Conspicuity of Suprathreshold Reflective Targets in a Driver's Peripheral Visual Field at Night

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Past investigations and experimental studies dealing with the visual detection of either nonreflectorized or reflectorized objects or targets in the driving environment at night have been limited primarily to foveal or line-of-sight visual detection. A geometric model is developed to analyze reflectorized targets located ahead of a car at different locations along a tangent-curve and curve-tangent section of a highway. Typical night driving eye scanning data are also presented. The model demonstrates that in many cases unknown or unexpected reflectorized targets, such as a reflectorized license plate or an advance warning sign, will appear initially at moderately large peripheral angles up to 15° or more away from a driver's foveal eye fixation point, or line of sight. A field study involving the foveal and peripheral detection of a reflectorized target is presented to show that peripheral visual detection distances decrease considerably as the peripheral visual angle away from the fovea, or line of sight, increases. A 10° peripheral visual detection angle results in an average visual detection distance approximately one-half of the average foveal detection distance. It is concluded that in a situation where drivers approach or negotiate a curve at night, where reflectorized objects or targets will become visible for the first time probably in the periphery of a driver's visual field, and where there is a need for early detection, the reflectivity of the target should be increased to ensure timely recognition, information processing, and decision making, and appropriate control actions.

Past investigations and experimental studies dealing with the visual detection of either nonreflectorized or reflectorized (made with reflective materials) targets in the driving environment at night have been limited primarily to foveal or line-of-sight visual detection. One exception in the current literature is a field study by Zwahlen (*1*) that investigated the ability of human subjects to detect an approaching reflectorized target at night in the field foveally and at peripheral visual angles of 10°, 20°, and 30°. Zwahlen found that at a 10-degree peripheral angle the average detection distance was 47 to 59 percent of the average foveal detection distance. At a 30-degree peripheral angle this distance declined to 25 to 33 percent of the average foveal detection distance. Past investigations of a driver's recognition capabilities also have been limited primarily to foveal or line-of-sight recognition of symbols or shapes of targets. One exception is a laboratory study by Karttunen and Hakkinen (*2*) that investigated the ability of subjects to recognize symbolic road signs commonly used in Finland at peripheral angles of 10°, 20°, 30°, 40°, and 50°. They found that when signs that subtended a visual angle of 4° of visual arc (from bottom to top) were projected on a screen in a laboratory for 125 ms, the ability of subjects to identify the road sign decreased from 100 percent for foveal presentation to 92.4 percent for a peripheral angle of 10° and to 32.5 percent for a peripheral angle of 50°.

Because Zwahlen (*1*) showed that a driver's ability to detect a reflectorized target at night decreases considerably as the peripheral angle at which the target is first presented increases and Karttunen and Hakkinen (*2*) showed similar results for peripheral recognition accuracy of commonly used symbolic road signs, data based solely on human foveal visual detection capabilities in the design of reflectorized targets in the highway environment may be inadequate if such a target is likely to first appear in the periphery of a driver's visual field and early detection is needed. Therefore, the objective of this paper is to investigate the importance of peripheral visual detection in the driving environment at night.

MAGNITUDE OF PERIPHERAL VISUAL DETECTION ANGLES IN THE HIGHWAY ENVIRONMENT

Knowledge of human peripheral visual detection capabilities would not be useful in traffic safety if it were not possible to demonstrate that driving situations exist where targets are likely to first appear in a driver's field of view at relatively large peripheral visual detection angles. Since highways are designed on geometric principles, it was possible to develop a geometric model to determine the peripheral visual detection angles that exist for particular driving situations and for targets in the driving environment. A computer was used to analyze multiple situations where large peripheral visual detection angles might be found.

The geometric model was based on the assumptions that: (a) the driver looks ahead of the car in a direction that is parallel to the longitudinal center of the car, (b) the driver is driving in the center of the right-hand lane on a two-lane highway, (c) the driver is driving on a level and flat road surface as opposed to a road with vertical curves, and (d) there are no physical barriers, objects, or foliage along the highway that might obstruct a driver's direct view of the target of interest. The analytical model was developed to evaluate tangent-curve sections of a highway, where a driver

