LBL-19423
EEB-L 85-03
L-99

This paper was presented at the IES Annual Technical Conference, 21-24 July 1985, Detroit, Michigan, July 21-24, 1985, and published in the Journal of the Illuminating Engineering Society, Volume 15, Number 1 (Fall 1985), pp. 167-180.

TARGET SIZE, VISIBILITY AND ROADWAY PERFORMANCE

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This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Synopsis

Analysis of roadway tasks in terms of the CIE 19/2 visibility parameters has been restricted to calculation of VL at a fixed distance because there has been no way to adjust for the change of apparent size with distance. We use a rough fit of the absolute threshold contrast data as a function of luminance and size to allow the computation of VL as a function of distance. Sample VL versus distance and VL versus time calculations are presented. A preliminary estimate of detection probability as a function of time is compared to Gallagher's measured results to see how current detection models compare to real results.

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1. INTRODUCTION

A distinguishing feature of the roadway visibility problem is that angular target size does not remain fixed. Unfortunately, the CIE technique for calculating visibility levels (VL) is not convenient for comparing targets of different sizes [1]. It is possible, however, to calculate a visibility index (VI), a quantity proportional to VL. Under the proper conditions VI should provide a relative ranking of the visibility of targets. In an important experiment Gallagher found that VIs measured at a fixed distance were correlated to driver performance [2]. Several studies since have used VI to analyze roadway problems.

A disadvantage of using Gallagher's correlation is that it provides no insight into the actual visibility at detection and hence provides no obvious way to produce a theoretical estimate of detection distances. A simple analogy to threshold experiments indicates that VL should be approximately constant at detection. To test this and a more complex hypothesis based on a field-of-view detection model, we used a modification of Adrian's procedure for estimating VL as a function of size and luminance [3].

The calculations showed surprisingly poor agreement between theory and measurement indicating that Gallagher's performance measure had a much larger nonvisual component than previously recognized. It therefore seems likely that the relationship Gallagher found between VI and performance is dependent on target reflectance, size, and vehicular speed.

Since our discussion presupposes some knowledge of the Gallagher experiment we present a brief description of it here. Gallagher placed a grey (29% reflectance) or black (6% reflectance) plastic cone in the center lane of one end of an 1800-foot straight stretch of road. The speed of a vehicle and the location of braking or swerving maneuvers was determined by sensors on the roadway. Driver performance was measured in terms of time-to-target (TTT), the distance between the target and the earliest avoidance maneuver divided by the vehicles speed. Drivers were not aware that they were part of an experiment. Data was not kept if there was the possibility of interference from a second vehicle in the test zone. Target visibility was varied by manipulating the lighting or the target location. Visibility (VI) was measured in a separate experiment at a single fixed distance, and did not include the effect of headlights. Gallagher fit TTT as a log-normal function of VI.

The next sections describe our calculations. We then present a discussion of our analysis and our interpretation of the results.

II. THRESHOLD CONTRAST

CIE 19/2 focuses on relative threshold contrasts as a function of luminance [1]. Absolute magnitudes are computed only for the reference four-minute disc. The CIE function is a generalized geometric combination of the limiting contrast behavior at low and high luminances. Thus, if g(L) and h(L) are the two limiting functions, the fit is $(g(L)^{1/n} + h(L)^{1/n})^n$, where n is a fitted constant.

In a recent paper Adrian suggests using this concept to get the threshold contrast (C_t) variation as a function of size [3]. Adrian's fits are based primarily on the 1946 Blackwell data showing C_t as a function of size and luminance [4]. This data is not ideal for our purposes because subjects were allowed to freely scan the target area for up to 30 seconds. The VL concept is based on foveal detection during a single fixation, with the fixation time set by convention at 0.2 seconds. We therefore decided to apply Adrian's approach to the more recent Blackwell-Taylor data, which follows this constraint [5]. Since our interest is in luminances and sizes appropriate for roadway lighting, we used the geometric averaging technique for both variables and restricted the range of the fit.

The Blackwell-Taylor data cover the range from 0.5 to 60 minutes of arc, and from 3.4×10^{-4} to 3400 cd/m^2. We fit the data with a standard deviation of 10%. This is almost identical to the accuracy of the CIE reference function to the four-minute-of-arc data points of this data set.

