken to an official inspection station for a check of the head-lamp alignment. The intent was to procure a vehicle that was representative of the late model car population and had head-lamp adjustment in conformance with state requirements. Prior to the readings, all windshields and head-lamp surfaces were cleaned.

Before luminance measurements were taken, the vehicles in the travel lanes were aligned with the lane line pavement markings. The driver accomplished this by driving several hundred meters toward the recording position and stopping without last second steering wheel alignment.

DATA RECORDED

At sites 1 through 4, the telephotometer measured the luminances in the areas of the signs designated by circles in Figure 6. Background measurements were taken at available spaces on the sign and at the center and four corners and were made at 91-m (300-ft) intervals up to a maximum distance of 457 m (1500 ft). The sign-legend luminance measurements were limited to distances of 91, 183, and 274 m (300, 600, and 900 ft) because of the 2-min probe used on the telephotometer. At greater distances the letter strokes were not of ample size to allow measurements. Whenever possible, the legend readings were secured as shown in Figure 6, but for some signs complete data could not be gathered because of the placement of the message. Measurements for these signs were taken at the top, center, and bottom to obtain average luminances of the legend materials.

Readings were taken from the left and right lanes of the roadway, and low- and high-beam headlights were used. Also, in an attempt to determine the effects of stream traffic, measurements were taken when other vehicles were adjacent to the observation vehicle. In the latter case, all vehicles in the traffic stream as well as the observation vehicle used low-beam headlights.

At site 5, the average luminances of the special signs were obtained by taking readings of the background and legend materials at the top, center, and bottom. Data were secured from vehicles in the right lane of the roadway under high beams, low beams, and stream traffic conditions. Another complete set of data was recorded from vehicles that approached the signs on a straight course. The centerline of the approaching vehicle was placed perpendicular to the sign face at 457 m (1500 ft); the reticle of the optical head was aligned on a reference target and locked into place.

For the 10 signs under study, 4821 readings were recorded under various weather conditions. Inclement weather affects the luminance of many sign materials, and at each site an attempt was made to secure readings during one evening while dew formations were present. Measurements could not be made during rainfall, but they were taken under icy conditions at site 4.

The roadway illumination in the vicinity of the signs was measured with a mobile illumination recording system developed by the Virginia Highway and Transportation Research Council (5). In addition to the luminance readings, relevant information was recorded at all sites for type of materials used for legend and background, sky cover, ambient lighting, presence or absence of external illumination, position of sign, sign dimensions, vehicle description, and position of vehicle.

At each site, a panel of people were requested to view the signs and express their opinions on the signs' effectiveness. Individuals such as engineers, clerks, secretaries, policemen, and motorists were included in the panels. Because of the hazards involved in stopping on the traveled lanes, these observations were made from a vehicle parked on the right shoulder. On each visit the signs were first viewed at 366 m (1200 ft), or at the maximum visibility distance, under the various lighting conditions. With the signs displayed at this distance, the panel members were asked for their opinions relative to the attention or target value of the signs through questions such as, Which sign did you observe first? What sign characteristics attracted your attention? and Do you feel that both signs have sufficient brightness to gain the attention of the motoring public at this distance? After the comments were recorded, the vehicle was moved forward and stopped at 183 m (600 ft). Questions were asked relative to legibility and the degree and uniformity of brightness. Upon leaving the site, each individual was requested to express a preference between the two traffic signs.

Figure 1. Experimental overhead signs at site 1.

Figure 2. Experimental overhead signs at site 2.

Figure 3. Experimental overhead signs at site 3.

Figure 4. Experimental overhead signs at site 4.

Figure 5. Experimental overhead signs at site 5.

ANALYSIS OF RESULTS

It is generally accepted that the sign legibility distance is 15 m (50 ft) for every 2.5 cm (1 in) of letter height (6). The letters on the signs under study had heights of 30.5 and 40.6 cm (12 and 16 in); therefore, the signs were legible in the 183 to 244-m (600 to 800-ft) range. A study has shown that the visibility distance is a function of the sign dimension, the brightness contrast of the letters to the sign background, and the contrast of the sign with its environment (7). Considering the size of the sign letters, the brightness values of the sign materials, and the surrounding terrain, the visibility recognition distance for the signs erected over nonilluminated roadways (sites 1 through 4) was in the 335 to 366-m (1100 to 1200-ft) range. At site 5 the visibility distance of the signs on the illuminated roadway was in the 244 to 305-m (800 to 1000-ft) range.

Since the brightness or luminance of a sign placed over the highway is a function of the characteristics of the sign material; the trigonometric relationship between the car, the sign, and the roadway; and the illumination reaching the sign from the headlights, it is necessary to

Figure 6. Brightness measurement locations.

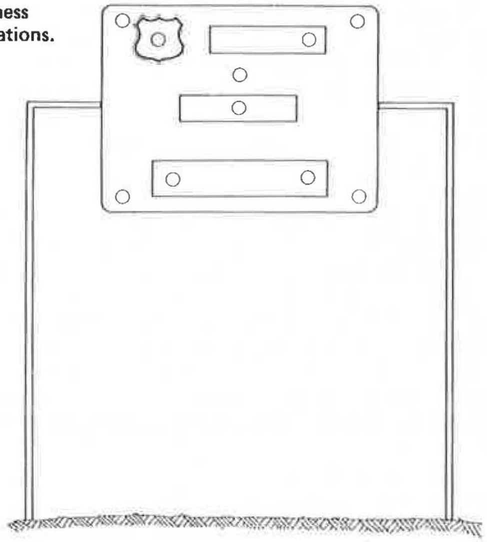


Table 1. Vehicles used in study.

Year	Make and Model	No. of Headlights	No. of Vehicles	Site
1970	Plymouth, 4-door sedan	4	1	1, 2, 3, 5
1974	Vega, 2-door coupe	2	3	1, 2, 3, 4
1974	Mercury, 4-door sedan	4	1	3, 5
1970	Ford, station wagon	4	2	1, 4
1971	Plymouth, 4-door sedan	4	1	4
1972	Ambassador, 4-door sedan	4	2	1, 2, 4
1973	Plymouth, 4-door sedan	4	1	2, 3
Total			11	

discuss each site separately because the roadway geometrics vary.

Site 1

Figure 7 shows the measured average luminances of the background and legend materials of the two signs at site 1 under high beams, low beams, and stream traffic conditions. For high-beam headlights, the average luminance of the unlighted high-intensity background material was brighter than that for the conventional material at 183, 274, and 366 m (600, 900, and 1200 ft). A statistical analysis revealed that, although the luminance of the conventional legend material was greater than that for the high-intensity material, the difference was not statistically significant.

For a motorist traveling alone on the highway and using low beams the average luminance of the lighted conventional material was greater than that for the unlighted high-intensity material. Under stream traffic conditions, the average luminances of the conventional materials were slightly higher than those for the high-intensity materials; however, the differences were not statistically significant within the visibility and legibility distances. The standard deviations revealed that the brightness of the high-intensity sign was much more uniform than that of the lighted conventional sign.

The majority of the 11 people viewing these signs stated that they first observed the conventional sign because of the bright spot created by the exterior lighting. However, they unanimously agreed that at 183 m (600 ft) the luminance appeared greater and more uniform for the high-intensity sign and that it was more legible than the conventional sign. Upon leaving the site, each person stated he or she would prefer the high-intensity sign.

Site 2

Because of roadway geometrics, more illumination from the headlights could reach the sign at site 2 than at site 1, and, as expected, the average luminance readings of the signs were greater. Figure 8 shows that with high beams the high-intensity material was brighter than the conventional material except at 91 m (300 ft). With low beams, the lighted conventional sign was brighter than the unlighted high-intensity sign. In stream traffic, the average luminances of the two background materials were practically the same, although the brightness of the conventional legend material was greater than that of the high-intensity material. The 13 people visiting this site responded in a similar manner to those who visited site 1, with the exception that one-third of the individuals stated that they observed the high-intensity sign before the conventional sign.

Site 3

The nighttime luminance data for site 3 are shown in Figure 9. The measurements were restricted to a maximum of 274 m (900 ft) because of a cut slope on the inside of the 3-deg horizontal curve. Generally, the luminance readings for these signs were lower than those recorded at the previous two sites. The degree of illumination reaching the signs from the vehicle head lamps was limited because of the horizontal curve, and at all observation locations the brightness of the conventional sign was superior to that of the high-intensity sign. The 13 people who viewed these signs stated unanimously that the lighted conventional sign provided better visibility and legibility.

Site 4

Figure 10 shows that the luminances of the signs at site 4 were similar to those measured at site 3. Although the conventional sign was brighter than the high-intensity sign, the luminances for both signs were generally low. The six persons who viewed the signs agreed that the conventional sign provided the better service. Measurements were made of the conventional sign without exterior illumination to determine the effect of a service interruption on the brightness of the sign. At 183 m (600 ft), with high-beam head lamps, there were brightness reductions of 23 and 53 percent for the background and legend materials respectively. By using low beams, the motorist would experience a reduction of 83 percent in the luminance of background material, and the brightness of the legend decreased by 90 percent when the external lighting was absent on the conventional sign. Readings were taken when the signs were covered with ice, and the brightness of the conventional sign, even under non-illuminated conditions, increased while the luminance of the high-intensity sign was not affected.

Site 5

The luminances of the overhead signs at site 5, the only location studied that had roadway lighting, are shown in Figures 11 and 12. Figure 11 shows the data recorded when the signs were approached on a curve, and Figure 12 shows the brightness of the signs when the vehicle traveled directly toward them on a straight approach.

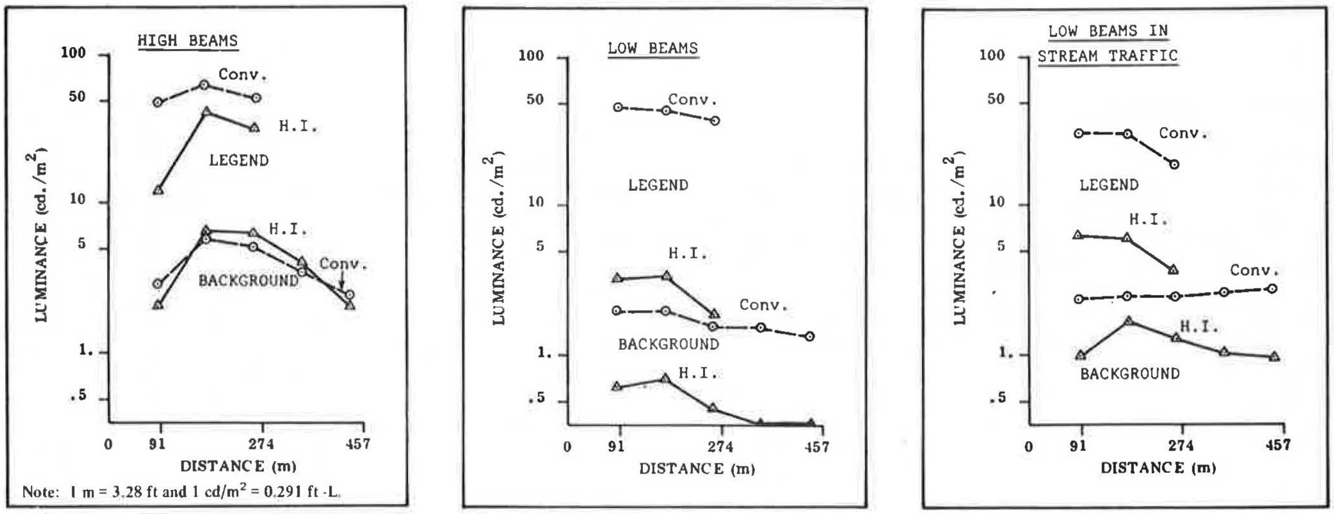
On the curved approach, under high-beam conditions, the luminances of the high-intensity background and legend materials exceeded those of the conventional materials within the legibility and visibility distances. Although the luminance readings of the conventional materials were greater than those of the high-intensity materials for low-beam and stream traffic conditions, there were no statistical differences between the background materials. On the straight approach (Figure 12) the special sign luminances, within the legibility range, were basically equivalent to those recorded on the curved approach; however, the brightness did increase at greater distances from the signs that were within the visibility distance range.

Six people viewed the special signs erected for this study site, and each expressed difficulty in observing the signs at 457 m (1500 ft); this fact emphasized the validity of the shorter computed visibility distances on illuminated roadways. For high-beam and stream traffic conditions, the unanimous preference of these people was for the high-intensity sign. The majority of the same individuals stated that they observed no difference in the brightnesses between the two signs under low-beam head lamps.

CONCLUSIONS AND RECOMMENDATIONS

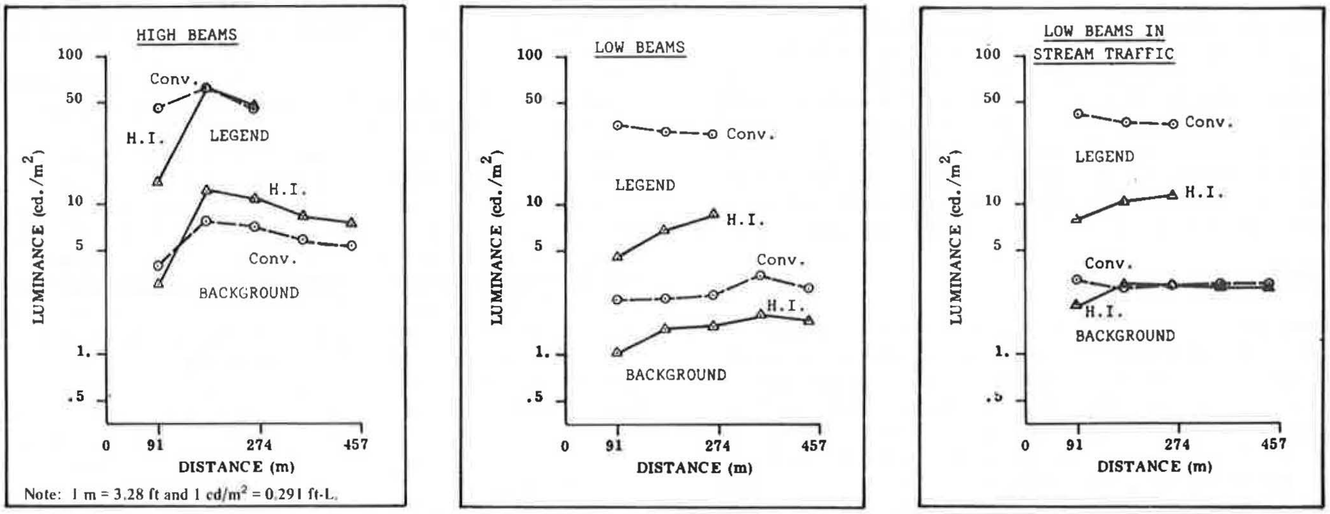
The objective of this study was to compare the field brightness of high-intensity overhead signs without external illumination to that of the lighted conventional signs. The sign luminances measured and reported in this study should not be interpreted as luminescent standards. The National Cooperative Highway Research Program is funding a project that will establish such standards. However, earlier investigators have suggested luminance levels for signs, and several of the measurements taken on the evaluated signs were below these levels (8). The analysis revealed a resemblance among the luminances of signs erected over roadways with similar configurations. The conclusions based on the findings from signs erected over straight, curved,

Figure 7. Nighttime average luminance versus distance at site 1.



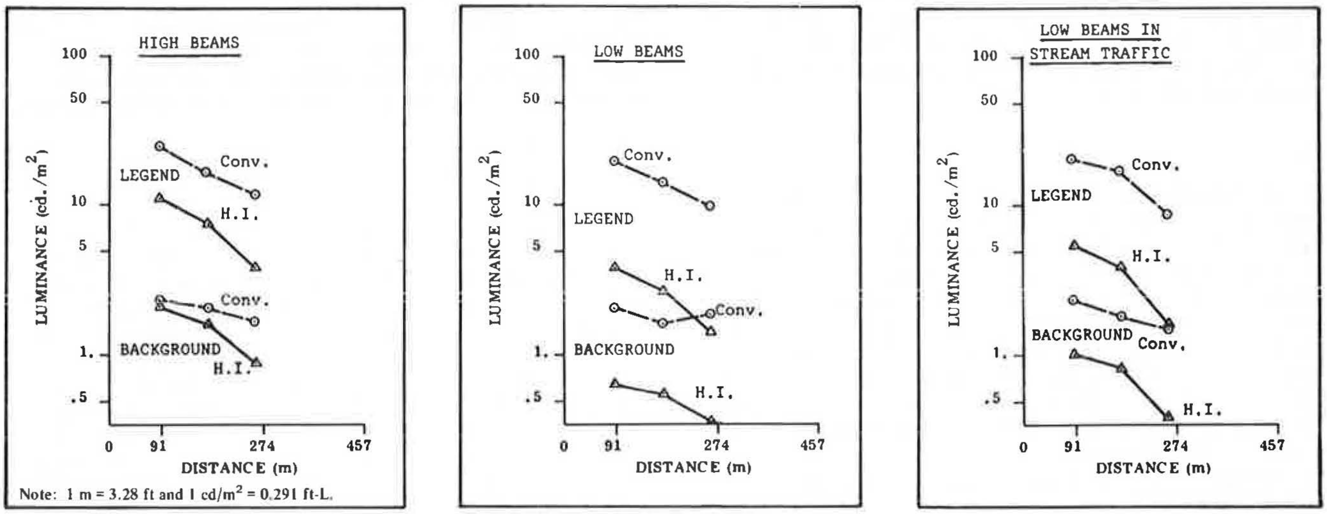
Note: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

Figure 8. Nighttime average luminance versus distance at site 2.



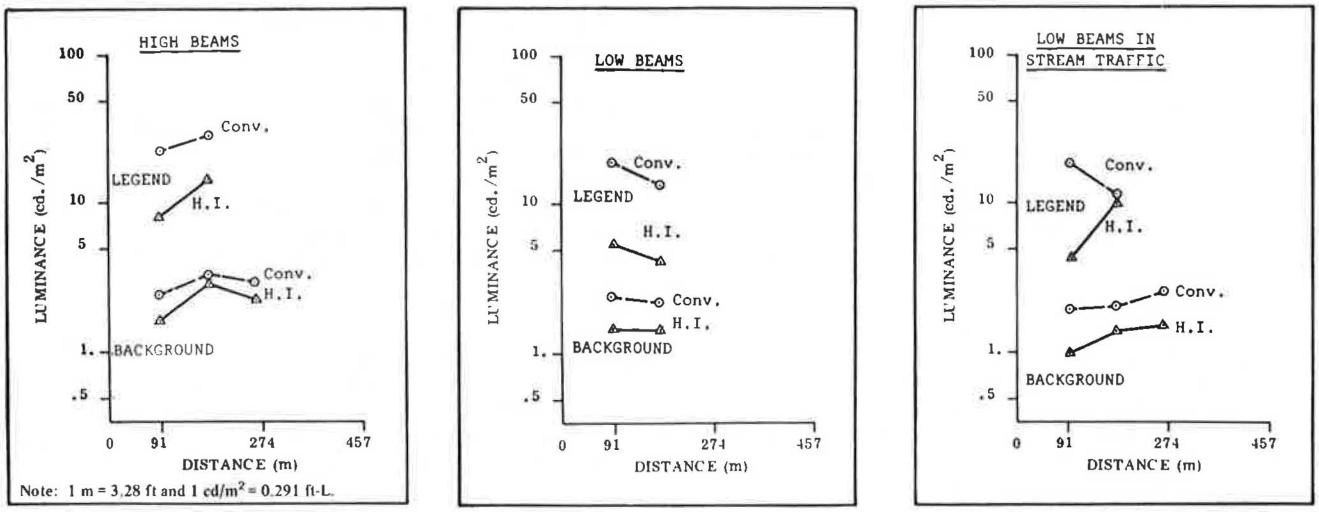
Note: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

Figure 9. Nighttime average luminance versus distance at site 3.