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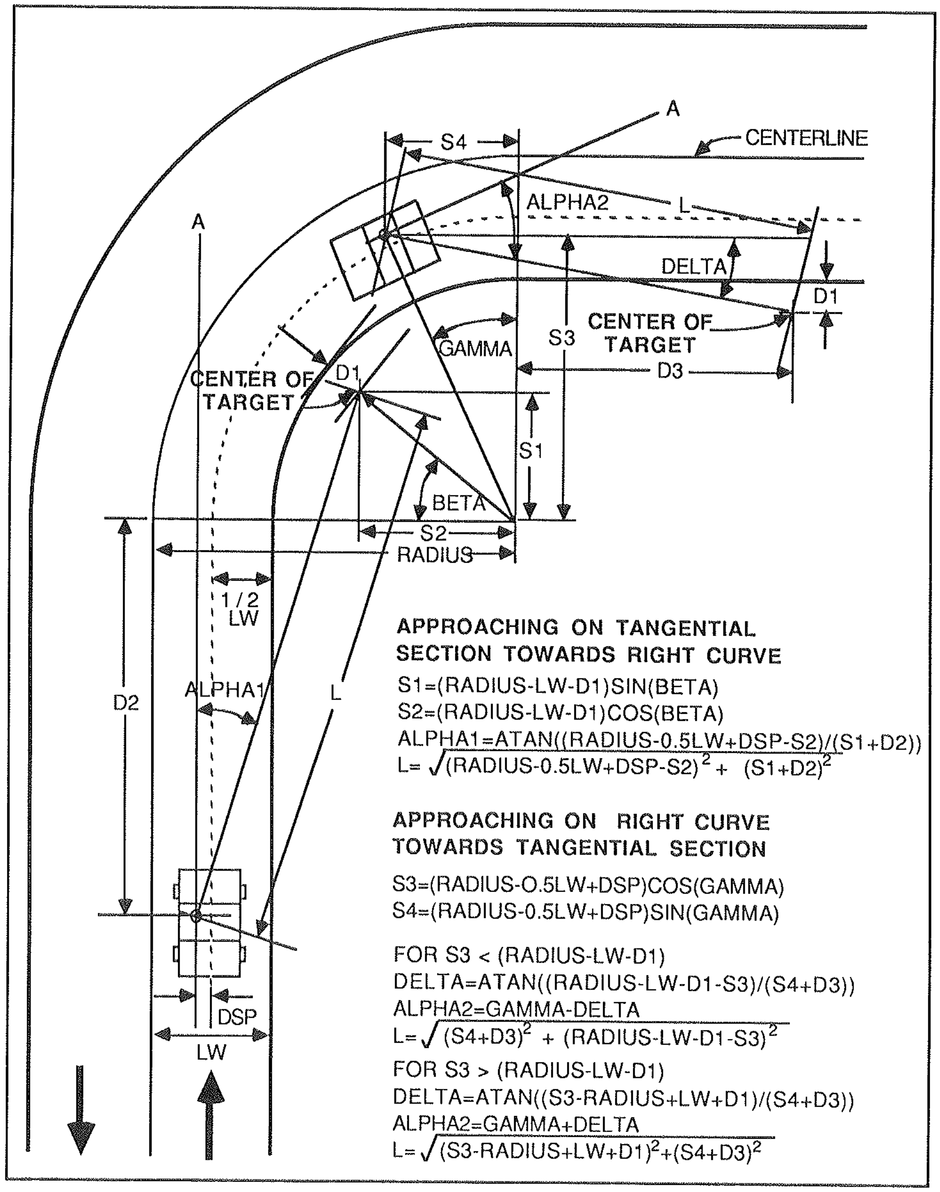

FIGURE 1 Geometric configuration and equations to calculate the peripheral visual detection angles for tangent-curve and curve-tangent sections for a right curve of a two-lane highway.

is on a tangent section of a highway appproaching a target located in the curve section of the highway, and curve-tangent sections of a highway, where a driver is negotiating a curve while approaching a target located along the tangent section of the highway beyond the end of the curve. Large peripheral visual detection angles may also occur when a driver is negotiating a long curve and is approaching a target located farther ahead in the same curve. However, this was not analyzed separately because when the driver and target are separated by short distances in the tangent-curve or curve-tangent sections of a highway both the driver and the target are very close to being in the same curve. Tangent-curve and curve-tangent sections occur frequently in the driving environment because each curve is preceded and succeeded by either a tangent section or another curve section of a highway, and curves along highways are common, especially in locations where there are hills or when highways follow natural rivers. For example, according to Zwahlen (*3*), in Ohio there are more than 18,000 curves along the two-lane rural state highways. Because Ohio has approximately 19,000 mi of highways, of which approximately 1,200 mi are interstate highways, one curve exists for approximately every mile of two-lane rural state highway.