A major focus of this study was to examine the Gallagher data. In Gallagher's experiment the luminance ranged from 0.3 to 6300 cd/m^2. The target was a truncated traffic cone 18 inches high with an average width of 6 inches. We treated it as an equal-area 12-inch disc to get angular sizes and multiplied the fitted threshold contrasts by a constant shape factor correction (SFC) factor to compensate for shape. Assuming an average speed of 30 mph and a reaction time of about one second, a minimum distance of interest of would be 44 feet. Gallagher measured responses at a maximum distance of 720 feet. Target sizes of interest ranged, therefore, from 5 to 80 minutes of arc. A fit of a subset of the Blackwell-Taylor data with luminance greater than 0.3 cd/m^2 and size greater than 2 minutes of arc had a standard deviation of only 6%, and differed significantly from the fit of the entire data set. Because differences between scotopic and photopic vision are reasonable, we have chosen to use this more restricted fit in our analyses. The fit is as follows:

$$C_t(L,S) = \{ 0.08583 \times (1 + 0.61075/L)^{0.5} + [0.15055 \times (1 + 1.3815/L^{0.2})^{2.5}] / S \}^2. \quad (1)$$

Here L and S are luminance (cd/m^2) and size (minutes-of-arc), respectively. It is important to note that this fit does not extrapolate well to smaller sizes or luminances. For the interested reader the full-range fit is:

$$C_t(L,S) = \{0.0317 \times [1 + 0.512/L^{0.53}]^{1.34} + [0.236 \times (1 + 1.68/L^{0.34})^{2.09}] / S^{1.43}\}^{1.40}. \quad (2)$$

A final important note about both these fits is that the Blackwell-Taylor data give a forced-choice C_t, whereas the CIE reference function is based on the method of adjustments. The latter contrasts are a constant factor of 2.5 times larger than the contrasts of Eqs. 1 and 2 [5]. Our values are scaled by this constant to maintain consistency with the VL values used in CIE 19/2.

The above contrasts are based on data for discs. The CIE 19/2 analysis is based on the assumption that different-shaped objects will have the same relative C_t curves, but the absolute level of the curves may differ. Gallagher measured equivalent contrasts, and Blackwell claims that these contrasts are 7.11 times the physical contrasts [2]. This value is relative to the 4-minute reference disc, and therefore includes the effect of both object size and shape. Gallagher's measurements were made at 200 feet where the equivalent size of his target was 17.5 minutes. To get the shape-factor correction (SFC), we estimated the effect of size alone by using Eq. (1) with L=1.0 cd/m^2 to estimate the size effect. This luminance value was chosen as the average of the 21 night measurements; the two daytime measurements were eliminated because they gave totally different results. The estimated SFC from this procedure is 1.3.

The Blackwell-Taylor experiment was performed with a reference group of observers 20 to 30 years old. Age affects sensitivity to both luminance and contrast. We use age modifiers that are similar to those in CIE 19/2, and are based on the same data [6]. The CIE 19/2

The Blackwell-Taylor experiment was performed with a reference group of observers 20 to 30 years old. Age affects sensitivity to both luminance and contrast. We use age modifiers that are similar to those in CIE 19/2, and are based on the same data [6]. The CIE 19/2 contrast multiplier (m_1) consists of straight-line segments with breaks at 20, 42, and 64 years. We could see no evidence in the data for breaks at these points and decided to define a contrast multiplier, CM(age), by linear interpolation between the points and a linear extrapolation beyond them. CIE 19/2 separates the luminance correction into two factors (s and t), to account for two different mechanisms. The two factors have sharp changes in slopes, which Blackwell hypothesized arose from different aging processes [6]. We found the arguments both for the method of separating the data into the two factors and for the sharp changes in slope unconvincing and refit the data as one factor with a simple log-linear function:

$$LM(age) = 10^{0.07 - 0.009 \times (age - 20)} \tag{3}$$

where LM is the luminance multiplier. This fit has a standard deviation of about 7%, which is about as good as the CIE fit, and it is a much simpler fit. The success of this simple fit shows that the added complexity of the CIE fit is not justified by the available data.

Our equation for VL is:

$$VL(L,S,C_p,age,SFC,DGF,TAF) = C_e / [\,2.5 \times CM(age) \times C_t(L \times LM(age), S)\,] \tag{4}$$

with

$$C_e = C_p \times SFC \times DGF \times TAF.$$

C_p, DGF, and TAF are, respectively, the physical contrast of the target, the disability glare factor, and the transient adaptation factor. Note that with our definition of LM and CM the multipliers do not equal one over an extended age range, as in CIE 19/2, and are slightly different from one for 20-year-olds. We discuss DGF and TAF in the next section.

III VL CALCULATIONS

The DGF and TAF factors are defined in CIE 19/2 [1]. In most papers TAF is set at one [1,2,7,8]. This appears to be a good approximation for analysis of the Gallagher experiment. In Gallagher's experiment, data was not recorded when more than one vehicle was on the course, thus eliminating the extreme luminance variations that could make TAF substantially different from one. In addition, variability in TAF between runs should be small because the luminance patterns are similar.

In Gallagher's experiment DGF was measured at the reference distance. No information was reported on the luminance pattern or DGF at other distances, and no attempt was made to include the effect of headlights. We calculated VL both with and without low-beam headlights. In our calculation without headlights we assume that Gallagher's DGF values will be largely independent of car-to-target distance. There probably is a cyclic change in DGF as a vehicle proceeds from one street light to the next, but we assume that this variation is small relative to the variation in VL over the distances of interest. A partial validation of this view is that the range of DGFs for Gallagher's targets, which were placed in a variety of locations under several different lighting conditions, was only 15%. By comparison our calculated VL values change by a factor of 10 as the driver approaches the target.