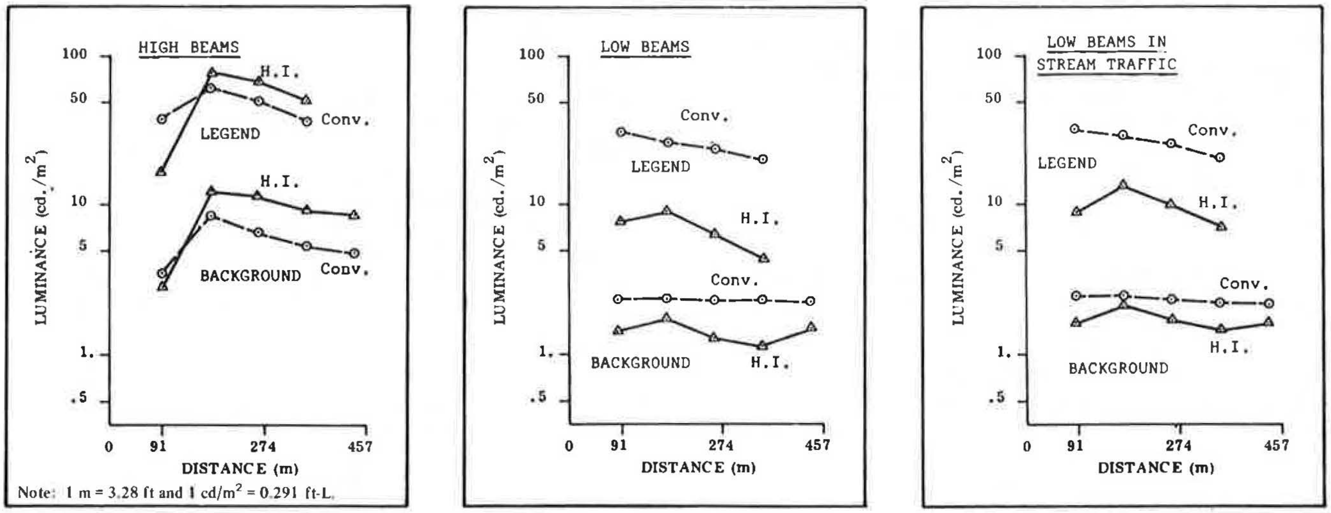
Note: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

Figure 10. Nighttime average luminance versus distance at site 4.



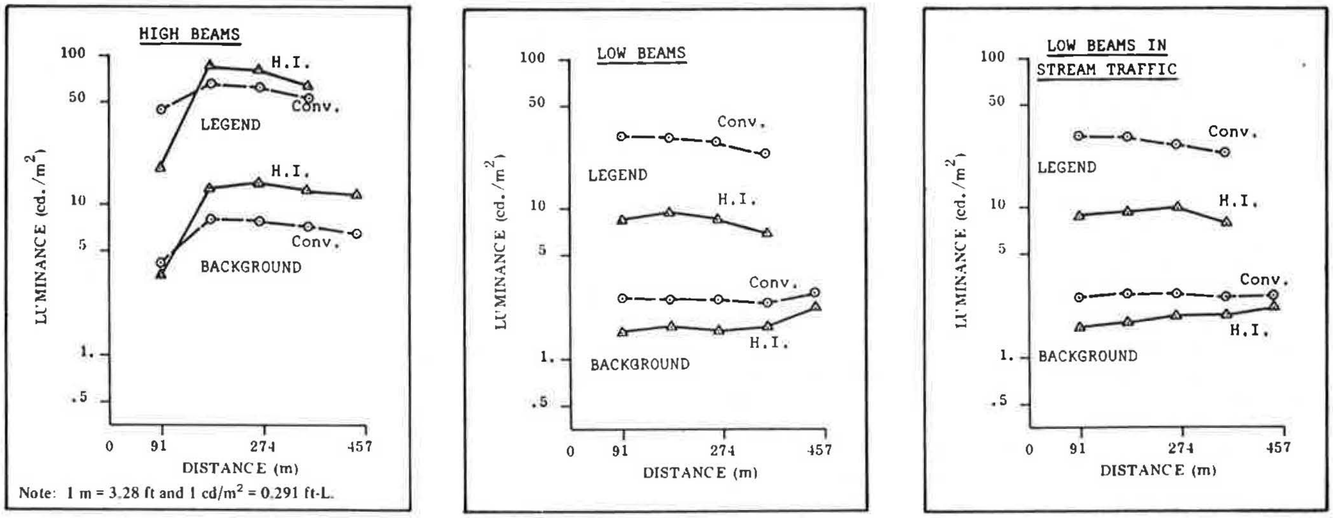
Note: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

Figure 11. Nighttime average luminance versus distance at site 5, curved approach.



Note: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

Figure 12. Nighttime average luminance versus distance at site 5, straight approach.



Note: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

and illuminated roadways are presented in the following sections.

Nonilluminated Straight Roadways

For signs erected over straight sections of roadway, there were no statistical differences in the brightnesses of the background materials for the two signs seen by motorists traveling in stream traffic. Although the average luminances of the high-intensity legend materials were not so bright as those of the illuminated conventional sign, the people who viewed the signs stated that the uniform brightness of the high-intensity sign provided greater legibility than the illuminated sign with the uneven light distribution. For a single vehicle traveling with high-beam lights, the high-intensity signs were much brighter; however, for the same vehicle using low beams, the luminance of the high-intensity signs was not so bright as that of the adjacent conventional signs. The people who conducted the study are of the opinion that there are only limited occasions when it is feasible for the lone motorist to use low beams on a freeway. In fact, it was not possible to collect the low-beam data at any of the study sites until after 1 a.m., when traffic volumes were low. The high-intensity materials provided a constant level of service whereas the brightness of conventional materials was governed by the external lighting. When the external lighting was off, the luminances of the conventional materials were reduced drastically, and the brightness was insufficient to provide the motorist proper service.

Nonilluminated Curved Roadways

On a curved approach, when only a limited amount of light from the vehicles was projected on the overhead signs, the luminances of the unlighted high-intensity materials were not sufficient to provide the motorists with the equivalent sign legibility and visibility obtained from the conventional signs. Although the luminance readings of the unlighted high-intensity sign were more uniform than those of the conventional sign, the persons who viewed the signs on the curved approaches were unanimous in the opinion that the lighted sign provided better service.

Illuminated Roadways

The presence of roadway lighting reduces the maximum visibility distance and thus increases the probability that a sign will not be seen even though the legibility distance may be adequate. Furthermore, the findings of this study indicated that roadway illumination did not significantly increase the luminances of the overhead signs at the one location tested.

For an approach on a straight course and with high-beam headlights, it was concluded that the luminances of the high-intensity materials exceeded those of the conventional materials within the legibility and visibility distances. For stream traffic conditions, the nonilluminated high-intensity sign was preferred. For the approach on a slight curve (0.24 deg) and with high beams, the luminances of the high-intensity signs were greater; however, at distances within the visibility range the luminance levels decreased at a greater rate than they did on the straight approach. Under low-beam conditions the conventional materials were brighter than the high-intensity materials on the straight and curved approaches. At 457 m (1500 ft) the signs did have poor attention value characteristics, but the persons visiting the site stated that within the legibility distance range the high-intensity sign provided better service than the lighted conventional sign under high-beam and stream traffic conditions.

The foregoing conclusions indicate that the external lighting can be eliminated on many overhead signs through the use of high-intensity sheeting without adversely affecting the service to motorists. Consideration should be given to disconnecting or removing the illumination on existing and proposed high-intensity overhead signs on roadways that are susceptible to high-beam and stream traffic lighting conditions and that have a straight approach equal to or greater than the visibility recognition distance. Generally the maximum visibility distances in Virginia are approximately 305 and 366 m (1000 and 1200 ft) for illuminated and nonilluminated roadways respectively. This recommendation should not be applied to signs on roadways where the lone motorist is required to use low-beam headlights, such as narrow median facilities for which state law requires motorists to dim their headlights to prevent the projection of glare into the oncoming driver's eyes. The provision of external lighting on all overhead signs erected over curved sections of illuminated and nonilluminated roadways should be continued. Although lighting is required, the use of the brighter, high-intensity overhead signs at these restricted visibility locations is beneficial, especially during service interruptions.

ACKNOWLEDGMENTS

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Abridgment

Indirect Factors Affecting Reflective Sign Brightness

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The effectiveness of traffic sign materials at night has been investigated in numerous studies and has resulted in recommended luminances for recognition and legibility. The importance of adequate sign luminance is of particular interest owing to threshold levels that must be satisfied for certain situations. In numerous field studies (1), we have noted unusual luminance enhancement during stream traffic when other vehicles are placed immediately ahead of or behind the driver. Under this circumstance, the contribution of other head lamps is easily measured, but vehicle spacing and head-lamp aim are usually unknown for all of the vehicles involved. Similar enhancement has been occasionally observed in rainfall.

DESIGN OF EXPERIMENT

The experiment simulated volumes of 300, 600, and 1500 vehicles/lane/h on a test road. All vehicles in all tests employ low-beam head lamps since common use of lower beams is well documented and is the rule with high volumes. Upper beams generally produce quite adequate sign luminance; however, lower beams on unlighted overhead guide signs provide only threshold values for legibility for single vehicles. Therefore, increases that may derive from a common operational circumstance would be very beneficial.

The test road is 670 m (2200 ft) long and was designed to represent a one-way tangent section of an Interstate highway. Measurements were made from five distances that ranged from 457 to 91 m (1500 to 300 ft). The road surface is made of a comparatively fine-textured asphaltic concrete. While single-vehicle sign luminance measurements were proceeding, unexpected rain produced a thoroughly wet road surface. A set of readings were taken under this condition, which approximated an estimated 25-mm/h (1-in/h) rate. The road surface condition and sign luminance readings were subsequently reproduced with a sprinkling truck.

Luminance measurements were made from a full-sized station wagon, which had untinted glass and was equipped with a telephotometer at the driver's eye position. The vehicle head lamps conformed to the Society of Automotive Engineers (SAE) recommended standard for photometrics and aim.

The sign materials studied are representative of silver-white retroreflective materials employed for traffic control signs. The materials used were as follows:

Material	Description	Illuminance (lx)	Angle (deg)	
			Divergence	Incidence
A	Encapsulated-lens reflective sheeting	2 691	0.2	-4
B	Enclosed-lens reflective sheeting	861	0.2	-4
C	Cube corner button	23 250	0.1	0
D	Cube corner reflective sheeting	10 763	0.2	-4

Panels 0.6 by 0.6 m (2 by 2 ft) were used for reflective sheeting, and a 457-mm (18-in) capital letter was used for material C and was positioned to represent the center of typical sign placement specified in the Manual on Uniform Traffic Control Devices (2).

Three densities of stream traffic were simulated by positioning 3, 6, and 15 vehicles at equal distances and by staggering the vehicles on the left and right lanes. These densities are representative of traffic volumes of 300, 500, and 1500 vehicles/lane/h.

RESULTS AND CONCLUSIONS

The luminance readings are given in Table 1 and shown in Figure 1. For unlighted overhead signs, the single vehicle with low beams produced luminances of 3.4 to 6.9 cd/m^2 (1 to 2 ft-L). With 3 vehicles spaced at 152-m (500-ft) increments, sign luminance for the test vehicle increased from 3.8 to 9.6 cd/m^2 (1.1 to 2.8 ft-L). With 6 vehicles spaced at 91-m (300-ft) increments, sign luminances for the test vehicle increased from 9.3 to 14.0 cd/m^2 (2.7 to 4.1 ft-L). For 15 vehicles spaced at 15-m

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(50-ft) increments, corresponding to near capacity for an average facility, sign luminances for the test vehicle increased from 26.7 to 28.4 cd/m^2 (7.8 to 8.3 ft-L); the greatest increase occurred at 366-m (1200 ft) increments. The increase from 3.4 to 4.1 cd/m^2 (1 to 1.2 ft-L) to approximately 24 to 27 cd/m^2 (7 to 8 ft-L) occurred at longer distances. For a 183 to 91-m (600 to 300-ft) range, sign luminance nearly doubled as compared with sign luminance for the single vehicle.

The improvement at the longer distance appears to be due to the close angular proximity of the adjacent headlights. This comparison is given in Table 1 and is shown in Figure 2. An approximation of the overhead sign luminance I may be expressed as follows:

$$I \cong I_1 \times (Vn + 1)/2 \qquad (1)$$

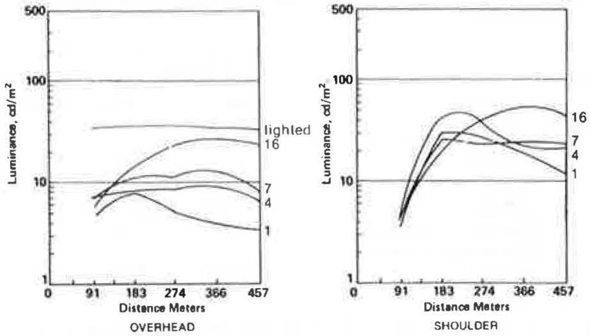
Table 1. Nighttime luminance of silver-white retroreflective sign materials in stream traffic with vehicles on low beam.

No. of Vehicles in Traffic Stream	Material	Overhead Sign Luminance (cd/m^2) by Distance From Vehicle					Shoulder-Mounted Sign Luminance (cd/m^2) by Distance From Vehicle				
		457 m	366 m	274 m	183 m	91 m	457 m	366 m	274 m	183 m	91 m
15	A	26.7	28.4	24.7	15.4	6.2	47.0	61.7	36.3	21.2	4.8
	B	15.1	16.4	13.0	10.3	5.5	25.7	32.6	23.6	12.7	5.1
	C	11.6	12.7	13.4	7.5	3.8	20.6	39.4	22.6	15.8	4.4
	D	60.0	64.1	60.0	33.6	12.3	106.3	120.0	85.7	44.2	13.0
6	A	9.3	14.0	12.7	12.0	4.1	25.0	26.4	24.0	27.4	3.8
	B	6.2	8.2	6.2	5.1	2.7	8.6	12.3	12.0	13.7	3.4
	C						8.6	9.2	12.0	12.0	3.4
	D	22.6	28.1	25.4	22.3	9.6	54.8	49.7	48.0	56.6	11.0
3	A	6.9	9.6	9.3	8.9	4.4	22.3	21.6	39.8	40.4	4.8
	B	5.1	4.4	4.1	4.4	3.1	10.3	10.3	33.6	23.0	4.1
	C						10.3	12.3	32.9	36.0	5.1
	D	15.1	20.0	18.2	18.8	10.6	41.1	42.8	72.0	99.4	13.0
1[a]	A	3.4	4.1	5.8	7.5	5.5	13.7	18.2	27.4	26.7	5.5
	B	1.2	1.5	2.4	3.2	4.1	6.2	8.9	13.0	13.0	4.1
	C						8.9	11.0	19.2	10.3	3.1
	D	5.3	8.9	11.3	14.0	9.9	27.1	35.3	59.0	55.5	13.0
1[a,b]	A	34.3	36.0	38.7	39.8	39.1	10.6	16.8	21.6	24.3	3.1
	B	41.1	41.8	42.8	44.6	45.6	4.8	8.6	10.6	13.7	3.1
	C	37.7	36.0	39.4	44.9	49.0	7.5	13.0	15.8	22.3	3.8
	D	34.3	29.1	30.8	32.6	29.1	21.9	32.6	49.7	60.0	8.6

Notes: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

[a] Test vehicle. [b] Additional luminance from roadway and sign lights.

Figure 1. Nighttime luminance of material A for stream traffic, single vehicle, and lighted sign conditions for overhead and shoulder-mounted guide signs.



Note: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.

Figure 2. Improved luminance ratio of overhead sign in stream traffic.

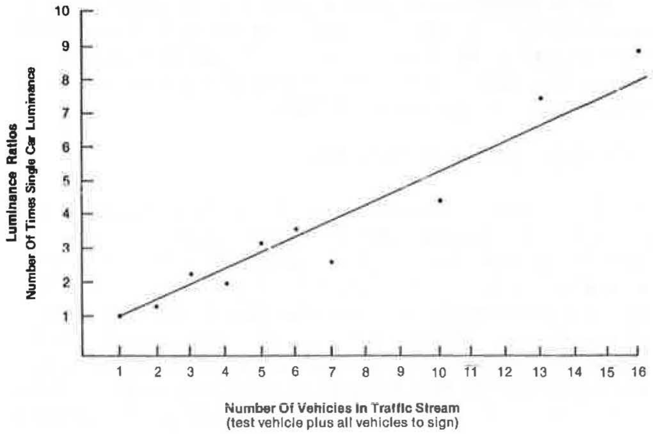
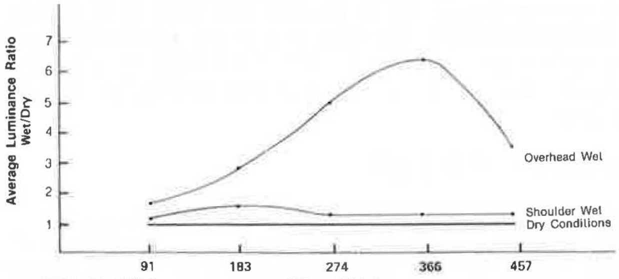


Figure 3. Improved luminance ratio of shoulder-mounted and overhead signs under dry and wet conditions.



Note: 1 m = 3.28 ft

Table 2. Nighttime luminance of silver-white retroreflective sign materials under wet and dry conditions with vehicles on low beam.

Distance to Sign (m)	Material	Overhead Sign Luminance (cd/m^2)			Shoulder-Mounted Sign Luminance (cd/m^2)		
		Wet	Dry	Wet/Dry Ratio	Wet	Dry	Wet/Dry Ratio
457	A	8.2	3.4	2.38	16.4	16.4	1.00
	B	7.2	1.2	6.00	6.5	6.2	1.08
	D	20.2	5.3	3.81	36.0	35.0	1.03
366	A	18.8	4.1	4.40	32.6	23.3	1.40
	B	12.7	1.5	6.89	11.0	9.6	1.16
	D	48.0	8.9	5.49	70.3	47.3	1.49
274	A	27.4	5.8	4.70	42.8	36.7	1.17
	B	13.0	2.4	5.0	17.1	14.7	1.18
	D	60.0	11.3	5.30	109.7	75.4	1.45
183	A	17.5	7.54	2.32	72.0	54.8	1.31
	B	11.6	3.3	3.57	12.2	23.0	1.42
	D	48.0	14.0	3.41	171.4	89.1	1.93
91	A	6.8	5.5	1.21	19.2	19.2	1.00
	B	5.1	4.1	1.25	12.7	12.0	1.07
	D	12.3	9.9	1.22	32.9	31.5	1.04

Notes: 1 m = 3.28 ft and 1 cd/m^2 = 0.291 ft-L.
No reading for material C at that location.

where

I_1 = overhead sign luminance for a single vehicle on low beams, and
V_n = number of vehicles between test vehicle and sign.

For shoulder-mounted signs, lower beam sign luminances were 13.7 to 54 cd/m^2 (4 to 16 ft-L) with the reflective sheeting material A for a single car. Additions for stream traffic are less beneficial and increased only 1.2 to 1.8 times for low to high volumes of vehicles respectively as compared with the test vehicle only. For the other materials tested, luminous increases were of a similar order.

During the experiment with 15 cars, the test vehicle switched off the lower beam lamps to determine for the overhead sign positions the luminance contribution attributable exclusively to other vehicles. Results of this comparison showed that, for all materials and distances, an average of 19 percent of the sign luminance comes from the driver's head lamps. Since the lone vehicle can comfortably switch to upper beams to provide sign luminances 10 times greater than with lower beams, this is not likely to happen in traffic so the effects of adjacent vehicle lights are beneficial.

A general opinion prevails that sign visibility deteriorates under rainfall conditions at night; however, the measurements made in rainfall conditions display generally higher luminances as shown in Table 2 and Figure 3. For shoulder-mounted signs, the ratios appear to maximize at the 183-m (600-ft) distance by a factor of approximately 1.4. Luminances of overhead signs increased an average of 3.8 times for all materials at all distances with rainfall. At longer distances, the improvement was 2.8 to 4 times for 457 m (1500 ft); at shorter distances, the improvement averaged 1.2 to 3 times the dry values. The greatest benefits occurred in the 274 to 366-m (900 to 1200-ft) distances where single-vehicle, low-beam overhead sign luminances increase from 4.8 to 6.9 times with rainfall.