Figure 1 shows the geometric conditions and equations to calculate the peripheral visual detection angles for tangent-curve and curve-tangent sections for a right curve. For the curve-tangent section, two equations had to be developed to calculate the peripheral visual angle. The appropriate equation may be chosen by first calculating the distance *S3*, which is then used to determine the appropriate equation for calculating the peripheral visual detection angle. Because of the optical properties of most retroreflective materials and the

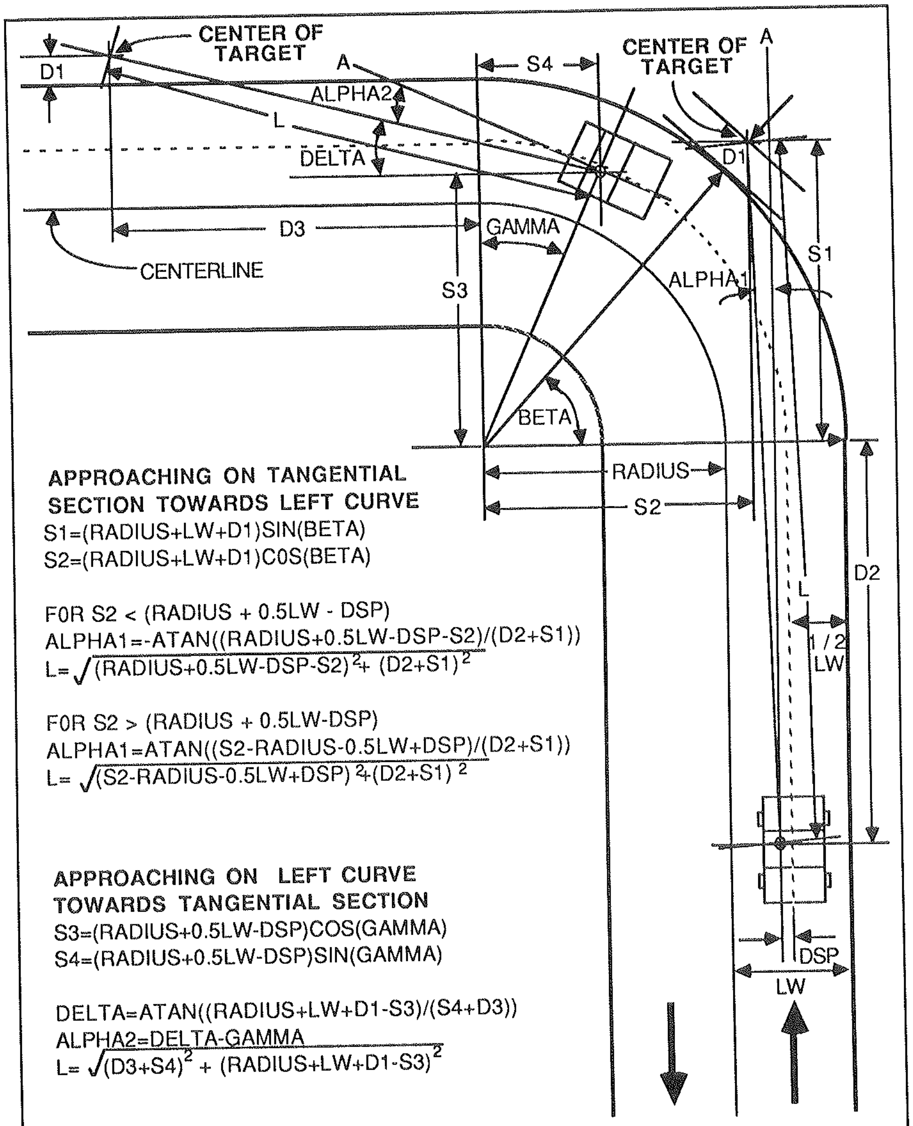

FIGURE 2 Geometric configuration and equations to calculate the peripheral visual detection angles for tangent-curve and curve-tangent sections for a left curve of a two-lane highway.

reduced projected areas of the targets, beta and gamma should not exceed 40°.