To calculate VL with headlights, we took advantage of the fact that DGF is a function of the background luminance and a veiling luminance, both of which were measured by Gallagher. We recalculated DGF adding a headlight contribution to the background luminance and assuming that the contribution to veiling luminance was small and could be ignored. This approximation has been used in other recent papers [8,9]. An estimate of its error indicates that it should be valid to a few percent as long as the headlight contribution to the background luminance is comparable to or less than the street lighting contribution. In the Gallagher experiment distances small enough to give larger errors were too small for the driver to avoid the target and therefore were not of interest in our preliminary calculations.

The calculation of contrast is also constrained by the available data. There are various ways one can evaluate luminance distributions to calculate target and background luminances [8]. Gallagher reported averages, and centered the background measurement on the target location [10]. We assume that the street lighting contributions are independent of the car-to-target distance. Headlight contributions were estimated using the iso-candela plot and headlight height and separation from Keck's paper, target reflectances from Gallagher's paper, and pavement back-reflectances from Bhise's formula [2,7,8]. The target was assumed to be centered between the headlights. Linear interpolation was used with the candlepower data, so mean values were simply estimated from the center of mass of the target area.

To calculate VL versus time to target (TTT), we assumed average speeds of 25, 30, and 35 mph to calculate the distances. Explicit information on speeds was not available from Gallagher's papers [2,10]. At these speeds, distances of interest are 40 feet or greater, and we therefore did not include corrections for headlight-to-wheel, or driver-to-wheel distances. Gallagher had no way of obtaining a driver's age. To estimate the effect of age we built age pyramids based on the 1970 and 1980 Census data. Calculations were performed at 10-year age intervals from 20 to 80 years old. The average age from the Census data was 41, and we found that calculations for age 40 were close to the average.

IV. RESULTS

Our interest was to better understand Gallagher's results. The first quantity we evaluated was VL at the mean detection time (DT), where we assumed DT to be equal to Gallagher's mean measured TTT plus an estimated reaction time. We hoped to find that these values would be approximately constant. Our argument was that if visibility was the limiting factor for DT, then targets are detected after visibility rises to approximately the same level. The mean DT is then just a measure of how close the target must be before its VL is large enough to make it visible. Figure 1 shows the results of our calculation for Gallagher's targets under the assumptions of: no headlights, 30-mph speed, 40-year-old driver, and one-second reaction time. The plot is fairly insensitive to the last three assumptions. Furthermore, as is shown later, headlights have little effect on the low-reflectance data points past 3.5 seconds, and of course no effect on the two daytime points.

Figure 1 shows some clustering of the VL values. The two daytime points, however, are not the same as the remaining points. The targets in the two daytime runs should be visible anywhere on the course, as their VL values are above 10 even at 720 feet (TTT = 16.4 seconds). The mechanism limiting TTT for the two daytime points is clearly not the same as that for night points, and they should therefore be treated separately in any extrapolations of the Gallagher fit.

Figures 2 and 3 show the nighttime points only, first without, and then with, the contribution from low-beam headlights. There are several points of interest. Headlights clearly affect the visibilities at the mean DT, and are particularly important for targets having high reflectance (29% vs. 6%) or poor visibility (low mean DT). This means that headlight status and target reflectance must be considered in addition to VI as correlates to the mean TTT. The shape of the lower part of the Gallagher curve is probably dependent on the reflectance of the target and on whether low- or high-beam headlights are used.

A second point of interest is that the high-reflectance, positive-contrast targets appear to require higher visibilities for detection than other targets. In a discussion with Gallagher, he noted that the low-reflectance cones were always seen as an object on the road, whereas the high-reflectance cones were first seen as a light stripe on the road, and then popped up as cones as the driver approached them. This difference obviously affects the time at which the driver recognizes the target as an obstruction, and depends upon more subtle visual cues than simple detection of the target. An important question is how much of the effect persists for different shapes, sizes, colors, and reflectances. A cone may be a special case, as it can be seen as a two-dimensional object in perspective. Size may also be an important parameter in identifying the object as three-dimensional. It is not clear that DT at a given VI would be as low for a person wearing light-colored clothes, as it was for a light-colored cone.

Perhaps the most noticeable features of the figures 2 and 3 are the distinct trend in VL with respect to mean TTT and the extremely low values of VL at detection for the less visible points. The lowest value in figure 3 represents a break-down in our assumption that visibility increases monotonically as the driver approaches the target. This is demonstrated in figure 4 where VL is plotted versus TTT for two targets under the convention that negative contrasts have negative VLs. The figure shows that headlights decrease the magnitude of VL for negative-contrast targets relative to no headlights until the contrast is driven positive. For the more visible target the magnitude of VL is still increasing at the mean TTT. This was typical of most of the targets in the Gallagher experiment. However, the target having the lowest VL in figure 3 (the low visibility target in figure 4) represents a pathological case where VL was near its minimum at the mean TTT.