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Overhead Signs Without External Illumination

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The basic objective of this research was the evaluation of high-intensity reflective sheeting for use on overhead sign installations without external illumination. The effects of height above the roadway and angle of sign tilt with respect to the vertical, headlight configuration, and vehicle approach speed to sign legibility distance were measured for both an externally illuminated sign and a high-intensity reflective sheeting sign. It was concluded that the nighttime legibility distance of overhead signs was not appreciably affected by increases in mounting height in the range of 5.5 to 7.0 m (18 to 23 ft), by changes in angle of the sign with respect to the vertical in the range of -5 to +5 deg, or by vehicle approach speed. Headlight configuration, as expected, was the dominant factor in the legibility distance of the unilluminated high-intensity sign. Further, the high-intensity sheeting can be used without external illumination for overhead sign installations in spite of the observed difference in legibility distances. The average legibility distance is 19 percent less with low beams and 5 percent more with high beams on the high-intensity sheeting without external illumination than on the standard installation without illumination.

Providing the necessary information to keep the driver fully informed regarding the geometric conditions and required maneuvers is the goal of every traffic operation engineer. Often, the information is located above the roadway to permit the proper association of the sign message with the geometric condition and to place a critical message in the direct line of sight of the driver. Usually, overhead sign installations are externally illuminated to be effective. The installation to get power to the site, the amount of power required, and the routine maintenance are costly. The lack of information at night due to a power failure or lamp outage is an additional problem.

A recently developed reflective sheeting, commonly referred to as high-intensity sheeting, shows considerable promise for use on overhead signs without external illumination. Field installations using this product indicate satisfactory performance and a high degree of public acceptance. There are some indications that the legibility distance is less for sign installations with high-intensity sheeting than for those with externally illuminated flat-top sheeting. This project was undertaken to evaluate the degree of legibility distance reduction and to study the effects of several design parameters on the legibility of overhead signs.

STUDY OBJECTIVES

This study compared the legibility characteristics during nighttime conditions for two overhead signs constructed of different materials. One sign used a kelly green flat-top (enclosed-lens) reflective-sheeting background with letters fabricated in accordance with overhead guide sign standards used by the Texas State Department of Highways and Public Transportation. This sign was externally illuminated and had white, 40.6-cm (16-in), series E letters arranged in accordance with Texas State Department of Highways and Public Transportation spacing standards.

The legibility distance for this assembly was compared to a similar sign constructed of high-intensity (encapsulated-lens) reflective sheeting. Both the green background and silver letters were of the high-intensity material. In this case, no external illumination was provided. Letter height and stroke were the same for both signs. Letter spacings conformed with those recommended by the Institute of Traffic Engineers. Specific research objectives are outlined as follows:

1. To compare legibility distances using the two signs described above, and
2. To investigate some of the effects on legibility distance associated with angle of sign tilt with respect to the vertical and mounting height of sign.

EXPERIMENTAL DESIGN

The qualitative variables included in the study were sign material (2) and headlight configuration (2). The quantitative variables were

1. X_1 = sign mounting height, 5.6, 6.2, and 6.8 m (18.5, 20.5, and 22.5 ft),
2. X_2 = angle of tilt, -5, 0, and +5 deg, and

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3. X_3 = approach speed, 56, 72, and 89 km/h (35, 45, and 55 mph).

A full factorial design that involves measurement of all combinations of variables (2 × 2 × 3 × 3 × 3) would require 108 observations. To reduce the number of observations needed and make inferences concerning the statistical reliability of the findings, a composite experimental design was recommended by Hartley (1) and was chosen for the study. Hartley (1) gives a detailed description of the principles involved in the experimental design.

The desired response for this experiment is legibility distance (Y). To use the composite design method, the response variable is fitted to a second order law consisting of coefficients (B or Beta) in combination with qualitative input variables (X_1, X_2, and X_3). The equation for legibility distance is defined as follows:

$$Y = B_0 + \sum_{i=1}^{n} B_i X_i + \sum_{i=1}^{n} B_{ii} X_i^2 + \sum_{i<j}^{n} B_{ij} X_i X_j \qquad (1)$$

The composite design is a combination of the star and fractional factorial designs. The schedule of observations for the star design section is

X_1	X_2	X_3	X_1	X_2	X_3
0	0	0	0	1	0
-1	0	0	0	0	-1
1	0	0	0	0	1
0	-1	0			

where

-1 = lowest level of measurement,
0 = intermediate level, and
+1 = upper or highest level of measurement.

The number of response surfaces equals the product of the number of qualitative variables (2 × 2 = 4). For each of the 4 combinations of the 2 sign materials with the 2 headlight configurations, a separate response relationship to the quantitative variables is computed (X_1, X_2, and X_3). Accordingly, 28 tests (4 × 7) are required by the star design.

The fractional factorial design section is combinations of the extreme values in the star design section. The schedule of observations for the fractional design section is

X_1	X_2	X_3	X_1	X_2	X_3
1	-1	-1	-1	-1	1
-1	1	-1	1	1	1

A total of 16 tests (4 × 4) is required for this part of the experiment.

When the tests from the two sections are combined (28 + 16), the total number of tests for the composite design is 44. To gain greater reliability for the results obtained, a complete replication of the extreme ends of the star design is desirable. This amounts to an additional 24 tests, or a total of 68 tests in all.

For purposes of reproducibility, more than one test subject was recommended to obtain the legibility distance measurements. This is not only important for statistical reliability, but it also reduces the problems of fatigue and becoming overly familiar with the testing sequence. Accordingly, three test subjects were chosen for the study.

METHOD OF STUDY

Whenever human response is involved, it is desirable to test in an environment that matches the actual situation as closely as possible. Care must also be exercised to prevent the test subject from being influenced by factors other than those being tested. Every effort was made to have this research conform to the normal driving task and to ensure that only the variables being studied were influential on the outcome.

This research was conducted at the highway test facilities of the Texas A&M University Research Annex. A 914.4-m (3000-ft) test road section was striped for a 3.8-m (12.5-ft) traffic lane approaching an overhead sign structure. The approach, with 0 percent grade, gave the appearance of a highway traffic lane with an overhead sign centered in the distance. No abnormal conditions were visible to the driver. Figure 1 is a diagram of the test assembly.

To measure the effects of mounting height and angle of tilt, the test sign backgrounds were mounted on specially designed supports. These supports were prefabricated so that manual adjustments could be made in short time intervals. The test vehicle was a 1969 Plymouth, four-door sedan, equipped with automatic transmission and a manual steering mechanism. Each subject served as the vehicle operator and was assigned a given approach speed and headlight configuration to maintain throughout the test. The subject responded by reading the word presented on the sign at the moment the legend was understood. In case the word was misread, the subject was instructed to follow through and correct his reading accordingly.

Legibility distances were recorded by an experimenter in the test vehicle. For measurement purposes, an event recorder was attached to a mechanism on the vehicle that automatically recorded an event mark every 17.3 m (56.8 ft). Manual event record marks were placed on the tape at the time the subject read the message and again at the sign structure. Distances were measured on the strip chart from the mark where the sign was read to the mark associated with the sign structure.

Three young male subjects with equal static visual acuities of 20/13 were used. The visual acuity for each subject was measured at 4.2 cd/m^2 (14.5 ft-L) of background brightness, and none of the subjects showed signs of night sight defects or other abnormal visual problems. A series of tests for constant mounting heights was conducted for each of the three nights. The test subjects were rotated in order, and the sequence of legends was preassigned on a random basis for each subject.

ANALYSIS OF DATA

The legibility study was designed so that any analysis of variance and of regression could be used to determine the statistical significance of the coefficients of the variables tested and their interactions. Analysis of variance principles included in most statistical references will not be discussed in great detail in this paper.

Briefly, the purpose of the statistical analysis is to estimate the effect of all quantitative and qualitative variables on the legibility distance. More specifically, these statistical estimates are based on (a) analysis of regression (for the effective coefficients, B_0, B_i, and B_{ij}, of the quantitative variables) and (b) analysis of variance (for the qualitative variables). All experimental variables were assumed to remain fixed and were predetermined to satisfy the normal range of actual applications.

The data collected were tabulated and arranged in a manner suitable for analysis of variance. A computer regression program was used to analyze the statistical significance of the data and to determine coefficients for the regression equation previously mentioned. Tabular and graphical methods for representation of the test results were selected for presentation and analysis purposes.

DISCUSSION OF RESULTS

Before proceeding with a detailed description and analysis of study objectives, we should clarify the concept of word legibility as opposed to legibility of individual letters comprising the words.

Individuals have a tendency to recognize groupings of letters or words without reading each letter involved. In addition, some common groupings are more easily recognizable than others. Research in the area of word legibility is somewhat limited to date and, therefore, must be treated to some extent before proper inferences can be made concerning the findings of this study. Words used for test purposes were selected from previous studies by Forbes (2) and Allen (3). In these studies, words were grouped according to differences in relative legibility of the letters that comprise them.

It was suggested by members of the Texas Transportation Institute staff and later became apparent that different words result in different legibility distances. To estimate the differences in legibility associated with the words used in this study, an indexing procedure was formulated as given in Table 1. Legibility distance measurements were obtained from three subjects (not the same three used in the basic legibility studies) who approached the overhead sign at very low speed under daylight conditions. Their observations were averaged, and the word that was the most legible at the average legibility distance was used as the base value and assigned an index of 1.00. The index for all other words was computed by dividing average legibility distance of each word by the average legibility distance of the most legible word. These indexes were then used to adjust the observed legibility distances from the basic study so that the comparison of the two signs would be on a common basis. It would have been desirable to use words of relatively common legibility; however, data are not readily available in the literature. Therefore, the selection of the words based on the legibility of the individual letters appeared to be a reasonable alternative. As given in Table 1, as much as 26 percent variation in the legibility distance could be associated with the difference in words, and it is apparent that letters of similar legibility do not combine to form words of similar legibility. The variability among words is greater than the expected variability among the other parameters studied.

Measured response distances for the variables tested are given in Tables 2, 3, 4, and 5. In view of the preceding observations concerning word indexes, the observed legibility distances (Y) were adjusted to the values indicated in the last column of Tables 2 through 5. These adjusted figures were used for analysis purposes, since it is believed that they permit a more accurate assessment of the effect of the quantitative and qualitative variables with which this study is concerned.

Analysis of variance summaries and calculated correlation values were obtained as previously described. From these tabulations, the statistical significance of variables tested and their interactions were determined by using the t-statistic at the 0.100 level. Inspection of these summaries revealed that none of the variables was significant at the 0.100 level. The multiple R-square (correlation value) associated with the four test conditions ranged from a low of 0.28 for the high-intensity sign with high beams to a high of 0.49 for the kelly green sign with low beams. The multiple R-square values measured the strength of the linear relation exhibited by the test results; for predictive purposes, the values should be a minimum of 0.80 to 0.85. Since correlation results were low, the data recorded by these tests do not lend themselves to regression by the second order equation or response surface previously described. This does not suggest that anything is faulty with the data or the regression model; however, no acceptable fit could be obtained by using this model.

The analysis of variance indicated that none of the quantitative variables was significant. However, the specific effects of the variables tested, descriptions of each, and their interactions with other variables are given in the following paragraphs.

Effects of Headlights

Since headlight configurations were defined as qualitative variables, they were not analyzed for statistical significance by the analysis of variance and regression operations. However, the headlight effects on the test outcome for both sign materials are shown in Figure 2. A sizable reduction in the relative legibility distance occurred for high- and low-beam configurations for the high-intensity sign. In comparison, the kelly green sign showed little variation in legibility distance for the two headlight configurations. The results can be explained by the characteristics of the signs and their reflectance qualities. The high-intensity sign is completely dependent on the vehicle headlight source, whereas the kelly green sign is provided with a constant external light source.

Effects of Mounting Height

The effects of mounting height on sign legibility distances are presented in Figure 3. The height measurements extended from ground level to the bottom of the sign panel. Since the legends were placed near the center of the signs, the sign was mounted an additional 0.9 m (3 ft) so the driver could read the bottom of the letters. When mounting heights were changed, a somewhat greater variation in legibility distance occurred for the kelly green sign than for the high-intensity sign. However, the analysis of variance revealed that mounting height was not a significant variable within the range of mounting heights studied. Observations during the field studies indicated that there is little change in legibility when signs are lowered or raised within the limits tested. In most cases, a higher range of heights is more desirable for highway clearance purposes. However, higher mountings can result in certain adverse effects and create the need for stronger supports.

Effects of Angle of Tilt

The effects of tilting the sign with respect to the vertical are shown in Figure 4. Between tilt angles of -5 and +5 deg, the kelly green sign appears to have a somewhat larger degree of variation. Since the external light source on this sign remained constant for the three angles tested, reflectance could have been influential. By changing the angles of incident and the reflectance for headlight illumination, the sign brightness would change as the vehicle approaches the sign. After these variables were adjusted for both the high-intensity sign and the kelly green sign, the variability of the legibility distances was relatively small. Angles of tilt within the range tested do not appear to offer significant effects.

Figure 1. Schematic diagram of test arrangement.

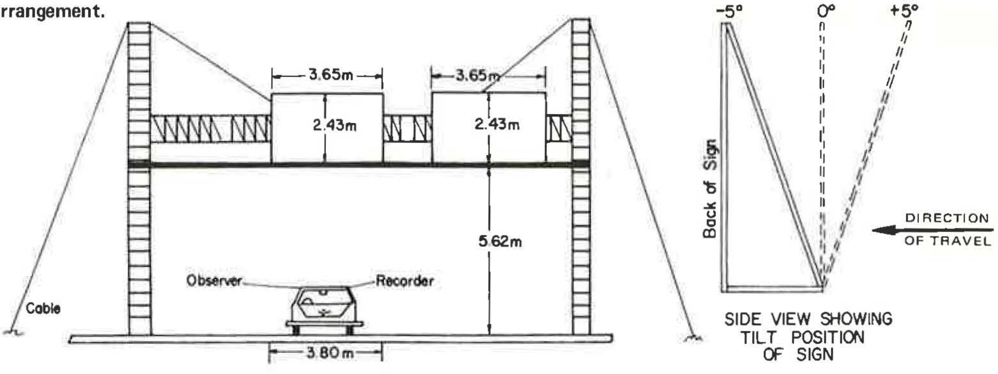


Table 1. Relative legibility of words.

Test	Sign	Legend	Legibility Distance (m) Subject 1	Subject 2	Subject 3	Average	Word Index
1	HI	REAR	235	354	290	293	0.75
2	HI	STAY	322	361	354	345	0.88
3	KG	CITY	360	385	427	390	1.0
4	HI	ROAD	NA	NA	NA	NA	NA
5	KG	BOOK	278	338	305	307	0.79
6	KG	BOAT	303	303	337	314	0.81
7	KG	ROAD	302	355	363	340	0.87
8	HI	GONE	286	329	306	307	0.79
9	HI	SAME	239	287	335	287	0.74
10	KG	CLAY	328	384	425	379	0.97
11	HI	COME	277	321	323	307	0.79
12	KG	ROCK	306	334	335	325	0.83

Note: 1 m = 3.28 ft.

Table 2. Summary of night sign legibility tests for externally illuminated kelly green sign with low beams.

		Quantitative Factor			Legibility Distance Factor		
Test	Legend	Height (m)	Tilt (deg)	Speed (km/h)	Word Index	Observed (m)	Adjusted (m)
1	CLAY	6.3	0	72	0.98	347	354
2	BOOK	6.3	-5	72	0.79	265	335
3	ROAD	6.3	-5	72	0.88	448	509
4	BOAT	6.3	+5	72	0.80	277	346
5	CLAY	6.3	+5	72	0.98	360	367
6	ROCK	6.3	0	56	0.84	424	505
7	CLAY	6.3	0	56	0.98	338	345
8	CITY	6.3	0	89	1.00	283	283
9	CITY	6.3	0	89	1.00	478	478
10	CITY	5.6	0	72	1.00	427	427
11	ROCK	5.6	0	72	0.84	360	429
12	ROCK	5.6	+5	56	0.84	491	584
13	BOOK	5.6	-5	89	0.79	320	405
14	BOOK	6.9	0	72	0.79	375	475
15	BOOK	6.9	0	72	0.79	293	370
16	ROAD	6.9	-5	56	0.88	375	426
17	ROAD	6.9	+5	89	0.88	439	499

Note: 1 m = 3.28 ft and 1 km/h = 0.622 mph.

Table 3. Summary of night sign legibility tests for externally illuminated kelly green sign with high beams.

		Quantitative Factor			Legibility Distance Factor		
Test	Legend	Height (m)	Tilt (deg)	Speed (km/h)	Word Index	Observed (m)	Adjusted (m)
1	CLAY	6.3	0	72	0.98	479	489
2	ROAD	6.3	-5	72	0.88	293	333
3	ROAD	6.3	-5	72	0.88	323	367
4	BOAT	6.3	+5	72	0.80	421	526
5	ROCK	6.3	+5	72	0.84	252	300
6	BOAT	6.3	0	56	0.80	335	419
7	CLAY	6.3	0	56	0.98	479	489
8	CITY	6.3	0	89	1.00	372	372
9	BOOK	6.3	0	89	0.79	351	444
10	CITY	5.6	0	72	1.00	466	466
11	ROCK	5.6	0	72	0.84	341	406
12	CITY	5.6	+5	56	1.00	396	396
13	BOOK	5.6	-5	89	0.79	427	541
14	ROCK	6.9	0	72	0.84	302	360
15	BOAT	6.9	0	72	0.80	475	594
16	ROAD	6.9	-5	56	0.88	326	370
17	CLAY	6.9	+5	89	0.98	369	377

Note: 1 m = 3.28 ft and 1 km/h = 0.622 mph.

Table 4. Summary of night sign legibility tests for high-intensity sign with low beams.

		Quantitative Factor			Legibility Distance Factor		
Test	Legend	Height (m)	Tilt (deg)	Speed (km/h)	Word Index	Observed (m)	Adjusted (m)
1	ROAD	6.3	0	72	0.83	366	441
2	COME	6.3	-5	72	0.79	213	270
3	ROAD	6.3	-5	72	0.83	268	323
4	STAY	6.3	+5	72	0.89	399	448
5	SAME	6.3	+5	72	0.73	180	247
6	GONE	6.3	0	56	0.81	283	344
7	REAR	6.3	0	56	0.75	299	399
8	ROAD	6.3	0	89	0.83	232	280
9	STAY	6.3	0	89	0.89	290	326
10	REAR	5.6	0	72	0.75	265	353
11	GONE	5.6	0	72	0.81	204	252
12	REAR	5.6	+5	56	0.75	207	276
13	SAME	5.6	-5	89	0.73	296	405
14	COME	6.9	0	72	0.79	244	309
15	COME	6.9	0	72	0.79	347	439
16	REAR	6.9	-5	56	0.75	232	309
17	ROAD	6.9	+5	89	0.83	305	367

Note: 1 m = 3.28 ft and 1 km/h = 0.622 mph.

Table 5. Summary of night sign legibility tests for high-intensity sign with high beams.

		Quantitative Factor			Legibility Distance Factor		
Test	Legend	Height (m)	Tilt (deg)	Speed (km/h)	Word Index	Observed (m)	Adjusted (m)
1	COME	6.3	0	45	0.79	335	424
2	COME	6.3	-5	45	0.79	454	575
3	ROAD	6.3	-5	72	0.83	238	287
4	SAME	6.3	+5	72	0.73	341	467
5	GONE	6.3	+5	72	0.81	341	421
6	STAY	6.3	0	56	0.89	253	284
7	REAR	6.3	0	56	0.75	384	512
8	SAME	6.3	0	89	0.73	451	618
9	GONE	6.3	0	89	0.81	308	380
10	ROAD	5.6	0	72	0.83	430	518
11	GONE	5.6	0	72	0.81	448	553
12	REAR	5.6	+5	56	0.75	341	455
13	COME	6.9	-5	89	0.89	323	363
14	COME	6.9	0	72	0.79	350	443
15	SAME	6.9	0	72	0.73	277	379
16	STAY	6.9	-5	56	0.89	448	503
17	ROAD	6.9	+5	89	0.83	338	407

Note: 1 m = 3.28 ft and 1 km/h = 0.622 mph.

Figure 2. Effects of headlight on legibility.