Figure 2 shows the geometry and equations to calculate the peripheral visual detection angles (*ALPHA1* and *ALPHA2*) and distances (*L*) for the tangent-curve and curve-tangent sections for a left curve. When calculating the peripheral visual detection angle (*ALPHA1*) and distance (*L*) for the tangent-curve section it was necessary to develop two equations from which one equation must be chosen based on the position of the target in the curve. As shown in Figure 2, the distance *S2* must be calculated before the appropriate set of equations can be chosen because the appropriate formula for the peripheral visual detection angle is based on the magnitude of *S2*. Calculated peripheral visual detection angles to the left of the driver's sagittal plane have negative values and calculated peripheral visual detection angles to the right of the driver's sagittal plane have positive values. Figure 2 also shows an equation to calculate the peripheral visual detection angle (*ALPHA2*) for the curve-tangent section of a left curve. It should be noted that all peripheral visual detection angles for tangent-curve and curve-tangent sections for right curves are measured to the right of the driver's sagittal plane and all angles for tangent-curve and curve-tangent sections for left curves are measured to the left of the driver's sagittal plane, except when $S2 > (RADIUS + 0.5LW - DSP)$ for the tangent-curve section for left curves. In this case, the peripheral visual detection angle is measured to the right of the driver's sagittal plane. A common spreadsheet package (Microsoft Excel) and a graphics package (Cricket Graph) for a Macintosh computer were used to calculate and display the results for selected combinations of the variables present in the model.

According to Zwahlen (*3*), the majority of these curves in the Ohio two-lane rural highway system have a curvature of between 3° and 28° with an average of 12°. Therefore, representative calculations were performed to determine the effect of curvatures of 3°, 12°, and 28° (radii of 1,906, 477, and 204 ft, respectively) on peripheral visual detection angles.

Two lateral offset values on the right-hand side of the driving lane were chosen to represent two typical reflectorized targets that might appear in a driver's peripheral visual field. These targets included a reflectorized license plate of a disabled or abandoned vehicle and a reflectorized roadside warning sign. It was assumed that the disabled vehicle was situated such that the longitudinal center of the vehicle and the reflectorized license plate would be positioned above the right edge line of the highway. It was assumed also that the reflectorized highway warning sign was positioned 12 ft to the right of the edge line (measured from the edge line to the closest edge of the sign) as specified by the *Manual on Uniform Traffic Control Devices* (4). Therefore, the center of a 24- × 24-in. roadside warning sign would be 1.4 ft to the right of this mark and the distance measured from the edge of the highway to the center of the sign would be 13.4 ft. To further reduce the number of calculations, it was assumed that: (a) the driver is driving in the center of his or her lane, (b) the driver is driving in a 12-ft wide lane, and (c) the driver's sagittal plane is located 1.25 ft to the left of the vehicle's longitudinal center.

Figures 3 and 4 show the peripheral visual detection angle (alpha) as a function of the distance from the driver's eyes to the reflectorized target (*L*), the curve position angle (beta), the radius of the curve (*RAD*), and the horizontal distance from the right edge of the road to the target of interest (*D1*) for the tangent-curve conditions for right and left curves. The figures show that as a driver approaches the target the peripheral visual detection angles increase for the tangent-curve sections of highway. Figure 4 shows absolute peripheral visual detection angles, because the values for a curve radius of 204 ft (28° curvature) with a curve position angle (beta) of 20° and a distance from the right edge of the road to the target of 13.4 ft is positive and the values for all other conditions are negative.

Figures 5 and 6 show peripheral visual angles as a function of the distance from the driver's eyes to the target of interest, the radius of the curve (*RAD*), the curve completion angle (gamma), and the horizontal distance from the right edge of the highway to the target of interest (*D1*) for the curve-tangent condition for a right and a left curve, respectively. From Figure 5, the peripheral visual detection angles decrease as the distance from the driver's eyes to the target decreases for the investigated conditions. The one exception occurs for a curve radius