Eliminating the problem targets does not eliminate the trend in figures 2 and 3. It does eliminate the lowest VL values, but points remain in the range of one to two. We have considered a number of possibilities to explain the trend. At the lowest values of TTT, we may underestimate VL. For instance we use average luminances. Distant targets appear small, and an average seems reasonable. However, at a distance of 100 feet or so (TTT = 1.6), target size is 30 minutes of arc, and internal contrasts may make all or part of the target more visible than predicted by the average contrast. This may be a particular problem for the headlight calculation because the driver is near the specular angle.

A second factor that may bias our calculation is our assumption that luminances from the street lights do not change as the driver approaches the target. This seems reasonable for the target luminance because the target has a diffuse surface, the driver is not near a specular angle with respect to street lights, and the angular changes are small. It is less reasonable for the background luminance because the road is very specular at the grazing angles at which it is viewed. Since street lighting is periodic, there should be a small cyclic variation in contrast, and of course VL, as the driver approaches the target. When VI (contrast) is high, these variations would just introduce noise in the results, but when it is low the variations in VL may become large relative to the mean VL and may be responsible for detection of the target.

There is a small error in our estimation of detection time at the lowest values of TTT. The driver who does not react to a target is credited with a TTT of zero. Since we add a fixed reaction time to TTT in order to estimate detection time, our estimate is incorrect if the driver sees the target but does not have time to react. Only about 5% of the drivers failed to react even at the lowest VIs, hence this is a small error [2].

The above considerations suggest that the real VLs at low values of TTT are higher than our estimates, thus perhaps eliminating some of the difference between the low and high TTT points. However, there appears to be a trend in VL for the high TTT points alone. This suggests that the overall trend and difference is real. Assuming that the trend is real, either we are overestimating visibility at large distances or the drivers did not react when they detected the target. It is possible that a driver feels no need to react quickly if the target is detected sufficiently far away. The distance that is sufficient depends upon the driver's speed. Gallagher appears to have assumed that the VI-versus-TTT relationship would be relatively unchanged at different speeds. However, visibility of the target depends on distance. We therefore believe that the first-order effect of speed would be to directly scale the TTT values. Under this hypothesis, this scaling would not affect the highest visibility points, and in fact TTT might become greater at higher speeds to allow for additional braking distance. The net effect is a more rapid change in TTT with VI.

A second possibility is that the driver detects the target earlier than is shown, but does not recognize it as an obstruction. This ties in with Gallagher's comment about the grey (29% reflectance) cones initially looking like stripes on the ground. There may also be a size effect here in that it is difficult to tell that a small, distant object will have to be avoided. This suggests that a large target may be avoided earlier than a small target of equal VI. Again the effect is to make TTT vary more rapidly with VI.

There is one other size effect to comment on before proceeding. Threshold contrasts go as size-squared when the target is small and eventually saturate as size increases [5]. A target that is bigger than the Gallagher target will be less visible than Gallagher's at distances less than 200 feet (the measurement point) and more visible at greater distances. The effect this will have on TTT depends on the visibility of the target at 200 feet.

V. TIME-TO-TARGET CALCULATIONS BASED ON DETECTION MODELS

Given the number of possible confounding factors described previously, it should come as no surprise that we had generally poor luck in predicting TTT. We nonetheless briefly describe some of the calculations here because they provide some insight.

The CIE 19/2 model unfortunately provides only an empirical fit to data, and cannot predict accuracies beforehand [11,12]. We have therefore used a field-of-view search model instead [13]. This model is based on an extension of the threshold-contrast function to include the degree to which the target is off the view axis. This makes VL a function of view angle eccentricity, and lets us extend estimates of detection probability as a function of VL to off-axis targets [1,13]. For consistency, we use the model in reference 13, but all the models should give similar results. Assume that the target is located within a target field of some fixed size. The probability of detecting the target in any particular glimpse is the integral over the product of the probability of the view axis being a given distance from the target, and the probability of detection at that distance. The probability of detection after a given number of glimpses can be calculated from the individual glimpse probabilities. If the target field is noisy (extraneous targets or nonuniform luminances) the effective VL is reduced and the detection probabilities will be affected accordingly.

In our case VL was calculated as described earlier, and the number of glimpses is fixed by the speed of the vehicle and the fixation time per glimpse. We assumed that the target field was equivalent in area to a 5-degree cone [14]. The noise factor always reduces VL, however, Inditsky et al. noted that there is little information about the magnitude of reduction [13]. A constant value of 1/2 was used as an example in the Inditsky paper, and we found that this gave rough agreement with the short TTT points in the Gallagher experiment. Figure 5 shows the best fit with the above parameters.