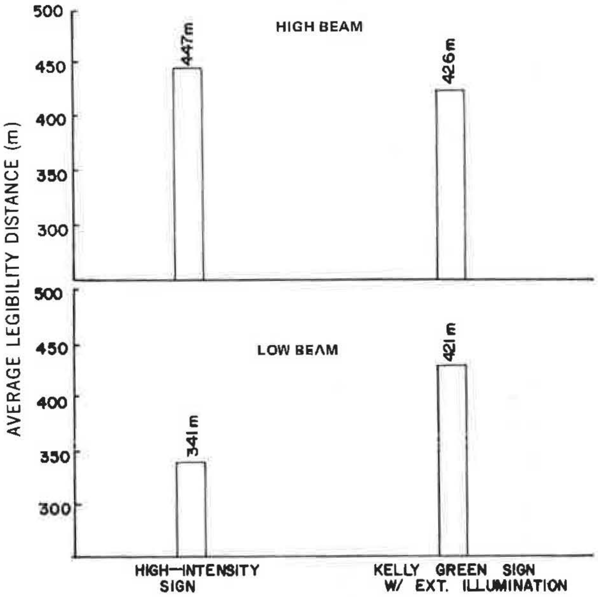


Figure 3. Effects of mounting height on legibility.

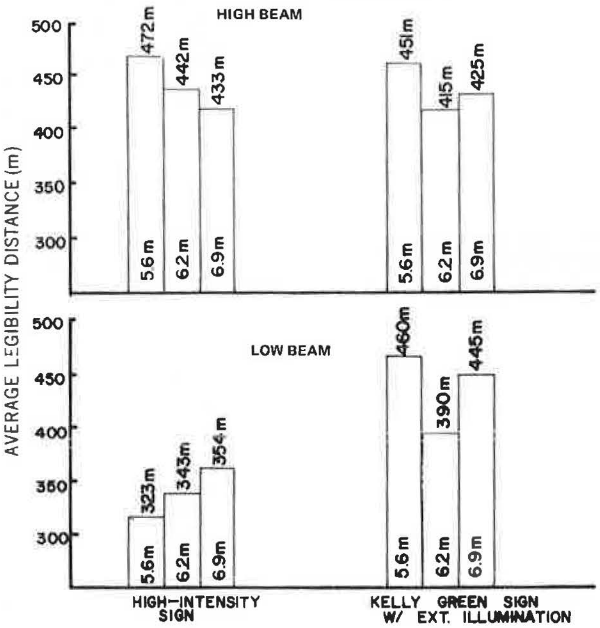


Figure 4. Effects of angle of tilt on legibility.

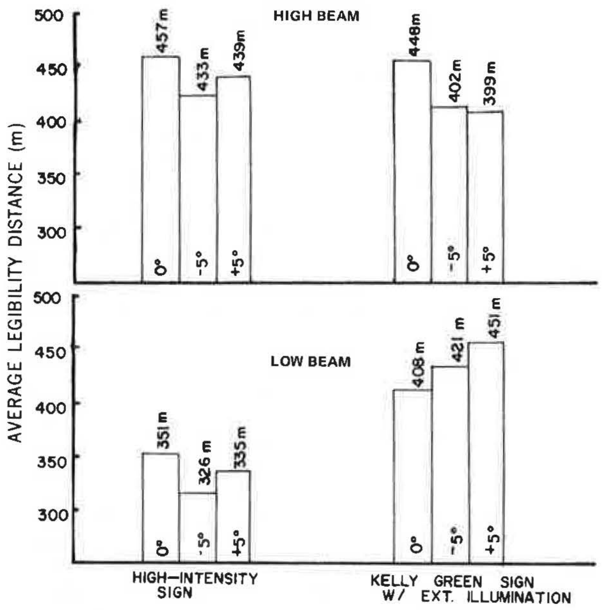
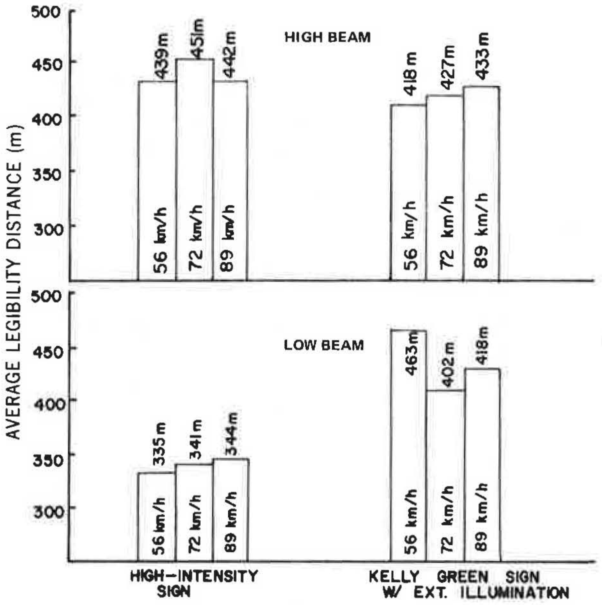


Figure 5. Effects of approach speed on legibility.



Effects of Approach Speed

Approach speed showed little effect on legibility distance. Figure 5 shows the average legibility distances recorded during this series of tests for the three approach speed levels involved, 56, 72, and 89 km/h (35, 45, and 55 mph). The results are substantiated by the fact that drivers tend to recognize words and not individual letters and that the time involved for recognition purposes is small. In fact, as many as three small words can be read at a single glance (5). Accordingly, the speed within the range specified and the driver's fast perception time account for little change in legibility distance.

STATISTICAL COMPARISON OF LEGIBILITY DISTANCES

One of the primary purposes of this study was to determine how the two types of signs compare from a legibility standpoint; therefore, a statistical analysis is needed to draw final conclusions. The mean legibility distances shown in Figure 2 were statistically compared by using an average value determined from all grouped data for each respective sign material. The difference between two means when the standard deviations are unknown but assumed to be equal can be tested by using the t-statistic (4). The equation for the t-statistic is

$$t = (\bar{Y}_1 - \bar{Y}_2)/S_p\sqrt{(1/N_1) + (1/N_2)} \qquad (2)$$

where

$\bar{Y}_1$ and $\bar{Y}_2$ = mean legibility distances afforded by the kelly green sign and the high-intensity sign respectively,
N_1 and N_2 = number of observations conducted on the kelly green sign and the high-intensity sign respectively, and
S_p = pooled standard deviation for each set determined by

$$S_p^2 = \sum_{i=1}^{2} V_i S_i^2 \Big/ \sum_{i=1}^{2} V_i \qquad (3)$$

where

V_i = degrees of freedom of the ith date set, and
S_i^2 = variance of legibility distances for each respective sign and headlight configuration.

To use this method of analysis, it is necessary to ascertain that the standard deviations of the compared signs are equal. This is accomplished by using the F-test, which is a test of variance but can also be used to test standard deviations. The ratio of the two variances is compared with an F-distribution chart by using a predetermined confidence limit. A 95 percent confidence limit was chosen; this limit is commonly used for studies of this type. The null hypothesis assumes that there are no significant differences in the variance for each data set and the pooled variance of the combined data.

The equation to determine if the variances are equal is

$$F_{MAX} = (MAX\ S^2/MIN\ S^2) = (14\,475.0/6778.3) = 2.135 \qquad (4)$$

By using a 5 percent significance level the critical F-value is 8.44. Since the value of the test statistics is less than 8.44, there is no evidence that the variances are different for the four treatment groups.

The error mean squares for the analysis are presented below:

Sign	Headlight Beam	Variable	Error Mean Square
Kelly green	High	S_1^2	9 113.4
	Low	S_3^2	7 483.2
High intensity	High	S_2^2	14 475.0
	Low	S_4^2	6 778.3

The pooled variance of all four headlight and sign configurations is

$$S_p^2 = [7(9113.4) + 7(7483.2) + 7(14\ 475.0) + 7(6778.3)]/28$$
$$= 26\ 4949.3/28 = 9462.48 \qquad (5)$$

The mean values of all data for each sign-headlight configuration are as follows:

Sign	Headlight Beam	Variable	Mean of Data (m)
Kelly green	High	$\overline{Y}_1$	426
	Low	$\overline{Y}_3$	421
High intensity	High	$\overline{Y}_2$	447
	Low	$\overline{Y}_4$	341

The averages for high and low beam are respectively 437 m (1433 ft) and 381 m (1249 ft).

The test to determine if there is a significant difference in the mean legibility distances for high-beam configuration is

$$t_1 = (\overline{Y}_1 - \overline{Y}_2)/S_p\sqrt{(1/N_1) + (1/N_2)} = (427 - 447)/97.27\sqrt{2/17}$$
$$= -20/33.36 = -0.60 \qquad (6)$$

The t-value (0.05) for 28 degrees of freedom is 2.05. Since the computed value (-0.60) is less than the tabulated value, there is no significant difference in the two sign materials under the high-beam headlight configuration (i.e., the null hypothesis is accepted).

The test for the low-beam configuration is

$$t_2 = (\overline{Y}_3 - \overline{Y}_4) / S_p\sqrt{2/N_p} = (421 - 341)/ 97.27\sqrt{2/17}$$
$$= 80/33.36 = 2.40 \qquad (7)$$

Since the t-value (0.05) for 28 degrees of freedom (2.05) is less than the computed value (2.40), the null hypothesis is rejected, and the significant difference between the two sign materials under the low-beam headlight configuration is indicated.

In summary, it appears that the high-intensity sign with high-beam legibility distance is not significantly greater in a statistical sense than the kelly green engineer-grade sign with external illumination, which is significantly less effective under the low-beam configuration. The differences are, however, small when compared to the magnitude of the observed legibility distance.

FINDINGS

The reduction in legibility distance under the low-beam and high-intensity sign configuration is undoubtedly cause for some concern. However, the legibility distance provided is sufficient to read a complex message. For example, a 345-m (1130-ft) legibility distance at 89 km/h (55 mph) provides 14 s of reading time at a visual acuity of 20/13. Even by adjusting to the 20/40 visual acuity, a 4.5-s reading time is provided. Considering that the target value of the high-intensity sign is high and thus prepares the driver to read the message, and considering that field installations have been relatively successful, it seems reasonable to conclude that high-intensity overhead sign installations without external illumination can be effectively used when the background brightness is not excessive and when the minimum direct line of sight to the sign installation is at least 450 m (1500 ft).

In support of this conclusion, the Louisiana Department of Highways in September 1975 issued a directive that overhead signs fabricated of high-intensity sheeting should not be externally illuminated. This decision was reached after a field test period of more than 3 years.

As a result of this study, the following conclusions can be made.

1. There is no substantial effect on legibility distance associated with increasing the height of overhead signs from 5.6 to 6.8 m (18.5 to 22.5 ft).
2. The angle of tilt of the sign with respect to the vertical, in the range of -5 to +5 deg, does not appear to affect substantially the legibility distance of overhead signs. A tilt of several degrees forward (top is farther forward than the base) would be desirable to reduce the problem of bird droppings marring the face of the sign.
3. Vehicle approach speed does not produce a significant effect on the legibility distance of overhead signs within the speed ranges tested.
4. The headlight configuration does not appreciably affect the legibility distance on the externally illuminated flat-top sheeting sign.
5. The legibility distance for the high-intensity sheeting installation is 24 percent less with low beams than with high beams.
6. The observed legibility distance is 19 percent less with low beams and 5 percent more with high beams on the high-intensity sheeting without external illumination than on the standard installation with external illumination. All legibility distances recorded (actual observed values) exceeded 179.3 m (590 ft), and this magnitude of change would not appreciably affect traffic operations.

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Abridgment

Review of Needs of Users of Ride Quality Technology

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The primary objectives of this paper are to provide a broad view of the needs of those who use ride quality technology and to propose a possible course of action to fulfill those needs. The quality of vehicle ride can be a significant factor in determining passenger acceptance and use of various modes of public transportation. Technology pertaining to various aspects of ride quality is therefore needed to aid design and operation of vehicles and to achieve acceptance of existing and planned transport vehicle systems. Much of the research in ride quality has been directed toward identifying crew tolerance of acceleration in a military environment. Although this research is pertinent, it has resulted in identification of safety and proficiency levels rather than comfort levels that are needed for evaluation of passenger response in commercial vehicles.

For commercial transportation, ride quality research has tended to be spotty and uncoordinated. Only in the past few years has there been an effort to systematically gain a better understanding of ride quality factors and to build a technology base adequate for designing transport vehicle systems. This effort has concentrated primarily on transport aircraft and has been undertaken primarily by research organizations. To address the question of whether this research is properly focused and broad enough to fulfill needs of research users, a critique of the research activities for better ride quality has been carried out from the viewpoint of the organizations that use the research results.

Needs of users of ride quality technology were assessed by means of both personal interviews and questionnaires. To aid interpretation of results, data collection methods were planned so that sufficient similarity existed between interview and questionnaire. A total of 20 organizations contributed information to this effort. Results indicate that a common basis of terminology is needed for meaningful discussion of ride quality. The different types of criteria in use are discussed, and the needs for improvements in the ride quality data base are presented. The needs of research users of air, marine, rail, and surface transportation were found to be similar and are presented. A recently developed method, generally applicable to all modes of transportation, was identified for quantifying passenger satisfaction and determining value decisions for existing and conceptual vehicles. Finally, a plan of action is proposed by which the needs of ride quality technology users identified by this study could be fulfilled.

Results of this study show that users of ride quality technology generally perceive technology weaknesses through the ride quality criteria that are subsequently developed. Also, technology results should be standardized so that adequate criteria may be developed. As part of this effort, units and methods of measurement must be standardized. Subjective passenger reaction to vehicle ride must be quantified so that the percent of passengers satisfied can be accurately predicted. Finally, advanced techniques for properly specifying and evaluating disturbance inputs must be developed based on a general method of evaluating passenger satisfaction.

To accomplish these requirements a plan of action has been proposed. The proposed action calls for the establishment of an organization with national responsibility to coordinate, evaluate, and analyze a total effort to quantify passenger satisfaction and value transfer functions for the four transportation modes. Information developed should be provided in a designer's handbook, which would document accepted techniques for both analytical estimate of passenger satisfaction and field measurements for verification of predicted passenger satisfaction.

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Comparison of Driver Dynamics With Actual and Simulated Visual Displays

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As part of a comprehensive program to explore driver-vehicle system response in lateral steering tasks, describing functions and dynamic data have been gathered in several milieu. These milieu include a simple fixed-base simulator with only an elementary roadway delineation display; a fixed-base statically operating automobile with terrain displayed by a wide-angle projection system; and a full-scale moving-base automobile operating on the road. Dynamic data with the two fixed-base simulators compared favorably and implied that the impoverished visual scene, lack of engine noise, and simplified steering wheel characteristics in the simple simulator did not induce significant driver dynamic behavior variations. The fixed-base versus moving-base comparisons showed that the moving base had substantially greater crossover frequencies on the road course; this frequency can be ascribed primarily to a decrease in the driver's effective latency. When considered with previous data, the moving-base full-scale versus fixed-base simulator differences are ascribed primarily to the motion cues present on the road course rather than to any visual field differences.

Over a period of several years, we have completed a variety of programs to explore driver-vehicle system behavior in directional control tasks. These programs have been conducted to satisfy different and, in general, unconnected purposes; yet, similar techniques and procedures have been applied. As a consequence of and incidental to the individual program purposes, we have gathered driver-vehicle system describing function and other dynamic data in several different milieu. Comparison of data from three of these settings gives some interesting insights into visual cue needs for driving and into the effects of motion and visual cues when these effects are contrasted with visual cues alone. Unfortunately, we have to be satisfied with the interesting insights rather than the concrete significant differences, since we have no common populations of subjects in the three situations.

The driver's visual field, in general, is extremely complicated and defies description. On the other hand, the importance of the visual field in relation to the driver's guidance and control may be very simple to describe in principle and to determine in practice. Imagine an experimental series in which the visual field content is successively modified by removing texture and objects in the surround, adjusting delineation features, and so on. Only the driver's visual field is varied, and the factors held constant include the vehicle dynamics, the driver subjects, and the excitation against which the car is to be regulated. For each treatment in this imaginary experimental series, a set of lane regulation tasks are run, and measurements are taken of the driver's dynamics and the driver-vehicle system performance. If the visual field variations indicated no change in the basic driver characteristics, then the differences between the complex and the simple visual scenes would be redundant for the development of appropriate guidance and control feedback signals by the driver. On the other hand, if driver dynamic differences were apparent, then the visual differences in the comparative scenes would be important in terms of the particular driver functions modified. If this experiment were performed for a sufficient variety of visual scenes, we would have a complete story on the driver's guidance requirements in general. This imaginary experiment can be expanded further to include the effects of motion cues by contrasting driver behavior measurements taken in a fixed-based situation with its full-scale automobile equivalent.

REVIEW OF EXPERIMENTS

We can now fill in the outline of this imaginary experiment with data taken from three experimental series. The first is the full-scale roadway experiments reported by McRuer and others (1). In that experiment, the physical scene was a complete roadway, well marked, and viewed through the windshield of a 1974 Chevrolet Nova. The automobile was fitted with a disturbance generator and a describing function analyzer so that the describing function and other driver-vehicle system measurements could be made. The general character and nature of the measurements in this and the other two experiments to be considered were accomplished as described by McRuer and others (2). The driver's task

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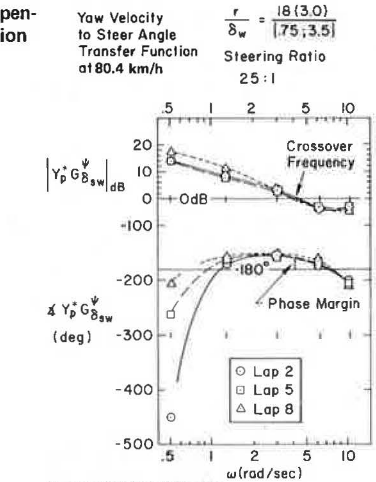
Figure 1. Effective open-loop describing function for initial test series.



Note: 1 km/h = 1.6 mph.

Figure 2. Comparison of full-scale automobile and fixed-base simulator dynamics for test driver subject.

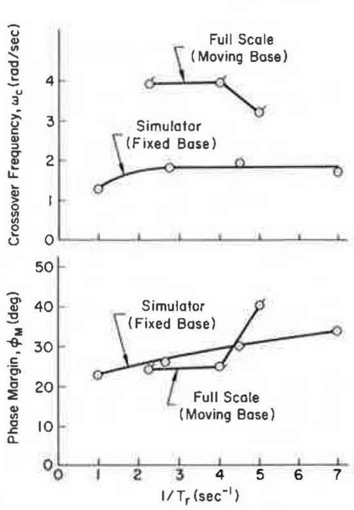


Figure 3. Comparison of full-scale automobile and fixed-based simulators inverse effective time delays.

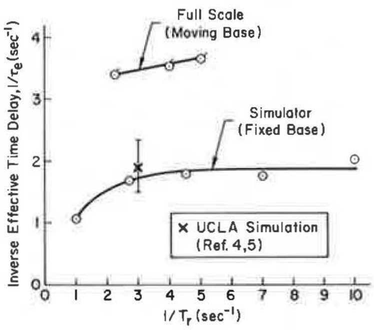


Figure 4. Comparison of data from fixed-base simulator with elaborate and impoverished visual fields.

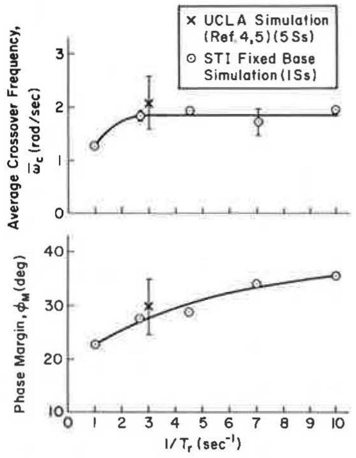
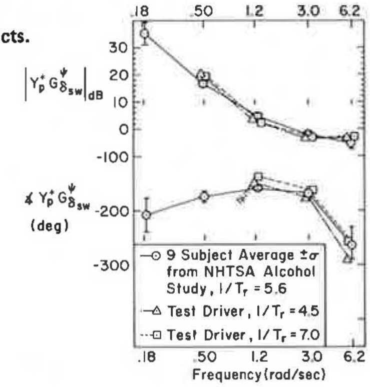


Figure 5. Comparison of test driver with nine subjects.



was lane regulation in the presence of a simulated strong crosswind disturbance. The disturbance was applied by moving the front wheels with an extensible link servomechanism. This servomechanism is installed in series and is backed up by the driver's power steering unit, which serves to isolate the servomechanism motions from the steering wheel. The driver's regulation task is simply to keep the car centered in the lane by applying corrective steering inputs. In the experiments by McRuer and others (1), this task was performed many times by all 16 subjects at 80 km/h (50 mph). The measurement interval was 25 s, and the primary response data of the driver vehicle system dynamics are given in terms of the effective single- and open-loop describing function ($Y_p^* G_{\delta_{sw}}^{\psi}$). This measurement was taken with the describing function analyzer (3), and a representative sample is shown in Figure 1. In this typical example, the amplitude ratio is very close to an ideal crossover model form (4).