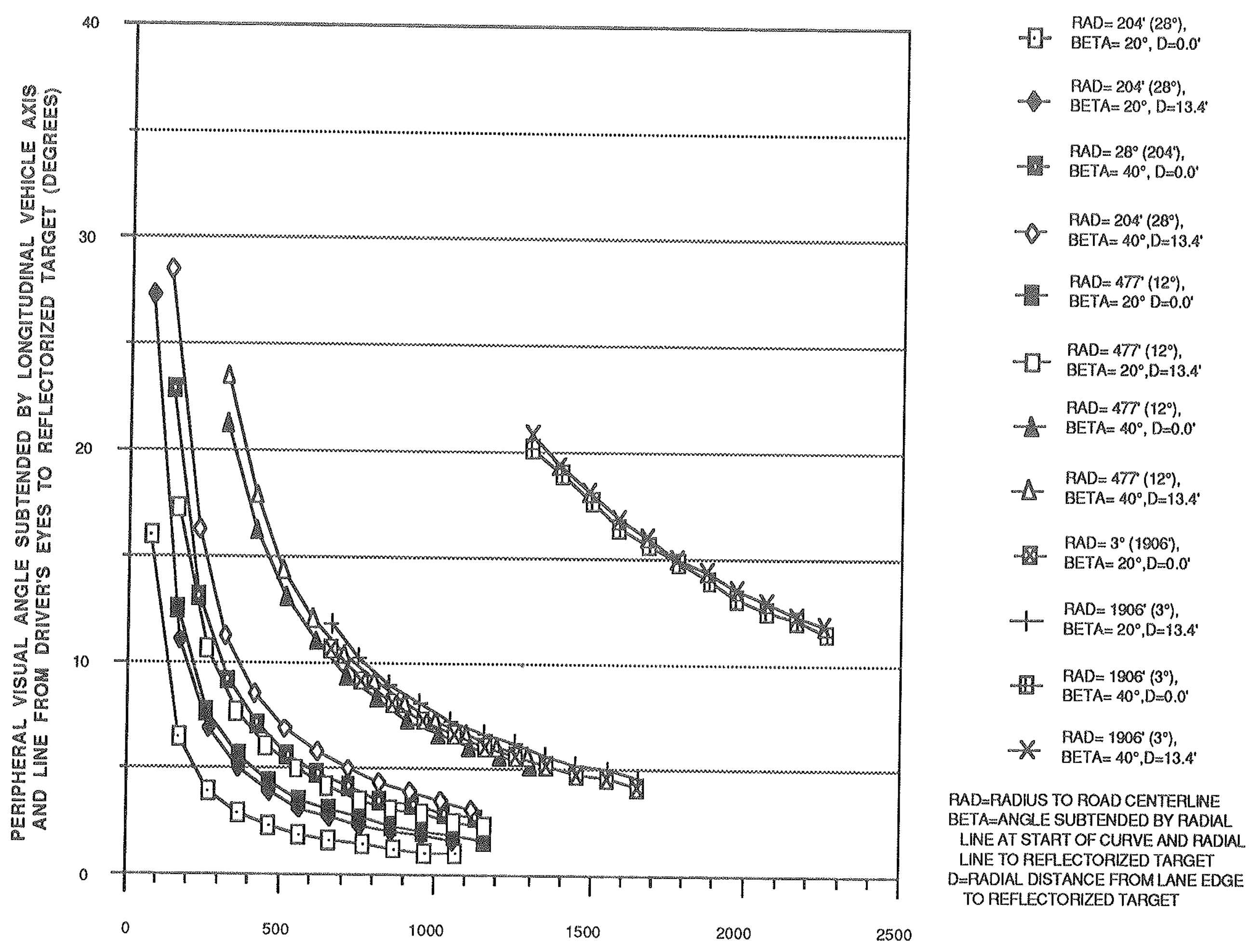

FIGURE 3 Peripheral detection angles for the tangent-curve section for a right curve of a highway for various distances, curve radii, curve position angles, and lateral distances.