Calculations were done in 10-year age blocks, but in the interest of clarity, only the average and half the blocks were plotted. In this example the average curve has a mean and standard deviation almost identical to Gallagher's measured curve. Figure 2 of Gallagher's paper indicates that 5% or more of the drivers failed to react to this target. This is consistent with the 7% level predicted by our average curve. The roughly Gaussian shape of the average curve is also consistent with Gallagher's results.

It appears that with small increases in effective VL, similar good agreement can be obtained for other short TTT points. This is encouraging because it supports modeling the problem with VL, and is consistent with our previously mentioned belief that we only slightly underestimate VL. In contrast to this situation, the fit to points with TTT > 3 seconds aisre disastrous. Using the above assumptions, predicted mean TTTs are approximately a factor of three too large. To get correct mean times, the effective VLs must be reduced by a factor of 6 instead of 2. This still does not give the correct average curve shape. Instead it pulls apart the age distributions so that for the average curve, the standard deviation, and probability of not reacting to the target, are grossly too large. This result adds weight to the notion that low and high TTT points differ.

Two mechanisms for this difference were suggested in the previous section. Consideration of the noise factor suggests yet a third mechanism. It seems logical that a noise factor should depend on the local complexity of the scene. For a given solid angle, the more distant the view point the larger the number of objects that will fit within the solid angle. In short, the complexity factor may be a function of the distance to the view point, instead of being uniform over the field of view. This kind of mechanism does not pull apart the age distributions and therefore should produce curves that are consistent with the measurements. Our work is still in an early stage; we have not attempted to distinquish between the different mechanisms, and in fact may not have sufficient information to do so.

VI. DISCUSSION

There is, of course, interest in using visibility calculations for street lighting design and evaluation. In a recent paper, Shelby and Howell investigated the distribution of VI for a standard target as a function of distance from a fixed car [8]. A question they raised is what is the best single measure of these distributions for design or evaluation. If we relate this question back to the Gallagher experiment, clearly we are interested in the probability that the driver can avoid a fixed obstacle. This probability obviously depends on vehicular speed. For instance, at 30 mph, Gallagher's estimate of the safe intercept time is 2.0 seconds. Adding a one-second reaction time gives a total time equivalent to 130 feet at 30 mph. At 15 and 45 mph the distances are 44 and 264 feet. These distances will vary somewhat if we allow for swerving, but the general point is clear: useful visibilities are those that allow the driver to safely avoid the target. Points closer than the safety cut-off distance should not be included in visibility calculations.

Simplification of the problem probably depends most on whether headlights affect the visibilities at the distances of interest. If headlights are unimportant, then VL at a fixed distance may be a useful guide to the entire distribution, and ultimately to the probability of detection for the target. At this point the problem becomes evaluating VLs for different target sizes and locations. Until we better understand the relationship between visibility and probability of detection, it is probably best to simply measure the moments (mean, variance, skewness, and so on) of the VL or log(VL) distributions. Experience with other visual performance problems indicates that the latter distribution probably is most appropriate [1,15]. Unless the relationship between visibility and detection probabilities is not monotonic, or is pathological, the latter should scale with the mean VL, or at worst be computable from the first few moments.

A feature of the theoretical calculations that may be important is that the safety margin between the time the target is detected and the time the driver has to brake in order to avoid the target is a very sensitive function of speed. As noted in the previous section, detection is related to the distance to the target, not the time to target. We therefore expected that the first-order effect of a change in speed would be a compensating change in TTT. In the detection calculation the number of available fixations is an important factor, and this factor also depends on speed. When the TTT is fairly large, the detection distribution tends to be fairly broad and low as a function of time (see the age = 20 curve in figure 5), and a change in the number of available fixations changes primarily the width and not the mean of the distribution. However, when visibility and TTT are low, the number of fixations becomes important; thus detection time can go as speed-squared. As Gallagher noted, the intercept time (IT) for safe braking increases linearly with speed. Gallagher claims IT is 2.0 seconds at 30 mph. Assume a detection time (DT) of 4.0 seconds and a reaction time of 1.0 second. This gives a safety margin of 1.0 second. Now let the speed be 35 mph. This increases IT to 2.33 seconds, and decreases DT to 2.94 seconds, leaving a "safety margin" of -0.39 seconds. At higher visibilities and speeds the relative changes in DT will be smaller, but the higher magnitude of DT means that there is little net improvement.

The situation may be somewhat better if the driver can swerve instead of brake, but the safety margin will still be a rapid function of speed. These conclusions are particularly pertinent for older drivers, who often do not see well.

Much of the above analysis assumes that roadway safety can be correlated to probabilies of avoiding fixed targets. A great deal of work needs to be done in further specifying what situations create accidents. At this point one can only hope that the VL concept will be germane to real problems.