The second experimental series (5, 6) was conducted on a fixed-based simulation by using the University of California, Los Angeles (UCLA), driving simulator. In this experimental series, the driver was seated in a 1965 Chevrolet sedan that was mounted on a chassis dynamometer. The dynamometer drum speed, controlled by the driver via the accelerator and brakes, determined the landscape velocity of a moving model landscape that was related by a black and white TV camera. The landscape was projected on a large screen to provide the driver's visual cues. The driver's steer angle output was fed to an analog computer containing the vehicle equations of motion and then to the TV camera servomechanism that moved the car over the model terrain. The net motions of camera and model landscape provided the displayed motion presented to the driver. Because the included horizontal angle of the visual field was about 40 deg, the relative motion and geometric cues used for directional control were adequate for foveal and parafoveal vision. The visual field resolution was such that an object the size of an oncoming vehicle could be distinguished at an equivalent full-scale distance of about 402 m (1320 ft) that was the length of the moving belt landscape. The overall impression with the UCLA simulator is of a highly realistic driving situation in desert terrain under a dark overcast.

The third series was a fixed-base operation in the Systems Technology, Inc. (STI), simulator. Data from two experiments (1, 7, 8) in which this simulator was used are appropriate. In these experiments, the visual scene was made as simple as possible, i.e., it consisted of only two-lane edges, drawn in perspective on the cathode ray tube with decreasing intensity in the distance. Heading and lane deviations of the car resulted in motions of the road relative to a fixed mask of a car hood, left fender, and windshield outline. The simulator consisted of a modified 1968 Mustang cab with the steering wheel adjusted to approximate the force-feel characteristics of a power steering unit.

DATA INTERPRETATION AND CONCLUSIONS

By comparing the driver-vehicle system performance data from these three experiments, we can deduce the relative importance of vehicle motion and of the features in the three visual scenes presented. The data more readily at hand are for the system crossover frequency and phase margin and primarily reflect the driver lead equalization and heading gain properties.

The first and most direct comparison is between the STI simulator and the full-scale moving-base results. In this comparison, the subject and the task are the same. The crossover frequency and phase margins for comparable vehicle dynamics are shown in Figure 2 as a function of the vehicle yaw time constant (T_r). The full-scale data have higher crossover frequencies but similar phase margins. These data can also be interpreted in terms of effective system latency. For the crossover model of manual control this is given by

$$\tau_e = (\pi/2 - \varphi_M)/\omega_c \tag{1}$$

Because the describing function data (1) are approximated quite well by the crossover model, this formula is applicable. A comparison of data in the form of $1/\tau_e$ is given in Figure 3 ($1/\tau_e$ is a preferred representation because it is approximately normally distributed and is also more readily related to frequency regions of interest). The general trends with $1/T_r$ appear parallel, but the moving-base results exhibit much lower effective system latencies. Over the common $1/T_r$ range, the average τ_e for fixed base is about 0.55 s while that for moving base is 0.28 s. Previous experiments (4, 9) in which separate describing function measurements were made for motion and visual cues indicate that this effective time delay difference can be attributed to motion (vestibular) feedback effects (due primarily to the semicircular canals) that are active in the moving-base case and not in the fixed-base case.

When the results from the UCLA simulation are compared with the STI fixed-base results, as shown in Figures 3 and 4, the crossover frequency, phase margin, and effective time delay are similar. The data points represent the mean and standard deviation for five drivers in the UCLA series and the mean and standard deviation of repeat runs using one test driver in the STI series. Because the crossover frequency and phase margin data for the two simulation series compare favorably, the implication is that the impoverished visual scene, lack of engine noise, and simplified feel characteristics of the steering wheel present in the STI simulator did not induce significant driver dynamic behavior variations.

Figure 5 is an associated comparison that contrasts the test driver with nine subjects taken from a previous study (7), all using the STI simulator. This comparison indicates that the test driver used for both simulator and full-scale results is representative of a much larger randomly selected sample of the driving population.

In summary, when the data for similar vehicle dynamics in moving-base and two fixed-base situations are compared, the differences between the impoverished visual field and an actual windshield field are unimportant to the development of the visual guidance cues. The experiments indicate that a visual field that has only two high-contrast lane markings presented to the driver with appropriate motion perspective is a sufficient visual scene from which to develop the requisite guidance and control information. Texture, other objects in the surround, and so on may provide information that is useful but not essential to the driver's steering operations in the regulation task. Finally, the principal effect of motion is to permit a reduction in the effective driver time delay when the total control task is treated only as an equivalent visual-input operation.

ACKNOWLEDGMENT

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Effectiveness of Automatic Warning Devices in Reducing Accidents at Grade Crossings

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In the last 17 years, California has experienced more than 17 000 vehicle-train accidents, which have claimed more than 550 lives. The California Public Utilities Commission and the California State Legislature have attempted to reduce the continuing human and economic loss by promoting the installation of flashing light signals and automatic crossing gates. This study is intended to gauge the effect of automatic warning devices on the frequency of vehicle-train accidents and to examine specific crossing locations to appraise the capabilities of automatic warning devices in reducing the number and severity of vehicle-train accidents. To determine the effectiveness of automatic warning devices under varying conditions, the before-and-after accident histories at 1552 grade crossings where automatic devices were installed between 1960 and 1970 were compared on a crossing-year basis and segregated by type of warning device, rural versus urban conditions, and the number of railroad tracks. While some limitations and adverse side effects do exist, the results indicate that the installation of automatic gates can be expected, on the average, to reduce vehicle-train accidents by approximately 70 percent per crossing-year and to reduce related deaths and injuries by 89 and 83 percent per year respectively. In addition, it would appear that the use of automatic gates eliminates many of those accidents that represent the greatest potential severity, since there were 64 percent fewer deaths per accident, 43 percent fewer injuries per accident, and 36 percent fewer deaths per injury. The data obtained on vehicle-train accidents and their severity were combined with average installation, maintenance, and operation costs for flashing lights and automatic gates to provide a brief economic analysis of the most cost-effective alternative.

Since 1958, there have been more than 17 000 vehicle-train accidents in California. These accidents have claimed more than 550 lives and resulted in an additional 7500 injuries, many of which the California Public Utilities Commission staff believes could have been averted by the installation of automatic railroad warning devices, especially automatic gates (1, 2).

It is the purpose of this paper to examine (a) automatic railroad warning devices, (b) what can be expected in terms of vehicle-train accident reduction, (c) how warning devices affect accident severity, (d) whether the effectiveness of automatic warning devices is dependent on the location of grade crossings or such physical conditions as the number of railroad tracks, (e) what the limitations of any warning-device system are, and (f) how the results can be used in economic analyses to point out the relative cost-effectiveness of each alternative.

The examination includes a comparison of accident histories at 1552 grade-crossing locations where automatic warning devices were installed between 1960 and 1970. Documented for each location are (a) the type of automatic warning device installed, (b) the previous type of warning device in service, (c) the accident history both before and after the installation of devices, (d) the number of vehicle-train accidents and related deaths and injuries before and after the installation of devices, (e) the current number of railroad tracks, and (f) the location of the grade crossing in terms of rural or urban characteristics.

California has for more than 20 years maintained a local assistance program aimed at promoting the installation of automatic warning devices. In conjunction with a maintenance fund program established in 1965 that pays the local agency's entire share of maintaining automatic warning devices, the California grade-crossing program has assisted in the installation of automatic warning devices at more than 2700 grade crossings.

Since the emphasis of the program changed from flashing lights to the installation of automatic gates, the results of the program have been dramatic. Since 1965, there has been a 50 percent reduction in the number of vehicle-train accidents (1219 in 1965 versus 608 in 1974), a 57 percent reduction in related deaths (110 in 1965 versus 47 in 1974), and a 36 percent reduction in resultant injuries (515 in 1965 versus 330 in 1974); this is in spite of an 87 percent increase in vehicle registration (11 191 199 in 1965 versus 20 933 000 in 1974) and an estimated 50 percent increase in the number of vehicle-kilometers (vehicle-miles) traveled in California. The number of vehicle-train accidents per registered vehicle has been reduced by more than 70 percent, and the number of vehicle-train accidents per vehicle-kilometer has been reduced by more than 66 percent. This reduction in vehicle-train accidents compares favorably with data on all California highway accidents per registered motor vehicle, which have only been reduced by approximately 20 percent since 1965, and the number of highway acci-

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dents per vehicle-kilometer, which has been reduced by only 1 percent since 1965. Railroad reporting requirements for grade-crossing accidents changed January 1, 1975, eliminating any possibility for updating accident trends.

Since 1953, the results of the California program have cost more than $9 500 000 in state funds, representing a total construction cost of more than $38 000 000. The accidents cited in this study include any and all accidents involving railroads and motor vehicles at crossings of public streets.

AGGREGATE RESULTS

The major thrust of this examination, a comparison of before-and-after accident histories at selected grade crossings where automatic warning devices were installed, was designed to help evaluate the capabilities of automatic devices to reduce vehicle-train accidents and casualties. The 1552 locations examined had at least three train crossings per day and included all crossings at which automatic warning devices were installed between 1960 and 1970. At the time of the study, these crossings represented 44 percent of all crossings in California with either flashing light signals or automatic gates. The 1960 through 1970 span was chosen to allow for a reliable accident history while considering only those factors (train and vehicular patterns) relevant to the current rail-street crossing situation.

Each crossing was examined individually, and the number and severity of accidents during the 10-year period before the installation of automatic warning devices were compared with the number and severity of accidents experienced from the date of installation until August 1, 1972. Ten-year accident histories were used for all cases except those in which the warning device had been previously upgraded within the 10-year period or in which new crossings had been established. Prior accident history was not considered at new crossings. For those crossings upgraded to flashing lights before being upgraded to automatic gates, only the period with flashing light signals was considered as the prior accident history. The gross accident figures divided by the number of years the device was in service were compared to determine the effectiveness of automatic warning devices for reducing accident and casualty rates.

Until the mid-1960s, the normal or predominant type of automatic device installed was flashing lights. After that, however, automatic gates were installed at the most hazardous crossings, and flashing lights were relegated to less hazardous locations. This change in policy made some of the flashing lights installed during the study period appear to be overly effective in comparison with similar devices installed before the study period and with flashing light devices at crossings that were upgraded to automatic gates. Although the results for the 434 locations where flashing lights were installed are furnished, the emphasis will be on those 1118 locations where automatic gates were installed (Table 1).

Tables 2 and 3 show that the use of automatic devices resulted in reductions per crossing-year of 69 percent in vehicle-train accidents, 86 percent in deaths, and 80 percent in injuries. For the automatic gates alone, the results are even more impressive: Reductions per crossing-year were 70 percent in vehicle-train accidents, 89 percent in deaths, and 83 percent in injuries. The data also indicate, at least superficially, that automatic gates are adaptable to all types of situations and can drastically reduce accidents at crossings no matter what the previous warning devices were. The accident rates before and after the installation of automatic gates ranged from a low of 0.24 and 0.03 accidents per crossing-year for crossings that previously had crossbuck warnings to 0.41 and 0.14 accidents per crossing-year for those that previously had flashing light warnings. The data on fatality rates coincided with the pattern established for accident rates; crossings that previously had crossbuck warnings exhibited the greatest rate of change.

This difference between accident- and casualty-rate reductions on a crossing-year basis indicated that automatic warning devices, in addition to reducing accident frequency, reduce disproportionately the expected death and injury rates for those infrequent accidents that do occur after the installation of flashing light signals or automatic gates. Tables 3 and 4 show that, in addition to the 70 percent reduction in accidents experienced at grade crossings upgraded to automatic gates, there were reductions of 64 percent in the number of deaths per recorded accident and 43 percent in expected injuries per accident. An additional measure of accident severity, deaths per injury, was reduced from 0.29 to 0.18 (more than 36 percent) by the installation of automatic gates.

The results shown in Table 4 seem to indicate that automatic gates eliminated most of the accidents that involved the greatest potential severity. Of the 745 vehicle-train accidents that occurred in 1973, roughly 66 percent were tentatively attributed to failure of the motor vehicle to stop in accordance with the California Motor Vehicle Code; this contributed to roughly 80 percent of the total casualties. Since automatic gates have an inherent ability to drastically reduce the options available to a vehicle driver, they eliminate most of the accidents involving a moving vehicle. Indeed, a close examination of accidents occurring at crossings with automatic gates between 1970 and 1972 revealed that the greatest number of these accidents was attributable to stalled vehicles or vehicles that stopped but did not clear the tracks; these accidents often gave the driver time to abandon his vehicle prior to impact. Although categories of causes of accidents may be oversimplified or biased to some degree, they can be relied on in a general sense to show basic trend lines and patterns.

The aggregate results clearly indicated the superiority of automatic gates in reducing accident frequency and eliminating accidents that are potentially the severest. The effectiveness of the automatic gates is undoubtedly due in part to visual and auditory signals that attract a driver's attention and to the barrier effect that eliminates any decision a driver might want to make. This effect is not shared by any other type of warning device, even flashing lights. Although crossings with flashing lights constituted only about 15 percent of the total number of crossings in California at the end of 1973, more than 26 percent of the vehicle-train accidents that occurred during 1973 occurred at crossings with flashing lights; although automatic gates were found at more than 21 percent of the total crossings, only 18 percent of the accidents occurred at these crossings.

RURAL VERSUS URBAN CONDITIONS

Each of the 1552 crossings examined was classified as either rural or urban according to its location within an incorporated or unincorporated community of 2500 persons or more. Unfortunately, it was not possible to check each crossing to verify whether it was truly urban or rural. This inadequacy should be weighed when comparing the results of the effectiveness of automatic devices at the 913 urban and 639 rural crossings in the sample.

Tables 5 and 6 give the accident rates before and after the installation of automatic warning devices at rural

Table 1. Accident experience at all crossings.

Category	Number of Crossings	Accident Experience							
		Before Installation				After Installation			
		Accidents	Deaths	Injuries	Crossing-Years	Accidents	Deaths	Injuries	Crossing-Years
Protection prior to installation of flashing light signals									
None (new crossing)	75	1	—	—	0.17[a]	49	6	24	631
Crossbucks	245	611	134	451	2 431.25	173	20	58	2019
Wigwag	98	290	10	148	972.83	118	6	54	781
Miscellaneous	16	60	4	20	160.00	28	1	7	135
Subtotal	434	962	148	619	3 564.25	368	33	143	3566
Protection prior to installation of automatic gates									
None (new crossing)	91	—	—	—	—	36	—	6	441
Crossbucks	243	565	139	370	2 396.83	36	2	14	1095
Wigwag	248	969	110	454	2 480.00	169	8	31	1332
Flashing light	498	1861	258	842	4 516.50	333	21	108	2462
Miscellaneous	38	221	6	90	365.25	43	1	13	274
Subtotal	1118	3616	513	1756	9 758.58	617	32	172	5607
Total	1552	4578	661	2375	13 322.83	985	65	315	9174

[a] Accident occurred before crossing was officially opened.

Table 2. Accident experience per crossing-year at all crossings.

Category	Number of Crossings	Accident Experience per Crossing-Year					
		Before Installation			After Installation		
		Accidents	Deaths	Injuries	Accidents	Deaths	Injuries
Protection prior to installation of flashing light signals							
None (new crossing)	75	6.00	—	—	0.08	0.01	0.04
Crossbucks	245	0.25	0.06	0.19	0.09	0.01	0.03
Wigwag	98	0.30	0.01	0.15	0.15	0.01	0.07
Miscellaneous	16	0.37	0.02	0.12	0.21	0.01	0.05
Subtotal	434	0.27	0.04	0.17	0.10	0.01	0.04
Protection prior to installation of automatic gates							
None (new crossing)	91	—	—	—	0.08	—	0.01
Crossbucks	243	0.24	0.06	0.15	0.03	—	0.01
Wigwag	248	0.39	0.04	0.18	0.13	0.01	0.02
Flashing light	498	0.41	0.06	0.19	0.14	0.01	0.04
Miscellaneous	38	0.61	0.02	0.25	0.16	—	0.05
Subtotal	1118	0.37	0.05	0.18	0.11	0.01	0.03
Total	1552	0.34	0.05	0.18	0.11	0.01	0.03

Table 3. Effectiveness results at all crossings.

Category	Number of Crossings	Percentage of Reduction After Installation					
		Accident Factor per Crossing-Year			Accident Severity per Accident		
		Accidents	Deaths	Injuries	Deaths	Injuries	Casualties
Protection prior to installation of flashing light signals							
None (new crossing)	75	-98.67	—	—	—	—	—
Crossbucks	245	-64.00	-83.33	-84.21	-45.45	-54.05	-53.13
Wigwag	98	-50.00	—	-53.33	+66.67	-9.80	-5.56
Miscellaneous	16	-43.24	-50.00	-58.33	-42.86	-24.24	-27.50
Subtotal	434	-62.96	-75.00	-76.47	-40.00	-39.06	-40.00
Protection prior to installation of automatic gates							
None (new crossing)	91	—	—	—	—	—	—
Crossbucks	243	-87.50	-100.00	-93.33	-76.00	-40.00	-51.11
Wigwag	248	-66.67	-75.00	-88.89	-54.55	-61.70	-60.34
Flashing light	498	-65.85	-83.33	-78.95	-57.14	-28.89	-33.90
Miscellaneous	38	-73.77	-100.00	-80.00	-33.33	-26.83	-23.26
Subtotal	1118	-70.27	-89.00	-83.33	-64.29	-42.86	-47.62
Total	1552	-68.60	-85.60	-80.05	-54.00	-38.46	-41.75

and urban crossings. The rates are significantly lower at rural crossings (0.28 accidents/crossing-year before and 0.08 after) than at urban crossings (0.39 before and 0.13 after). The percentage of reduction in all accident and casualty rates is also higher at rural crossings (Tables 7 through 10).

These results appeared reasonable since it was assumed that there was a significant physical difference between rural and urban locations. Urban crossings were assumed to carry much more vehicular traffic and to possess additional hazards such as obstructions to continuous traffic flow (intersections, driveways, lane interaction, access control), sight restrictions, and possibly inadequate or restrictive geometrics. It was

Table 4. Accident severity at all crossings.

		Accident Severity per Accident					
		Before Installation			After Installation		
Category	Number of Crossings	Deaths	Injuries	Casualties	Deaths	Injuries	Casualties
Protection prior to installation of flashing light signals							
None (new crossing)	75	–	–	–	0.12	0.49	0.61
Crossbucks	245	0.22	0.74	0.96	0.12	0.34	0.45
Wigwag	98	0.03	0.51	0.54	0.05	0.46	0.51
Miscellaneous	16	0.07	0.33	0.40	0.04	0.25	0.29
Subtotal	434	0.15	0.64	0.80	0.09	0.39	0.48
Protection prior to installation of automatic gates							
None (new crossing)	91	–	–	–	–	0.17	0.17
Crossbucks	243	0.25	0.65	0.90	0.06	0.39	0.44
Wigwag	248	0.11	0.47	0.58	0.05	0.18	0.23
Flashing light	498	0.14	0.45	0.59	0.06	0.32	0.39
Miscellaneous	38	0.03	0.41	0.43	0.02	0.30	0.33
Subtotal	1118	0.14	0.49	0.63	0.05	0.28	0.33
Total	1552	0.14	0.52	0.66	0.07	0.32	0.39

Table 5. Accident experience per crossing-year at rural crossings.

		Accident Experience per Crossing-Year					
		Before Installation			After Installation		
Category	Number of Crossings	Accidents	Deaths	Injuries	Accidents	Deaths	Injuries
Protection prior to installation of flashing light signals							
None (new crossing)	35	–	–	–	0.06	0.01	0.02
Crossbucks	137	0.23	0.07	0.22	0.06	0.01	0.02
Wigwag	23	0.26	–	0.15	0.13	0.01	0.06
Miscellaneous	4	0.50	0.07	0.30	0.26	0.03	0.08
Subtotal	199	0.24	0.06	0.22	0.08	0.01	0.03
Protection prior to installation of automatic gates							
None (new crossing)	47	–	–	–	0.09	–	0.01
Crossbucks	156	0.23	0.07	0.15	0.03	–	0.01
Wigwag	67	0.29	0.06	0.16	0.10	0.01	0.02
Flashing light	168	0.35	0.07	0.16	0.13	0.01	0.03
Miscellaneous	2	0.34	–	0.11	–	–	–
Subtotal	440	0.29	0.07	0.16	0.08	0.01	0.02
Total	639	0.28	0.07	0.17	0.08	0.01	0.02

Table 6. Accident experience per crossing-year at urban crossings.

		Accident Experience per Crossing-Year					
		Before Installation			After Installation		
Category	Number of Crossings	Accidents	Deaths	Injuries	Accidents	Deaths	Injuries
Protection prior to installation of flashing light signals							
None (new crossing)	40	6.00	–	–	0.09	0.01	0.05
Crossbucks	108	0.28	0.04	0.14	0.12	0.01	0.04
Wigwag	75	0.31	0.01	0.15	0.16	0.01	0.07
Miscellaneous	12	0.33	0.01	0.07	0.19	–	0.04
Subtotal	235	0.30	0.03	0.14	0.13	0.01	0.05
Protection prior to installation of automatic gates							
None (new crossing)	44	–	–	–	0.07	–	0.02
Crossbucks	87	0.24	0.03	0.16	0.05	–	0.01
Wigwag	181	0.43	0.04	0.19	0.14	0.01	0.02
Flashing light	330	0.44	0.05	0.20	0.14	0.01	0.05
Miscellaneous	36	0.62	0.02	0.25	0.16	–	0.05
Subtotal	678	0.42	0.04	0.20	0.12	–	0.04
Total	913	0.39	0.04	0.18	0.13	0.01	0.04

further assumed that the outstanding characteristic at rural crossings was the speed of vehicle and train. Before the installation of automatic warning devices, rural crossings experienced 28 percent fewer accidents than urban crossings but suffered 55 percent more casualties per accident. However, after the automatic warning devices were installed, many of the previously severe accidents were eliminated and there were 38 percent fewer accidents at rural crossings than at urban crossings, although there was approximately the same number of casualties per accident at rural and urban crossings.

Table 7. Effectiveness results at rural crossings.

Category	Number of Crossings	Percentage of Reduction After Installation					
		Accident Factor per Crossing-Year			Accident Severity per Accident		
		Accidents	Deaths	Injuries	Deaths	Injuries	Casualties
Protection prior to installation of flashing light signals							
None (new crossing)	35	—	—	—	—	—	—
Crossbucks	137	-73.91	-85.71	-90.91	-58.06	-70.71	-67.69
Wigwag	23	-50.00	—	-60.00	250.00	-24.14	-13.33
Miscellaneous	4	-48.00	-57.14	-73.33	-33.33	-50.00	-46.67
Subtotal	199	-66.67	-83.33	-86.36	-56.00	-63.74	-61.21
Protection prior to installation of automatic gates							
None (new crossing)	47	—	—	—	—	—	—
Crossbucks	156	-86.96	-100.00	-93.33	-64.52	-15.15	-30.93
Wigwag	67	-65.52	-83.33	-87.50	-77.27	-60.00	-64.47
Flashing light	168	-62.86	-85.71	-81.25	-47.62	-40.91	-43.94
Miscellaneous	2	-100.00	—	-100.00	—	-100.00	-100.00
Subtotal	440	-72.41	-89.60	-87.50	-62.50	-49.06	-54.55
Total	639	-70.80	-88.30	-86.20	-59.82	-53.10	-55.00

Table 8. Accident severity at rural crossings.

Category	Number of Crossings	Accident Severity per Accident					
		Before Installation			After Installation		
		Deaths	Injuries	Casualties	Deaths	Injuries	Casualties
Protection prior to installation of flashing light signals							
None (new crossing)	35	—	—	—	0.11	0.37	0.47
Crossbucks	137	0.31	0.99	1.30	0.13	0.29	0.42
Wigwag	23	0.02	0.58	0.60	0.07	0.44	0.52
Miscellaneous	4	0.15	0.60	0.75	0.10	0.30	0.40
Subtotal	199	0.25	0.91	1.16	0.11	0.33	0.45
Protection prior to installation of automatic gates							
None (new crossing)	47	—	—	—	—	0.11	0.11
Crossbucks	156	0.31	0.66	0.97	0.11	0.56	0.67
Wigwag	67	0.22	0.55	0.76	0.05	0.22	0.27
Flashing light	168	0.21	0.44	0.66	0.11	0.26	0.37
Miscellaneous	2	—	0.33	0.33	—	—	—
Subtotal	440	0.24	0.53	0.77	0.09	0.27	0.35
Total	639	0.25	0.63	0.87	0.10	0.30	0.39

Table 9. Accident severity at urban crossings.

Category	Number of Crossings	Accident Severity per Accident					
		Before Installation			After Installation		
		Deaths	Injuries	Casualties	Deaths	Injuries	Casualties
Protection prior to installation of flashing light signals							
None (new crossing)	40	—	—	—	0.13	0.57	0.70
Crossbucks	108	0.13	0.48	0.61	0.10	0.37	0.47
Wigwag	75	0.04	0.49	0.53	0.04	0.46	0.51
Miscellaneous	12	0.02	0.20	0.22	—	0.22	0.22
Subtotal	235	0.09	0.46	0.55	0.08	0.42	0.50
Protection prior to installation of automatic gates							
None (new crossing)	44	—	—	—	—	0.22	0.22
Crossbucks	87	0.13	0.64	0.77	—	0.22	0.22
Wigwag	181	0.09	0.45	0.54	0.05	0.17	0.22
Flashing light	330	0.11	0.46	0.56	0.04	0.35	0.39
Miscellaneous	36	0.03	0.41	0.44	0.02	0.30	0.33
Subtotal	678	0.10	0.47	0.56	0.04	0.28	0.32
Total	913	0.09	0.47	0.56	0.05	0.33	0.38

Although the effectiveness of automatic warning devices appears to be somewhat dependent on the site of the crossing, significant benefits in terms of reduction in the number and severity of accidents are realized at both rural and urban locations.

TRACK INFLUENCE

There is reluctance in some circles to install automatic gates except at double-track main-line locations ("main line" is an actual railroad designation that distinguishes the important lines from the less important lines), since these locations are the only ones where sufficient benefits are received to justify the cost. Although the records could not be constructed to reflect the previous physical conditions, 1269 of the crossings included in the sample were segregated into three distinct categories: (a) single-track crossings, (b) crossings with two or more main or branch tracks, and (c) other multiple-track crossings with fewer than two main or branch tracks but with additional spur tracks.

The results in Tables 11 and 12 show that, while the percentage of reduction in accident rates is nearly identical for all three categories, there is a more than 80 percent greater chance of accident at double-track main- or branch-line crossings than at single-track crossings, before and after the installation of automatic warning devices. In terms of casualties per accident, severity rates, at least before the installation of automatic gates, were 25 percent greater at single-track crossings than at double-track main-line crossings. The number of casualties per crossing-year was higher at double-track main- or branch-lines due to the significant difference in accident frequency, and the results seem to show that improving the warning device at double-track main- or branch-line crossings provides the greatest amount of benefit in absolute numbers. The effectiveness of automatic gates in terms of the percentage of reduction in accident frequency, however, is nearly equal for all categories. This reduction indicates that automatic gates have a similar effect in most instances and are clearly adaptable to and productive in varied crossing conditions.

ECONOMIC ANALYSIS

Although the effectiveness results developed in this study are useful in formulating a balanced grade-crossing safety program, the vehicle-train accident frequency and severity comparisons can also be used to test the economic feasibility of installing various warning devices at individual crossings or at a group of crossings. Complete examples and explanations of the technique have been published (3, 4, 5).

One method, which considers only a single crossing location, involves estimating the future potential for vehicle-train accidents by comparing the expected frequency and severity of accidents with the existing warning devices and with the more sophisticated devices installed, taking into account the monetary difference. The reduction in expected annual economic loss through the installation of higher order warning devices on an incremental basis compared with the annual cost of installing, maintaining, and operating each of the various devices on an incremental annual basis would indicate which warning device would be the most cost-effective.

To compare the relative effectiveness of the various types of warning devices, two distinct considerations are involved: accident frequency and accident severity. The data from Tables 2 and 4 indicate that both accident frequency and accident severity, as well as the number of recorded deaths and injuries per accident, are reduced by the installation of flashing light signals or automatic gates. It is imperative that both accident frequency and accident severity be included in any comparative economic analysis. Therefore, the factors considered for a reasonable estimate of the relative value of warning devices in California are as follows:

		Accident Severity	
Warning Device	Accident Frequency	Deaths per Accident	Injuries per Accident
Crossbucks	1.00	1.00	1.00
Flashing lights	0.33	0.54	0.57
Automatic gates	0.13	0.25	0.46

The first unknown, and one that is subject to considerable critical speculation, is the potential accident frequency and severity at a crossing with or without improvement of the warning device. There are several methods available for determining these potentials; the least attractive is to extend past accident rates and to use a simple hazard index or sufficiency rating equations that may or may not correlate with actual accident experience. The more reasonable method, if a significant correlation exists, is to develop predictive equations by using multiple regression techniques that forecast vehicle-train accidents as a function of the physical conditions that describe each crossing such as train and vehicle volumes, respective speeds, and geometrics or distractions. Regression equations estimate as much as possible of the variation in the dependent variable—the vehicle-train accident experience—by simultaneously combining several independent variables. The equations can be used, with differing levels of confidence, for individual crossings or for groups of similar crossing types. The California Public Utilities Commission has attempted to develop regression equations for use in California, but for a variety of reasons, including a limited data base, it has failed to arrive at a set of equations that could be used with any degree of certainty for individual crossings. For this analysis, the typical accident and severity rates (accidents per year, deaths per accident, and injuries per accident) shown in Tables 2 and 4 are used in Table 13 to determine the economic loss expected per year with each type of warning device.

Once the predicted accident frequency and severity rates have been developed, the economic benefits are estimated by defining the cost of the unit hazard—the economic loss incurred by vehicle-train accidents, deaths, and injuries. As in the case of estimating accident potential, there is little conformity among public agencies; estimates vary considerably, depending on the source and the method. For this analysis, the National Highway Traffic Safety Administration (NHTSA) figures of $133 000 per fatality and $3500 per injury are used (6). Although the NHTSA actually uses figures of $200 000 and $7300 respectively, only discounted wage loss and medical costs were considered applicable. Flashing lights reduce the anticipated economic loss by $9410 from what would be expected with crossbucks, and automatic gates reduce the expected economic loss by $1870 from what would be expected with flashing lights.

To determine which device offers the most cost-effective alternative, it is necessary to calculate the annual cost of installing, maintaining, and operating each type of warning device. This is computed in Table 14. The installation cost figures of $16 250 for flashing lights and $27 290 for automatic gates are actual 1975 California estimates; the $190 for crossbucks is a 1972 figure, updated by using a construction cost index. The maintenance and operation cost figures of $500 for flashing lights and $1000 for automatic gates are based on Association of American Railroads figures that use a unit cost of $30, which the Public Utilities Commission currently recognizes. The annual cost of capital recovery was calculated by using a useful life of 30 years and an interest rate of 10 percent. On an incremental basis, it costs $2190/year more to install, maintain, and operate flashing lights than crossbucks and $1670 more for automatic gates than for flashing light signals.

Given the accident frequencies and severity and accident costs, the most effective alternative would be automatic gates. This sample analysis acts only as a brief outline; a detailed analysis should include consideration of vehicular delay, property damage, and accidents that do not involve trains. In addition, it is evident that such

Table 10. Effectiveness results at urban crossings.

		Percentage of Reduction After Installation					
		Accident Factor per Crossing-Year			Accident Severity per Accident		
Category	Number of Crossings	Accidents	Deaths	Injuries	Deaths	Injuries	Casualties
Protection prior to installation of flashing light signals							
None (new crossing)	40	-98.50	—	—	—	—	—
Crossbucks	108	-57.14	-75.00	-71.43	-23.08	-22.92	-22.95
Wigwag	75	-48.39	—	-53.33	—	-6.12	-3.77
Miscellaneous	12	-42.42	-100.00	-42.86	-100.00	10.00	—
Subtotal	235	-56.67	-66.67	-64.29	-11.11	-8.70	-9.09
Protection prior to installation of automatic gates							
None (new crossing)	44	—	—	—	—	—	—
Crossbucks	87	-79.17	-100.00	-93.75	-100.00	-65.63	-71.43
Wigwag	181	-67.44	-75.00	-89.47	-44.44	-62.22	-59.26
Flashing light	330	-68.18	-80.00	-75.00	-63.64	-23.91	-30.36
Miscellaneous	36	-74.19	-100.00	-80.00	-33.33	-26.83	-25.00
Subtotal	678	-71.43	-100.00	-80.00	-60.00	-40.43	-42.86
Total	913	-67.60	-82.25	-77.00	-45.79	-29.79	-32.14

Table 11. Effect of type of railroad track on number of accidents.

		Accident Experience per Crossing-Year								
					After Installation					
		Before Installation			Accidents		Deaths		Injuries	
Type of Crossing	Number of Crossings	Accidents	Deaths	Injuries	Number	Decrease (%)	Number	Decrease (%)	Number	Decrease (%)
Crossings upgraded to flashing light signals										
Single track	179	0.29	0.06	0.25	0.09	-69	0.01	-83	0.04	-84
Double main line or branch track	14	0.48	0.01	0.22	0.24	-50	0.01	0	0.09	-59
Other multiple track	108	0.26	0.04	0.13	0.13	-50	0.01	-75	0.03	-77
Crossings upgraded to automatic gates										
Single track	482	0.31	0.06	0.17	0.08	-74	0.01	-83	0.02	-88
Double main line or branch track	119	0.57	0.06	0.28	0.16	-74	0.00	-100	0.05	-86
Other multiple track	367	0.37	0.05	0.15	0.12	-68	0.01	-80	0.04	-73

Table 12. Effect of type of railroad track on severity of accidents.

		Accident Severity per Accident								
					After Installation					
		Before Installation			Deaths		Injuries		Casualties	
Type of Crossing	Number of Crossings	Deaths	Injuries	Casualties	Number	Decrease (%)	Number	Decrease (%)	Number	Decrease (%)
Crossings upgraded to flashing light signals										
Single track	179	0.21	0.86	1.07	0.08	-61	0.45	-47	0.54	-50
Double main line or branch track	14	0.02	0.45	0.47	0.03	-50	0.39	-13	0.42	-11
Other multiple track	108	0.16	0.49	0.66	0.11	-31	0.27	-45	0.38	-42
Crossings upgraded to automatic gates										
Single track	482	0.19	0.56	0.75	0.09	-53	0.22	-61	0.31	-59
Double main line or branch track	119	0.10	0.50	0.60	0.03	-70	0.29	-46	0.32	-52
Other multiple track	367	0.13	0.41	0.54	0.05	-62	0.32	-22	0.37	-31

Table 13. Economic analysis of incremental benefit calculation.

Warning Device	Fatalities per Accident		Injuries per Accident		Total Cost per Accident ($)	Total Accidents per Year		
	Number	Cost ($)	Number	Cost ($)		Number	Cost ($)	Incremental Difference From Next Highest Alternative (rounded $)
Crossbucks	31 920	0.24	2345	0.70	34 265	0.34	11 650	–
Flashing light	17 290	0.13	1340	0.40	18 630	0.12	2 236	9410
Automatic gates	7 980	0.06	1072	0.32	9 052	0.04	362	1870

Table 14. Economic analysis of incremental cost calculation.

Warning Device	Installation Cost ($)	Annual Maintenance and Operation Cost ($)[a]	Annual Cost of Capital Recovery ($)[b]	Total Annual Cost ($)	Incremental Cost Over Next Lowest Alternative ($)
Crossbucks	190	15	20	35	–
Flashing light	16 250	500	1725	2225	2190
Automatic gates	27 290	1000	2895	3895	1670

[a] From Association of American Railroads.

[b] Useful life of 30 years at 10 percent interest.

an analysis must be sensitive to several of the unknowns that deserve close scrutiny, including (a) predicted vehicle-train accident rates; (b) installation, maintenance, and operational costs of the various devices; and (c) the economic value placed on human life.

LIMITATIONS OF AUTOMATIC WARNING DEVICES

Much has been said about the reduction in the frequency of vehicle-train accidents that can be expected from the installation of automatic warning devices; however, certain limitations do exist. Some trends have developed in California that indicate that considerable research is still required. The most obvious disadvantage entailed in the installation of automatic warning devices is the increased number of secondary or gate accidents that occur. In 1973, there were 745 vehicle-train accidents in California but there were also 2197 crossing gate accidents, and that number is expected to increase steadily with increased gate installations. The key point, however, is severity of accidents. While 59 persons were killed and almost 300 injured because of vehicle-train accidents in 1973, there was not a single reported casualty in any of the 2197 gate accidents recorded. The effectiveness of automatic gates is partially dependent on and limited by street design and crossing geometrics. Between 1970 and 1972, there were more than 200 recorded vehicle-train accidents at crossings with automatic gates that were classified as being caused by stalled vehicles or vehicles that stopped but did not clear the tracks.

Another limitation of automatic gates that indicates a trend that should be viewed with dismay is the increasing number of vehicle-train accidents at crossings with automatic gates that are caused by failure of the vehicle driver to stop at the crossing. While the number of such accidents is still small compared with other causes, during the same period there were 150 accidents attributed to failure of the vehicle to stop. Part of the increase in such accidents is probably due to the increased number of gate installations, but there has been an unaccountable increase in vehicles driving around or through lowered gates. Driving around lowered gates is probably a result of frustration or disrespect, but driving through lowered gates can be due to inattention or excessive speed, both of which should be examined closely to determine whether the underlying hazard could be mitigated by improving the warning design, either at the crossing or through more sophisticated advance warning devices.

CONCLUSIONS

Automatic warning devices are quite effective in reducing vehicle-train accidents and casualties at public railroad-highway grade crossings in California. The installation of automatic crossing gates can be expected, on the average, to result in 70 percent fewer vehicle-train accidents per year and an additional 48 percent fewer casualties per accident. Theoretically, if automatic gates were in service for the entire study period, there would have been about 2500 fewer accidents, 450 fewer deaths, and 1450 fewer injuries.

Automatic gates eliminate many of those accidents involving moving vehicles that offer the greatest potential severity; they reduce the number of deaths by 64 percent/accident, injuries by 43 percent/accident, and deaths by more than 36 percent/injury. The effectiveness of automatic warning devices is dependent, in part, on crossing locality. Accident rates before and after the installation of automatic warning devices were far lower at rural than at urban crossings. The percentage of reduction in all accident and casualty rates was higher at rural crossings.

While the percentage of reduction in vehicle-train accidents was equal for single-track and double-track main or branch crossings, the latter were far more hazardous in terms of accidents per crossing-year and, therefore, showed the greatest benefit in terms of numbers of accidents and casualties reduced. The equal percentage of reduction would seem to indicate, however, that automatic gates were adaptable and effective at all crossing situations. Automatic gates are superior to other types of warning devices because they have a visual and auditory impact on driver response. Gates act as a physical or psychological barrier and drastically reduce or simplify any decision a vehicle driver might want or need to make. However, automatic devices may have a practical limit, and the final responsibility for preventing accidents must rest with the vehicle driver. Automatic warning devices will help prevent vehicle-train accidents caused by natural conditions such as inadequate sight distance or the general inability to see or perceive an approaching train; accidents caused by traffic or rail volumes; accidents caused by trains operating on multiple tracks; and, in part, accidents caused by distractions and other road hazards. Automatic devices will probably not prevent vehicle-train accidents caused by complete driver inattention, excessive vehicular speed, violations of the law, or lack of sound driver judgment. Automatic warning devices are a preventive tool, but they will only fulfill their potential if the driver is aware of his or her obligation to face the hazards involved when approaching a rail-street crossing.