VII. CONCLUSIONS

Our analysis shows that the visual detection problem is much more complex than indicated by the excellant correlation Gallagher obtained between VI and TTT. Headlight status (off, low-beam, or high-beam), target reflectance and size, and speed must be considered when evaluating visibility. Although we have partially clarified the role of some of these parameters, we have raised more questions than we have answered. There is an obvious need for more research.

Acknowledgement

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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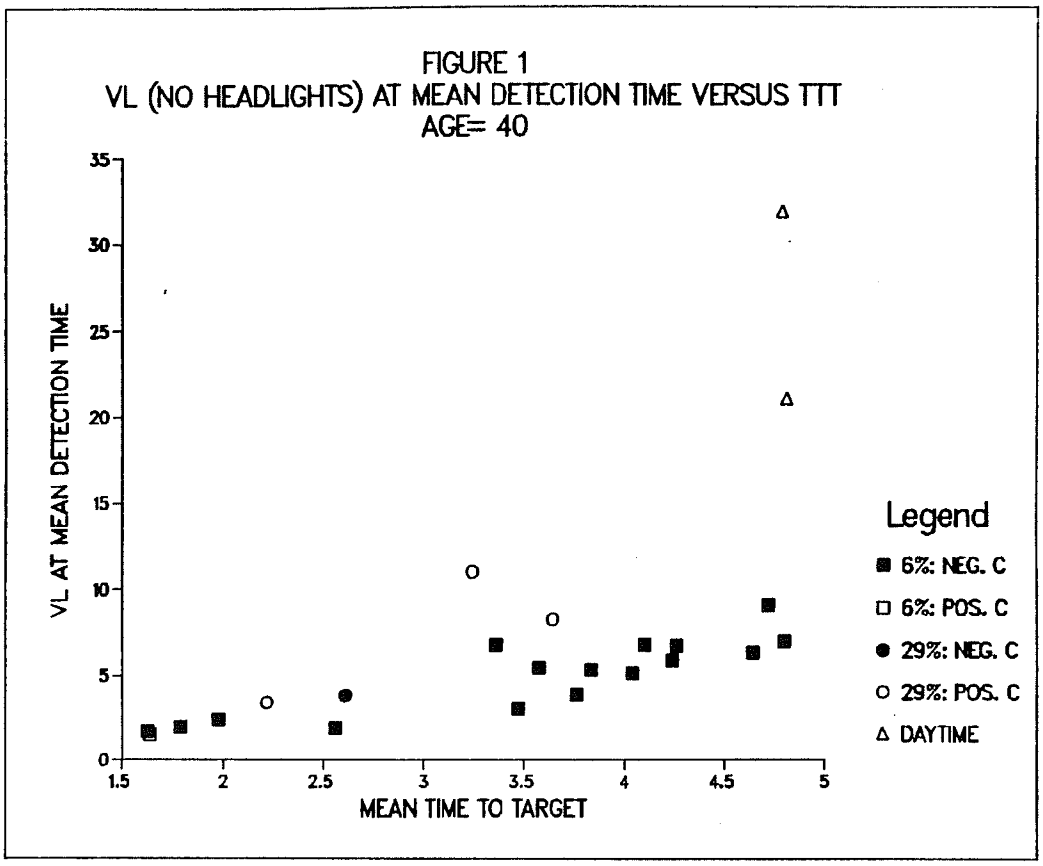


FIGURE 1
VL (NO HEADLIGHTS) AT MEAN DETECTION TIME VERSUS TTT
AGE= 40
VL AT MEAN DETECTION TIME
MEAN TIME TO TARGET
0
5
10
15
20
25
30
35
1.5
2
2.5
3
3.5
4
4.5
5
Legend
6%: NEG. C
6%: POS. C
29%: NEG. C
29%: POS. C
DAYTIME