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Passive Control at Railroad-Highway Grade Crossings

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Between 1968 and 1972, there was an average of one fatality for every seven accidents at railway-highway grade crossings. Accidents at these crossings accounted for 0.06 percent of all accidents and 1 percent of all fatalities. The seriousness of this kind of accident necessitates the development of an effective warning design as soon as possible. In New Jersey, over 60 percent of all railroad crossings have only passive control.

Because of the great expense of installing active control, this project concentrated on evaluating and attempting to improve the designs for passive control. Three basic objectives for passive control were established:

1. Make the motorist aware that he or she is approaching the crossing (awareness of the presence of a train is beyond the scope of passive protection),
2. Make the motorist aware that his or her judgment alone will determine whether it is safe to go over the crossing, and
3. Create a uniform motorist response both on the approach and at the crossing to reduce the likelihood of conflict between vehicles in the traffic stream.

The first phase of this project concentrated on the development of field techniques to measure the effectiveness of passive designs. Four measures were formulated and subsequently tested in three pilot studies conducted at two sites. The following conclusions were made from these studies.

1. The standard deviation of the spot speeds on the crossing was high in relation to the variation of spot speeds on the approach. (Spot speeds at the crossing were one measure used for evaluation.)
2. Head movements of motorists looking down the tracks were found to be virtually nonexistent. (This measure was not used for evaluation.)
3. Brake lights were applied on the approach to the rail crossing in only 7.6 percent of the vehicles, even though during the pilot studies over 60 percent of the motorists claimed to slow down at crossings. (This measure was used for evaluation, although specific conclusions were not made.)
4. Motorist interviews were believed to be the most effective method for determining the effect of experimental designs. (This measure was used for evaluation.)

After measures of effectiveness were developed, attention was focused on developing experimental signs. Two combinations of experimental advance and crossbuck signs were chosen for evaluation:

1. A yellow diamond-shaped advance sign with a black silhouette of a train and a yellow diamond-shaped sign with a superimposed crossbuck located at the crossing; and
2. A brilliant yellow-green, diamond-shaped advance sign with a black silhouette of a track crossing a road and a brilliant yellow-green, diamond-shaped sign with a superimposed crossbuck located at the crossing.

Each combination was installed at three locations for a total of six experimental sites. New conventional signs were installed at four additional sites. Before and after studies measured the effectiveness of two control changes: (a) as is conventional to upgraded conventional and (b) upgraded conventional to experimental.

The before and after studies were compared, and an increase of motorist awareness was noticed at all sites where experimental signs were used. Differences among experimental signs were noticed when the signs were considered together (advance and crossbuck) and in combination with other changes. It was found that the experimental signs using brilliant yellow-green scotchlite were more noticeable than the yellow experimental signs. Other changes included a reduction in the variance of spot speeds at nine out of ten sites and an increase in the percentage of motorists observed applying brakes at seven out of seven sites.

The results indicate that all control changes increased awareness of the crossings. However, the increase was statistically significant at only two sites. The general

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reduction in standard deviation of spot speeds implies a more uniform motorist reaction at the crossing. The increases in percentage of motorists observed applying brakes and in average spot speed reductions at the track and the decrease in percentage of motorists responding to the question of slowing down imply a more pronounced slowing with experimental signs than with conventional signs.

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Investigation of Accident Data for Railroad-Highway Grade Crossings

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This paper discusses some of the results of investigations of railroad-highway accidents and accident-related inventory information that was collected from 15 states and three railroad companies. Statistical techniques were applied to tabulated data to obtain prediction equations for accident frequency and severity of various grade-crossing situations. The results of the analysis and the uses of prediction equations for the development of warrants for safety improvements are also discussed.

The 1971 and 1972 reports to the Congress on railroad-highway safety described the grade-crossing problem and presented recommendations for a nationwide program to improve safety at grade crossings (1, 2). The 1973 Federal-Aid Highway Act specifically made available to all states large sums of money for safety improvements at crossings. Moreover, this legislation requires that a ranking or priority method be used in the selection of crossings for safety improvement.

The major purpose of the safety improvement program is to reduce the number of accidents and degree of accident severity at railroad-highway grade crossings (3). The accidents, injuries, and fatalities prevented by safety improvements are viewed as benefits that can be evaluated in economic terms. Reductions in accident costs are compared with installation and maintenance costs for various types of safety improvements to give cost-benefit measures that are used for determining (a) the crossings to be improved, (b) the nature of the improvements, and (c) the priorities for improvements. The accident frequency equations and the accident severity prediction rates are, therefore, the items of major influence in the development of economic warrants and priorities for safety improvements (4).

Historically, there have been difficulties in establishing statistically significant relationships between crossing characteristics and the occurrence of accidents at the crossing (5, 6, 7). This difficulty can be partially attributed to the lack of uniform data regarding the factors that influence grade-crossing accidents. Therefore, the reliability of the methods used for assessing true accident potential is frequently questioned. Although many existing methodologies have been modified and are currently being used by state transportation agencies, no single evaluation method has been universally accepted (7).

In an effort to provide improved capabilities for evaluating grade-crossing safety, the Federal Highway Administration (FHWA) initiated a study (4, 8) to refine and extend the accident prediction and accident severity models that had been developed for the 1972 report to Congress (2). The initial tasks of the study included reviewing and refining existing railroad grade-crossing accident, inventory, and accident severity data that were collected from different states and railroad companies. Statistical analysis techniques were then used to investigate relations between characteristics of grade crossings and accident frequency and between vehicle and train speeds and accident severity. The final tasks of the study were to summarize the results of the analyses for developing prediction equations and to establish guidelines for integrating the results of the analyses with economic data for use in developing warrants and priorities for safety improvements.

GRADE-CROSSING ACCIDENT AND INVENTORY DATA

Data for accidents that involved trains at grade crossings and inventory data were received from 45 states. Due to difficulties in matching accident data with specific crossing inventory data, only data from 37 230 grade crossings in 15 states could be used in the final data base. In the tabulation of accident data, crossings were classified according to the number of tracks (single or multiple), the location (urban or rural), and the type of warning device (automatic gates, flashing lights, other active, crossbucks, stop signs, or none). A summary of these data is given in Table 1.

The sample crossings were then stratified according to the volume ranges of train and highway traffic given below.

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Average Vehicles per Day	Average Trains per Day
1 to 250	1 to 2
251 to 500	3 to 5
501 to 1 000	6 to 10
1 001 to 5 000	11 to 20
5 001 to 10 000	21 to 40
10 001 to 40 000	41 to 100

This stratification yielded 24 sets of two-way tables. For each cell within these tables, the following information was tabulated:

N = number of grade crossings,
N^* = number of crossing-years of data (cumulative years of available accident data),
A = total number of accidents reported for the N^* crossing-years,
$\bar{A}$ = the average number of accidents per crossing-year (A/N^*),
$\bar{V}$ = the weighted average daily traffic volume for the N crossings (the weights are the number of years of available accident data for each of the N crossings), and
$\bar{T}$ = the weighted average train volume for the N crossings (the weights are the number of years of available accident data for each of the N crossings).

The distribution characteristics of the 37 230 sample grade crossings and 9490 accidents are shown below.

Crossing Type	Grade Crossings (%)	Reported Accidents (%)
Single track	71	52
Urban		
Percentage of total	23	26
Percentage of single tracks	32	50
Rural		
Percentage of total	48	26
Percentage of single tracks	68	50
Multiple track	29	48
Urban		
Percentage of total	16	32
Percentage of multiple tracks	54	67
Rural		
Percentage of total	13	15
Percentage of multiple tracks	46	33

GRADE-CROSSING ACCIDENT SEVERITY DATA

Three railroad companies submitted information regarding the severity of 6876 accidents involving trains. In the tabulation of severity data, accidents were classified according to the six types of warning devices and the type of collision. A summary of these data is given in Table 2. The data were further stratified according to the reported speeds of the trains and vehicles involved in the accidents. The speed ranges used in the severity tabulations are given below.

Vehicle Speed (km/h)	Train Speed (km/h)
0	0 to 19.2
1.6 to 22.4	20.8 to 38.4
24.0 to 46.4	40.0 to 57.6
48.0 to 70.4	59.2 to 76.8
72.0+	78.4+

The following information was computed for each of the 25 combinations of vehicle and train speeds:

n = number of accidents,
x = number of injuries,
y = number of fatalities,
$\bar{S}_V$ = average speed of the vehicle involved in the n accidents,
$\bar{S}_T$ = average speed of the train involved in the n accidents,
r_x = injury rate (x/n), and
r_y = fatality rate (y/n).

Information concerning the number of tracks, the locations of crossings, and the vehicle and train traffic volumes was not available for the severity data.

ACCIDENT PREDICTION EQUATIONS

The number of accidents that will occur for a group of similar grade crossings during a fixed time period may be viewed as the product of the rate of accident occurrence per crossing per unit of time ($\bar{A}$) and the number of crossing-years of exposure to accidents. A crossing-year of exposure is defined as one grade crossing exposed to accidents for 1 year.

In previous work (5), attempts were made to develop a predicted accident rate for individual crossings. The attempts were not successful and the equations developed for individual crossings did not explain a significant amount of the variation in accidents. To account for more variation, the method presented here concentrated on analyzing groups of crossings.

For purposes of generalization, one may assume that each individual crossing within a group has an accident potential equivalent to the average rate ($\bar{A}$) for that group; therefore, the development of accident prediction equations focused on the relations between observed accident rates for groups of crossings with similar physical characteristics and the associated average daily train and vehicle volumes. As a group, crossings are considered to be similar if they fall within a common range of such characteristics as location, number of tracks, warning device, and highway and train volumes.

Seventy percent of the sample data base was randomly selected for testing alternative models for multiple linear regression, and the remaining data were reserved for validation purposes. The following models were both found to offer a reasonable and statistically significant explanation of the observed accident rates for the grouped data.

Model 1:

$$\log_{10}\bar{A} = C_0 + C_1\log_{10}\bar{V} + C_2\log_{10}\bar{T} \tag{1}$$

Model 2:

$$\log_{10}\bar{A} = C_0 + C_1\log_{10}\bar{V} + C_2\log_{10}\bar{T} + C_3(\log_{10}\bar{T})^2 \tag{2}$$

In some situations, the additional terms $C_3(\log_{10}\bar{T})^2$ enabled model 2 to achieve an improved fit for accident rates in the higher volume categories. For this reason, the model 2 regression results given in Table 3 represent the preferred accident prediction equations. With a few exceptions, the signs of the coefficients correspond to a priori expectations.

It is important to note that the regression results give predicted logarithms of accident rates (9). Since the equations would be used in terms of expected numbers of accidents rather than the logarithms of accident rates, correlations between the observed and predicted numbers of accidents were calculated and are given in Table 4. The 30 percent sample of crossing data originally withheld were used for a cross validation (10) of the model 2 equations. The results are also given in Table 4. In a cross-validation procedure, the regression results from the analysis are applied to a separate independent sample of validation data to obtain predicted values of the depen-

Table 1. Accident data according to type of crossing.

Item	Accidents	Crossings	Crossing-Years
Single-track urban			
Automatic gates	240	685	2 077
Flashing lights	680	1 986	6 411
Other active	509	668	2 837
Stop signs	60	185	1 054
Crossbucks	931	4 307	17 076
None	91	716	3 358
Subtotal	2511	8 547	32 813
Single-track rural			
Automatic gates	145	508	1 558
Flashing lights	480	2 441	6 714
Other active	173	352	1 432
Stop signs	188	900	5 115
Crossbucks	1477	13 005	63 026
None	45	772	3 779
Subtotal	2508	17 978	81 624
Multiple-track urban			
Automatic gates	432	838	2 854
Flashing lights	1087	1 439	4 725
Other active	547	607	2 491
Stop signs	192	185	1 076
Crossbucks	694	2 366	9 618
None	60	340	1 631
Subtotal	3012	5 775	22 395
Multiple-track rural			
Automatic gates	145	461	1 915
Flashing lights	360	1 071	3 625
Other active	73	154	629
Stop signs	170	413	2 604
Crossbucks	702	2 672	12 052
None	9	159	716
Subtotal	1459	4 930	21 541
Total	9490	37 230	158 373

Table 2. Distribution of accidents, injuries, and fatalities by warning device and type of collision.

Item	Accidents	Injuries	Fatalities
Warning device			
Automatic gates	284	115	38
Flashing lights	2031	1096	304
Other active	325	176	43
Crossbucks	3602	1608	449
Stop signs	57	24	5
No warning	577	107	16
Total	6876	3125	855
Collision type			
Train strikes automobile	4055	1795	530
Train strikes truck	1107	324	115
Train strikes other	183	63	37
Automobile strikes train	1242	785	140
Truck strikes train	223	108	18
Other strikes train	46	44	11
Total	6856	3119	851

dent variable. The correlation between the observed and predicted values is an estimate of the validity of the derived regression results.

One may conclude from the results in Tables 3 and 4 that the accident prediction equations for crossbucks, flashing lights, and other active devices will generally be reliable for translating the train and vehicle volume characteristics for grouped crossings into predicted numbers of accidents. On the other hand, the relation between volume characteristics and accidents seems to be much weaker in the case of automatic gates. Also the prediction equations for stop signs are weak except for the single-track crossings.

Figures 1 through 4 show the comparison of model 2 automatic gates, flashing lights, and crossbuck equations for combinations of location and number of tracks with train volume fixed at 10 trains/d. Examination of these curves shows that gates generally have the lowest predicted accident rates for all four cases. In the low average daily traffic values for urban single-track crossings, rural single-track crossings, and rural multiple-track crossings, the accident rates for crossings with gates are higher than the rates for crossings with flashing lights or crossbucks. This may be due to the small sample of gate-protected crossings available in these traffic ranges. For urban areas at both single- and multiple-track crossings, the curves for flashing lights are higher than the curves for crossbucks. Additional variables may be needed in these cases to fully explain accident occurrence patterns. For multiple-track crossings in rural areas, the curves for flashing lights and crossbucks are extremely close and intersect at 3000 vehicles/d. Again, further analysis with additional variables might result in an improved discrimination between crossbucks and flashing lights.

ACCIDENT SEVERITY PREDICTION RATES

The purpose of the severity analysis was to explain the structure of the relations between differences in severity rates for different groups of accidents. The expected number of fatalities and injuries that would result from a group of similar accidents may be viewed as the product of the rate of injury or fatality per accident and the number of accidents for which the rate applies. For a group of similar accidents, the ratio of the observed number of injuries or fatalities to the number of accidents in the group may be considered as a measure of the rate of injury or fatality for those accidents. In general, it may be assumed that severity rates will be lower for slow-speed crashes and higher for high-speed crashes. However, in some cases, injury rates will be lower for high-speed crashes because greater numbers of fatalities occur in these cases.

Accidents were stratified into groups according to train and vehicle speeds and the type of warning device. The relations between severity rates and the speed characteristics of the 6876 sample accidents were analyzed using the following two-way analysis of variance model:

$$r_{ij} = \mu + \alpha_i + \beta_j + \epsilon_{ij} \quad (3)$$

where

r_{ij} = rate of injury or fatality,
μ = mean rate,
α_i = effect of vehicle speed class,
β_j = effect of train speed class, and
ϵ_{ij} = error.

It was assumed that r_{ij} would exhibit the behavior of a binomial proportion (11). This allowed the assumption that r_{ij} has approximately a normal distribution with variance

$$V(r_{ij}) = [p_{ij}(1 - p_{ij})]/n_{ij} \quad (4)$$

where

p_{ij} = probability of injury or fatality in a typical acci-

Table 3. Model 2 regression results.

Item	C_0	C_1	C_2	C_3	R^2	Item	C_0	C_1	C_2	C_1	R^2
Single-track urban						Multiple-track urban					
Automatic gates	-2.17	0.16	0.96	-0.35	0.186	Automatic gates	-2.58	0.23	1.30	-0.42	0.396
Flashing lights	-2.85	0.37	1.16	-0.42	0.729	Flashing lights	-2.50	0.36	0.68	-0.09	0.691
Crossbucks	-2.38	0.26	0.78	-0.18	0.684	Crossbucks	-2.49	0.32	0.63	-0.02	0.706
Other active	-2.13	0.30	0.72	-0.30	0.770	Other active	-2.16	0.36	0.19	0.08	0.65
Stop signs	-2.98	0.42	1.96	-1.13	0.590	Stop signs	-1.43	0.09	0.18	0.16	0.35
None	-2.46	0.16	1.24	-0.56	0.24	None	-3.00	0.41	0.63	-0.02	0.58
Single-track rural						Multiple-track rural					
Automatic gates	-1.42	0.08	-0.15	0.25	0.200	Automatic gates	-1.63	0.22	-0.17	0.05	0.142
Flashing lights	-3.56	0.62	0.92	-0.38	0.857	Flashing lights	-2.75	0.38	1.02	-0.36	0.674
Crossbucks	-2.77	0.40	0.89	-0.29	0.698	Crossbucks	-2.39	0.46	-0.50	0.53	0.780
Other active	-2.25	0.34	0.34	-0.01	0.533	Other active	-2.32	0.33	0.80	-0.35	0.31
Stop signs	-2.97	0.61	-0.02	0.29	0.689	Stop signs	-1.87	0.18	0.67	-0.34	0.32
None	-3.62	0.67	0.22	0.26	0.756	None	—[a]	—[a]	—[a]	—[a]	—[a]

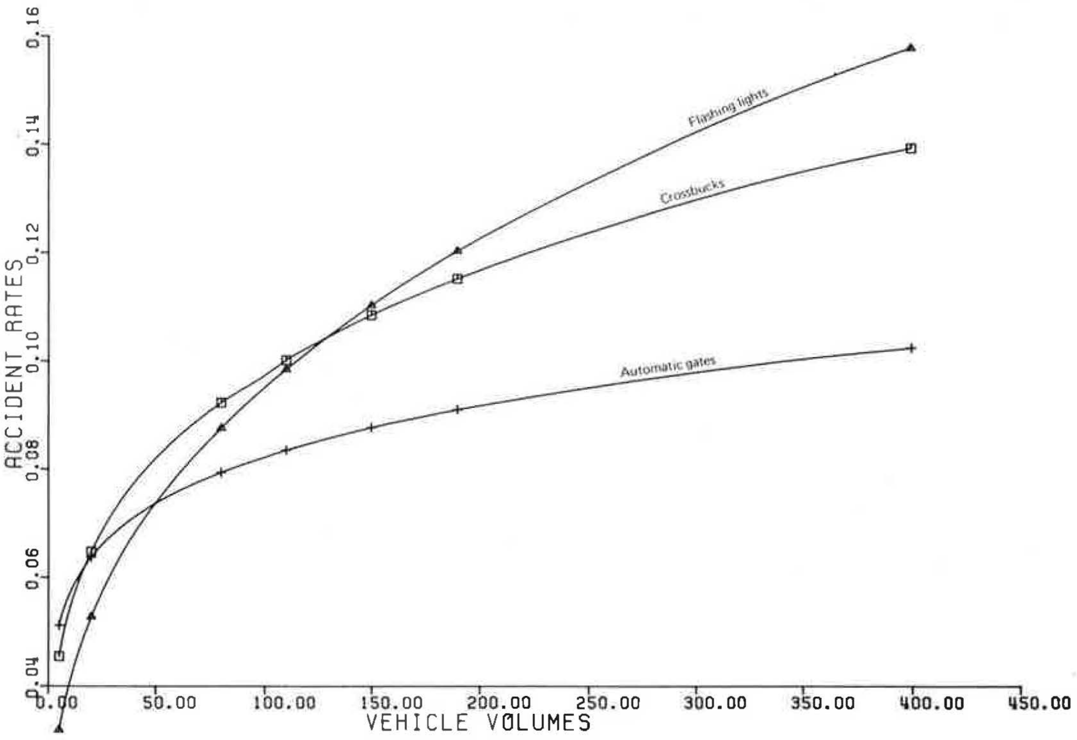
[a] Insufficient data.