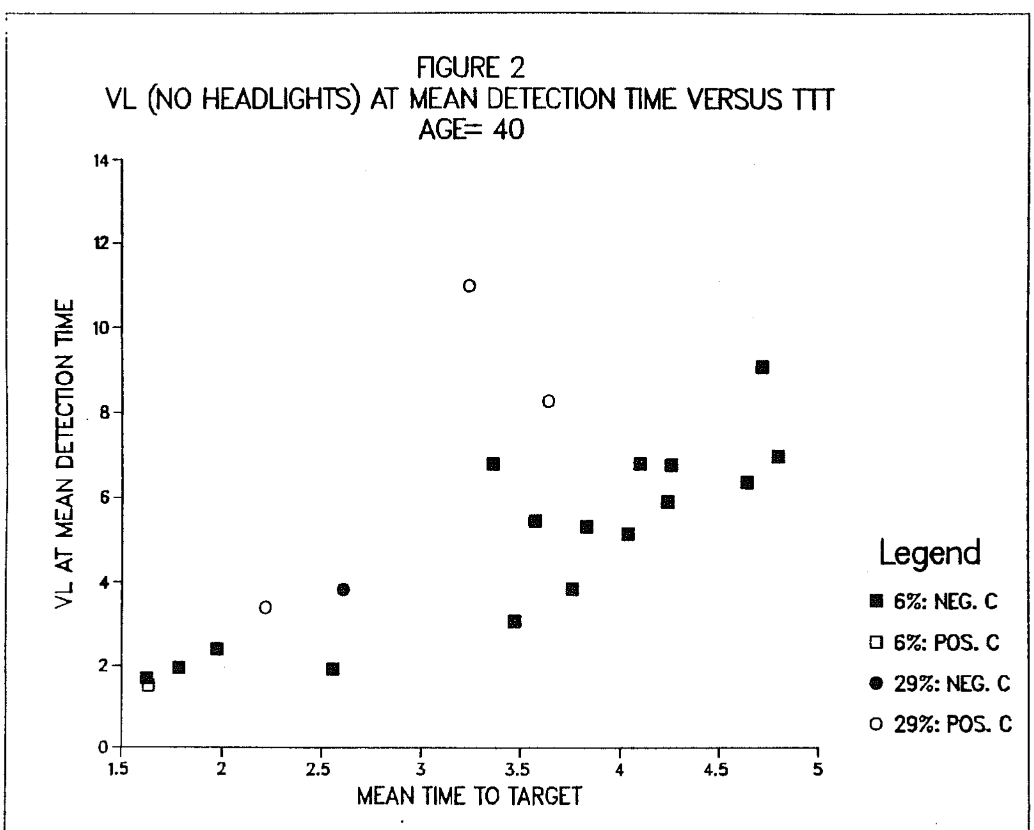


FIGURE 2
VL (NO HEADLIGHTS) AT MEAN DETECTION TIME VERSUS TTT
AGE= 40
VL AT MEAN DETECTION TIME
MEAN TIME TO TARGET
0
2
4
6
8
10
12
14
1.5
2
2.5
3
3.5
4
4.5
5
Legend
6%: NEG. C
6%: POS. C
29%: NEG. C
29%: POS. C

FIGURE 3
VL (HEADLIGHTS) AT MEAN DETECTION TIME VERSUS TTT
AGE= 40

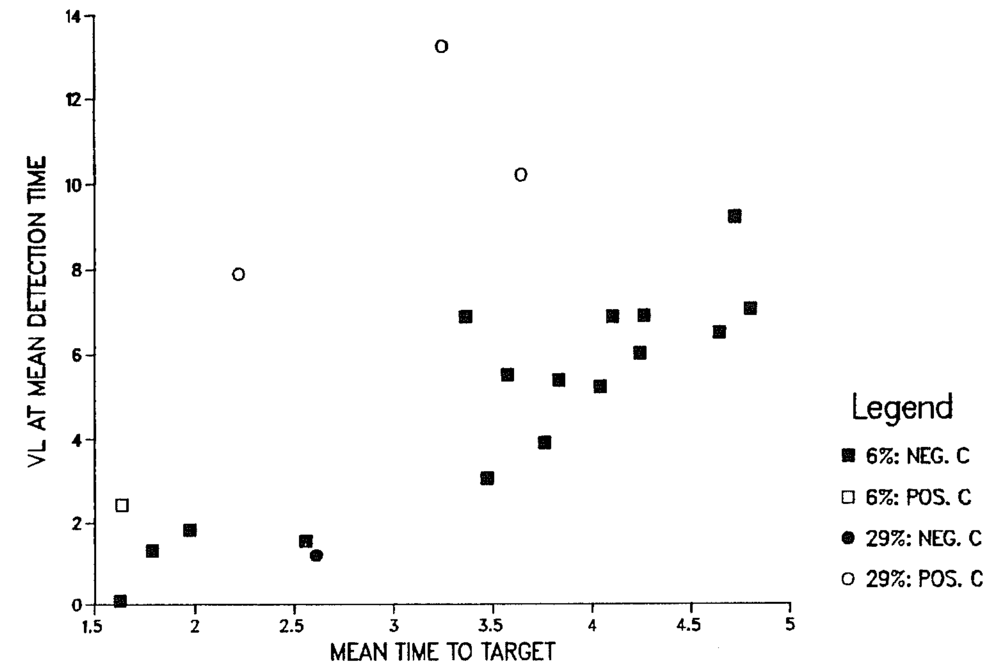
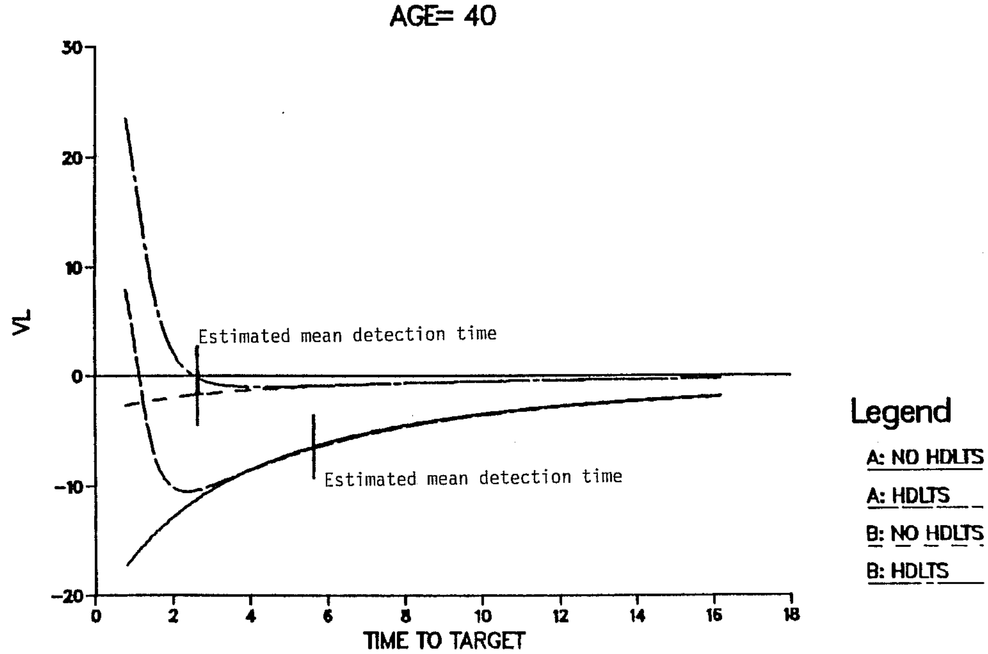