Table 4. Model 2 validation results.

	Correlation Between Accidents			Correlation Between Accidents	
Item	Regression Data	Validation Data	Item	Regression Data	Validation Data
Single-track urban			Multiple-track urban		
Automatic gates	0.7916	0.5959	Automatic gates	0.8954	0.8705
Flashing lights	0.9183	0.7309	Flashing lights	0.9129	0.7567
Crossbucks	0.9308	0.7963	Crossbucks	0.8775	0.7629
Other active	0.9421	0.7564	Other active	0.9130	0.6046
Stop signs	0.7377	0.8451	Stop signs	0.9142	0.5565
None	0.6804	0.4938	None	0.4548	-0.2921
Single-track rural			Multiple-track rural		
Automatic gates	0.7107	-0.4573	Automatic gates	0.8027	0.7443
Flashing lights	0.9640	0.8564	Flashing lights	0.6728	0.4148
Crossbucks	0.9229	0.8892	Crossbucks	0.7670	0.6570
Other active	0.8675	0.7652	Other active	0.9442	0.9898
Stop signs	0.7976	0.7414	Stop signs	0.9081	0.7952
None	0.7490	0.8095	None	—[a]	—[a]

[a] Insufficient data.

Figure 1. Single-track crossings in urban areas (10 trains/d).



dent occurring for a given range of vehicle and train speeds and

n_{ij} = total number of observed accidents.

These assumptions suggested performing a weighted least squares analysis using estimated weights:

$$w_{ij} = n_{ij}/[r_{ij}(1 - r_{ij})] \quad (5)$$

The results of the analysis give estimates for the parameters μ, α_i, and β_j that were then used to predict accident rates for each of the 25 combinations of vehicle and train speed classifications. The predicted rates of injury and fatality for crossbucks and flashing lights are given in Tables 5 and 6. These tables also give the observed distribution of accidents by vehicle and train speed. Severity prediction rates for other types of protection were not developed because of insufficient data.

The validity of the severity analysis results was considered by computing correlations between predicted

Figure 2. Multiple-track crossings in urban areas (10 trains/d).

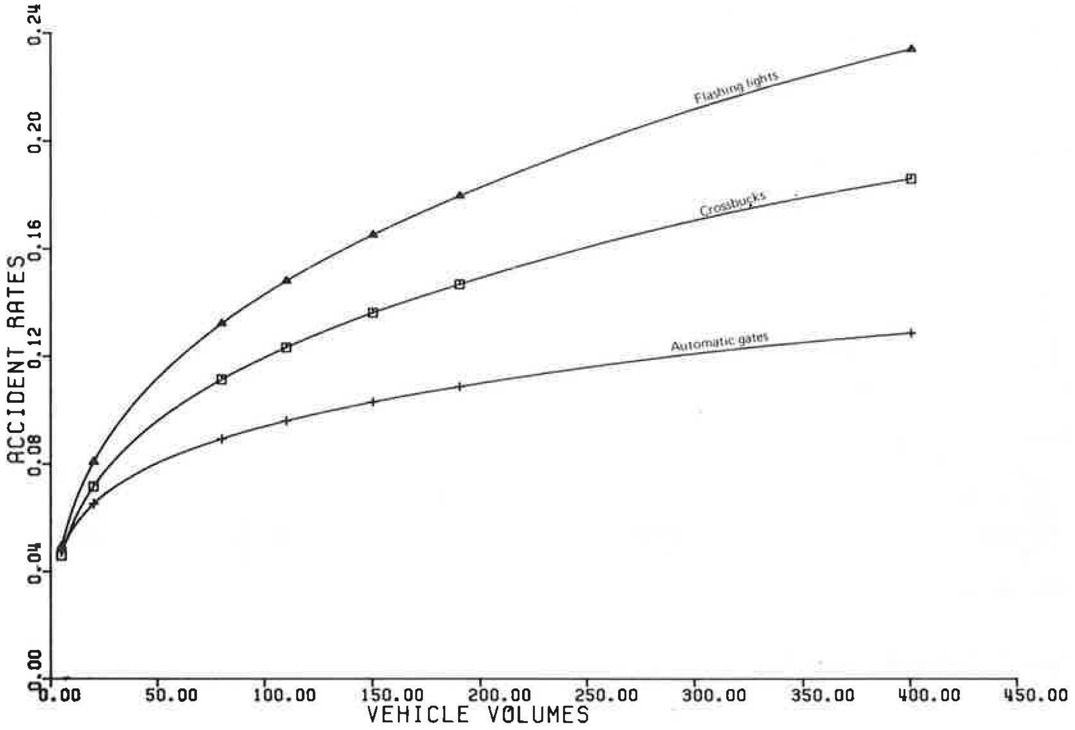
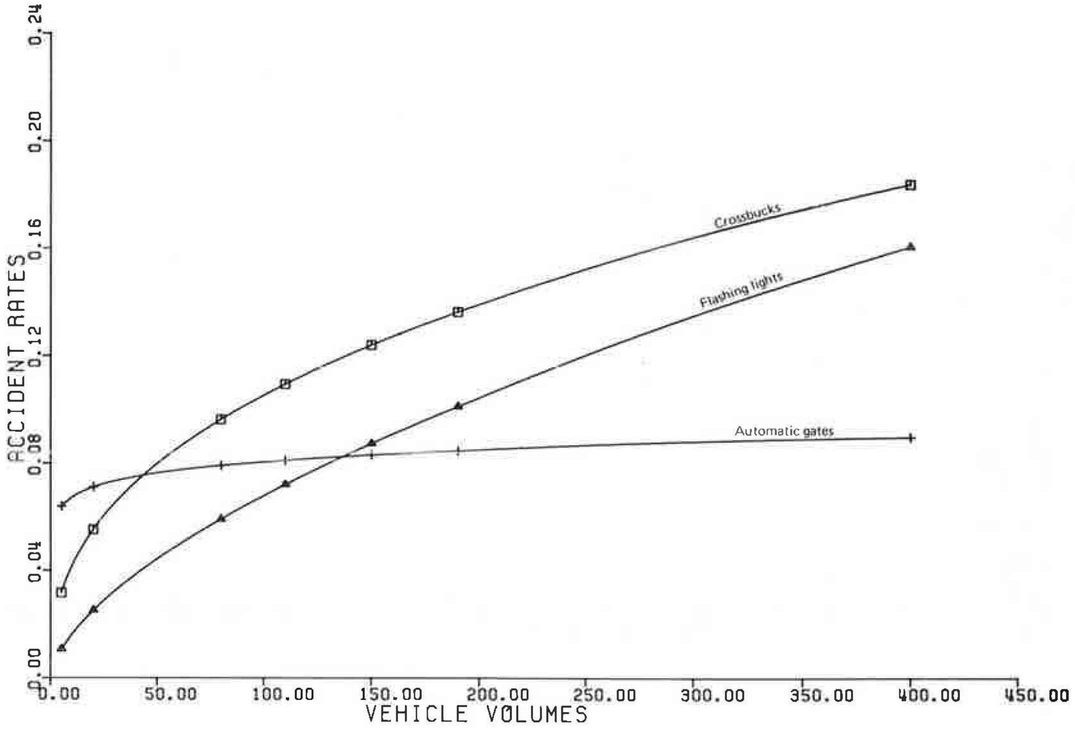


Figure 3. Single-track crossings in rural areas (10 trains/d).



values and observed values. For the crossbuck analysis, the correlations for number of injuries and number of fatalities were 0.97 and 0.69 respectively. For flashing lights, the correlations for number of injuries and number of fatalities were 0.97 and 0.85 respectively.

Investigations of the distribution of accidents over the speed classifications revealed that, for all forms of warning, 37 percent of the accidents occurred when vehicles were standing on the tracks, 33 percent when vehicle speeds were between 1.6 and 22.4 km/h (1 and 14 mph), and 19 percent when vehicle speeds were between 24.0 and 46.4 km/h (15 and 29 mph). Only 11 percent of the accidents occurred at speeds greater than 48 km/h (30 mph). Forty-six percent of the accidents occurred for train speeds between 0 and 19.2 km/h (0 and 12 mph), 17 percent for train speeds between 20.8 and 57.6 km/h (13 and 24 mph), and 21 percent for train speeds between 40 and 57.6 km/h (25 and 36 mph). The remaining 16 percent of the accidents occurred at train speeds greater than 57.6 km/h (36 mph).

Figure 4. Multiple-track crossings in rural areas (10 trains/d).

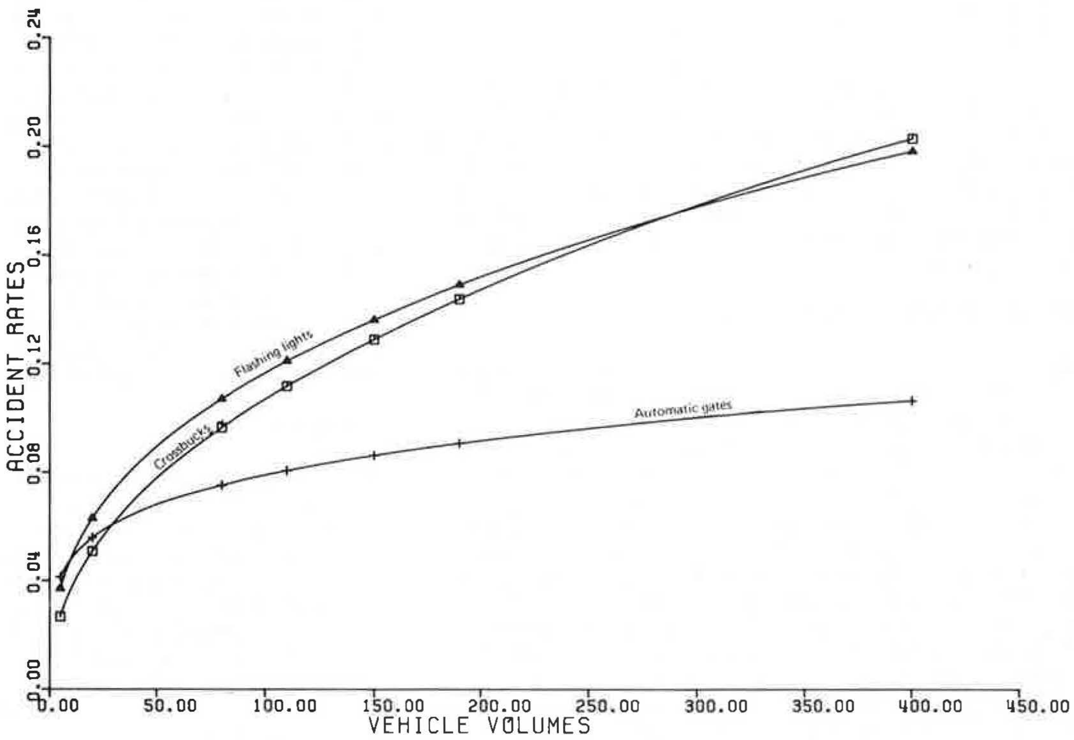


Table 5. Accident severity results for crossbucks.

Vehicle Speed (km/h)	Distribution of Accidents (%)					Predicted Rate of Injury					Predicted Rate of Fatalities				
	Train Speed (km/h)					Train Speed (km/h)					Train Speed (km/h)				
	0 to 19.2	20.8 to 38.4	40.0 to 57.6	59.2 to 76.8	78.4+	0 to 19.2	20.8 to 38.4	40.0 to 57.6	59.2 to 76.8	78.4+	0 to 19.2	20.8 to 38.4	40.0 to 57.6	59.2 to 76.8	78.4+
0	10.1	6.8	8.6	5.6	2.7	0.085	0.283	0.376	0.341	0.149	—[a]	—[a]	0.061	0.150	0.210
1.6 to 22.4	15.8	5.6	7.0	4.3	2.2	0.316	0.513	0.606	0.572	0.380	0.001	0.097	0.167	0.256	0.316
24.0 to 46.4	6.4	4.1	4.3	2.3	1.1	0.542	0.739	0.832	0.797	0.605	0.052	0.147	0.218	0.306	0.366
48.0 to 70.4	3.6	1.8	2.4	0.7	0.4	0.596	0.794	0.887	0.852	0.660	0.049	0.144	0.214	0.303	0.363
72.0+	1.7	0.8	1.0	0.4	0.3	0.630	0.827	0.920	0.885	0.694	0.193	0.288	0.358	0.447	0.507

Note: 1 km/h = 0.6 mph.

[a] Negative model predictions.

Table 6. Accident severity results for flashing lights.

Vehicle Speed (km/h)	Distribution of Accidents (%)					Predicted Rate of Injury					Predicted Rate of Fatalities				
	Train Speed (km/h)					Train Speed (km/h)					Train Speed (km/h)				
	0 to 19.2	20.8 to 38.4	40.0 to 57.6	59.2 to 76.8	78.4+	0 to 19.2	20.8 to 38.4	40.0 to 57.6	59.2 to 76.8	78.4+	0 to 19.2	20.8 to 38.4	40.0 to 57.6	59.2 to 76.8	78.4+
0	13.9	7.3	6.7	3.1	1.7	0.242	0.520	0.476	0.459	0.273	0.054	0.112	0.181	0.346	0.401
1.6 to 22.4	17.5	5.3	5.8	2.4	1.0	0.399	0.676	0.633	0.615	0.430	0.049	0.108	0.176	0.341	0.396
24.0 to 46.4	10.1	3.2	5.2	1.5	0.5	0.634	0.912	0.868	0.851	0.666	0.064	0.122	0.191	0.356	0.411
48.0 to 70.4	4.4	1.8	2.1	0.9	0.6	0.653	0.930	0.887	0.870	0.684	0.141	0.199	0.267	0.433	0.487
72.0+	1.8	1.0	1.3	0.5	0.5	0.612	0.890	0.846	0.829	0.643	0.212	0.270	0.339	0.504	0.559

Note: 1 km/h = 0.6 mph.

As stated earlier, insufficient data precluded the development of prediction rates for severity in the warning-device categories except for crossbucks and flashing lights. In lieu of formal prediction rates, the overall average number of injuries and fatalities per train-involved accident, for crossings afforded gates, other active devices, stop signs, and no protection is given below.

Warning Device	Injury Rates	Fatality Rates
Automatic gates	0.40	0.13
Other active	0.54	0.13
Stop signs	0.42	0.09
None	0.19	0.03

The rates refer to the average number of injuries or fatalities that are expected for an average train-involved collision. The average rates for stop signs and no warning in particular are not considered representative due to the small sample of accidents at stop-sign-protected crossings and the disproportionate number of collisions at a reported motor vehicle speed of zero at crossings with no protection.

USE OF PREDICTION MODELS

One possible application of the accident prediction equations and severity prediction rates is to study the potential accident experience for groups of crossings over a certain period of time. To do this, the crossing inventory data must first be stratified into similar groups determined by type of warning device, type of area, and number of tracks. The mean train and vehicle volumes for each group are then calculated. Next, the coefficients shown in Table 3 are applied to the mean vehicle and train volumes to obtain a predicted accident rate for each group. These values are adjusted by the appropriate number of crossing-years of exposure (product of number of crossings and length of analysis period) to yield the predicted number of accidents for each group of crossings with the current type of warning device.

Additional insight can be obtained by computing the predicted number of injuries and fatalities associated with these accidents. The total number of predicted accidents for each group can be distributed into the vehicle-train speed categories by using the results given in Table 5. The corresponding average injury and fatality rates are then selected from Table 5 and applied to the predicted number of accidents.

One approach for the development of a grade-crossing protection improvement program would be to evaluate the potential reduction in number of accidents, injuries, and fatalities for several mixes of protection improvement. Calculating the accidents, injuries, and fatalities for the existing conditions can be useful in indicating which groups of crossings offer the best opportunities. Many different sets of candidate crossing improvements may be considered. The purpose of safety improvements is to reduce the numbers of accidents, injuries, and fatalities as much as possible with the most economical expenditure of funds. Differences in numbers of accidents, injuries, and fatalities for various improvement plans can be related to the differences in the warning devices and their cost of installation and maintenance. This relation can then be used to formulate cost-benefit measures for various safety improvement programs (12).

The final selection of those grade crossings within a given group that are to receive an improved type of protection must be based on an engineering assessment of the relative hazard associated with the unique features at each crossing. Although the accident prediction equations and severity prediction rates that resulted from this research can be an important input in the development of a grade-crossing improvement program, they are not a substitute for an on-site evaluation of potential hazard on a crossing-by-crossing basis (6, 13).

SUMMARY AND CONCLUSIONS

This research has resulted in improved techniques for predicting railroad-highway grade-crossing accidents and accident severity. Although many variables could not be investigated in the study, the capability for considering subsequent variables has been established. A framework for using accident prediction equations has been outlined and may be expanded as additional factors relating to safety improvements are investigated.

There are still many unanswered questions regarding the occurrence of accidents and degree of severity at grade crossings. In this study, the ratio of the number of accidents for a group of crossings to the number of crossing-years of exposure has evolved as a measure of the accident potential for a group of crossings. Future studies based on the nationwide grade-crossing inventory by the U.S. Department of Transportation and Association of American Railroads and the revised Federal Railroad Adminstration accident information will be helpful in establishing many other useful relations between crossing characteristics and accident potential.

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Abridgment

Driver Reaction to Improved Warning Devices at a Rural Grade Crossing

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In early 1972, the Indiana State Highway Commission sought an immediate solution to a grade-crossing problem because of pressure by the press and local citizens due to the high accident and death rates at the site. In addition to taking immediate steps to correct the problem, the State Highway Commission wanted an evaluation of improvements that were made in the warning system.

Spot speed at specific points on the approaches was selected as the parameter most likely to be related to the degree of improvement. Determining the speeds of approaching drivers at several points provided an approach-speed profile for each driver. Inferences from the evaluation of these approach-speed profiles and changes in them due to each improvement or to change of conditions within a particular system were used to evaluate the effectiveness of the improvements.

Time and budget constraints led to the implementation of a photographic system employing a 16-mm variable-speed movie camera. The camera setup position for each approach was approximately 225 m (750 ft) from the roadway and 180 m (600 ft) from the railway track. By filming a vehicle at a set film speed and by counting the number of frames it took a vehicle to traverse a pair of markers that intersected the line of sight from the camera to a 16.5-m (55-ft) speed trap, the average speed of the vehicle between marker pairs could be calculated from the frame counts. This average speed was assumed to be the spot speed of the vehicle at the center of the trap.

The primary objectives of the research were

1. To analyze the effect on motorists of improving the warning devices at a rural grade crossing with a high accident rate, by replacing 20.3-cm (8-in) flashers on automatic gates with 30.5-cm (12-in) flashers activated by a Marquardt speed predictor and supplemented by additional strobe lights;
2. To evaluate and analyze suitable parameters;
3. To study accident history and site conditions before and after system improvement and relate these changes to motorist reaction to the system; and
4. To evaluate the data collection system itself.

Spot speeds were taken at eight points on each approach to obtain an approach-speed profile for various groups under various conditions after the signal system was improved. These were compared with similar data taken before system improvement. It was shown that an activated gate arm can be as effective in slowing the average approaching vehicle as can seeing a train. The strobe lights made the warning system more visible after activation.

Most drivers approach a grade crossing safely. Although analysis of the mean speeds of various groups showed some useful trends, these are relatively weak parameters for testing effectiveness of the changes because they do not isolate the occasional unsafe driver. The percentage of reduction in speed of the fastest vehicles, along with observation of individual speeding vehicles, provides a better measure of improved effectiveness than do mean speeds and deceleration. Other conclusions included the following.

1. All free-flow plots and several statistical tests showed a consistent lowering of mean entry speeds 330 m (1100 ft) from the crossing. This implied that drivers became aware of the crossing sooner after the improvement was made, probably because of the greater visibility of the gate arms in the raised position.
2. Both before and after installation of signals, the approach speeds of following vehicles were more affected by other vehicles than by the signal, and vehicle approach-speed profiles were independent of signal type.
3. Both before and after upgrading the protection at the grade crossing there were no deceleration rates that could be classified as emergency stops. There were deceleration rates that could be classified as undesirable, but the numbers were too small to permit statistical comparison.
4. Deceleration rate is a weak parameter for determining effectiveness of the new signals.

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