FIGURE 4
VISIBILITY VERSUS TIME TO TARGET
AGE= 40



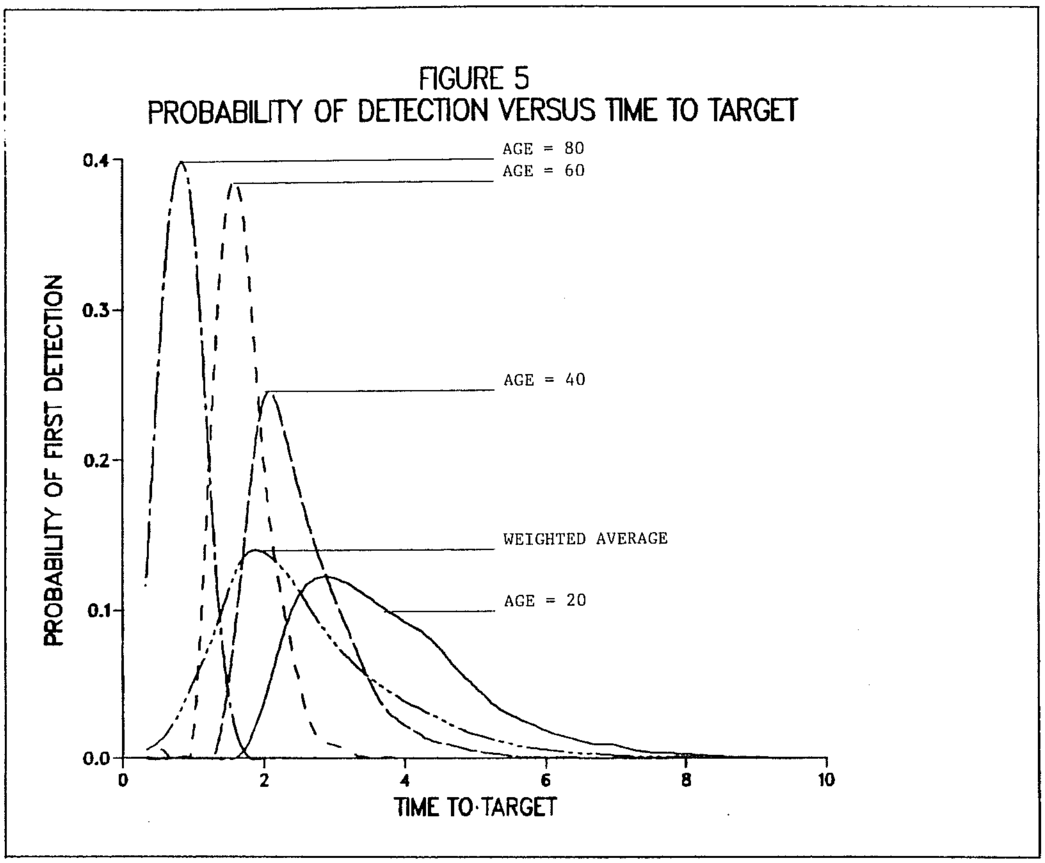


FIGURE 5
PROBABILITY OF DETECTION VERSUS TIME TO TARGET
AGE = 80
AGE = 60
AGE = 40
WEIGHTED AVERAGE
AGE = 20
PROBABILITY OF FIRST DETECTION
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
TIME TO TARGET