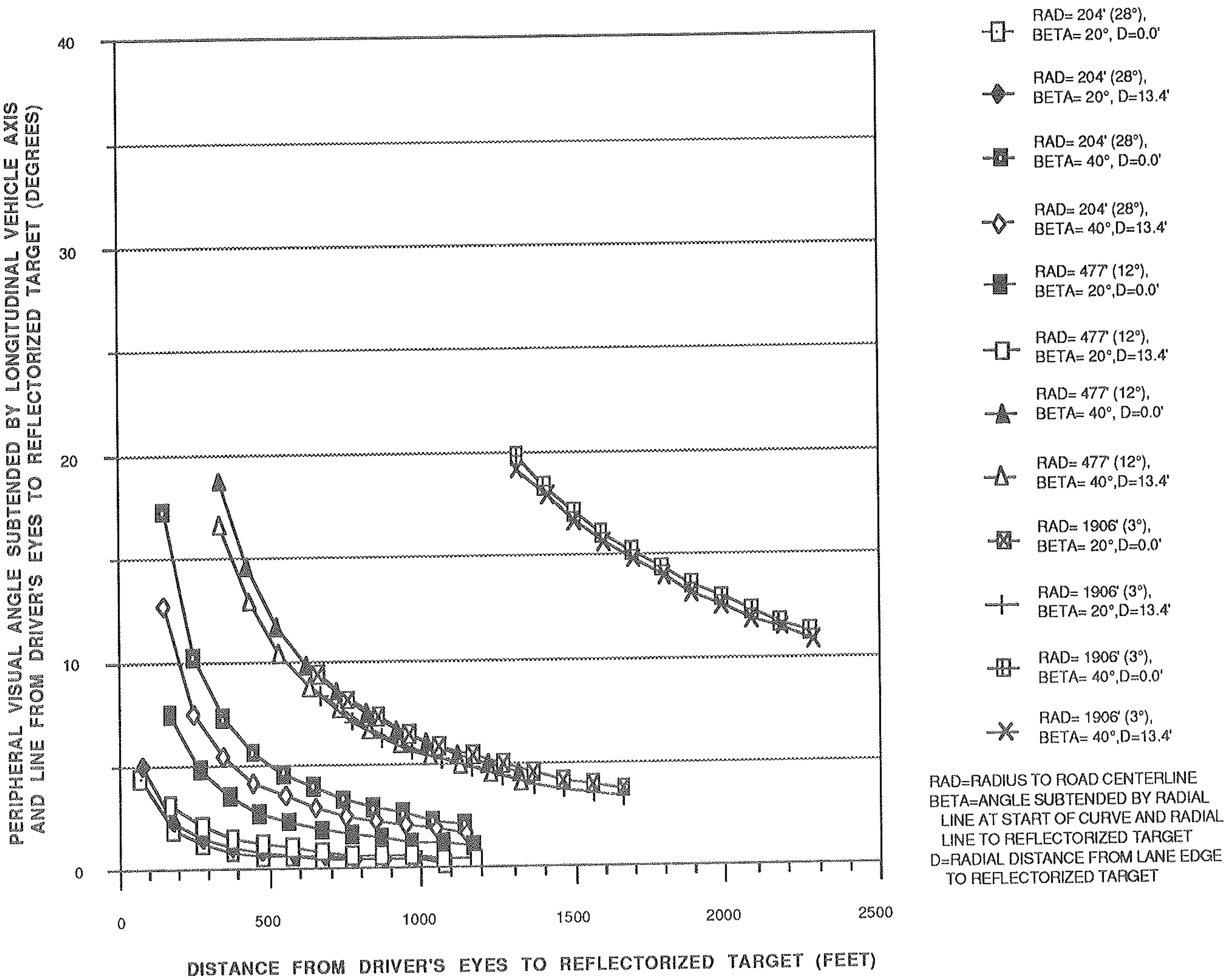

FIGURE 4 Peripheral detection angles for the tangent-curve section for a left curve of a highway for various distances, curve radii, curve position angles, and lateral distances.

of 204 ft (28° curvature) with a curve completion angle (gamma) of 20° when the target is located 13.4 ft to the right of the right edge of the highway. For this condition, the peripheral visual detection angle increases as the distance from the driver's eyes to the target decreases.

From the data shown in Figures 3 through 6, it would appear that relatively large peripheral visual detection angles may exist for targets located along or just beyond a curve. However, reviewing the assumptions made in developing the geometric model it was assumed that the direction of a driver's foveal fixation, or line of sight, is along a line parallel to the longitudinal center axis of the car. This assumption may not be valid because a driver fixates upon various targets located ahead of the car in the driving environment. Therefore, it might be necessary to adjust the obtained calculated peripheral visual detection angles according to the experimentally obtained spatial driver eye fixation densities. It should also be noted that only flat and level highways with horizontal curves were considered and vertical curves or combinations of horizontal and vertical curves, which could further increase the magnitude of the peripheral visual detection angles, were not considered.

In a prior study, Zwahlen (*5*) investigated driver eye scanning behavior. Subjects drove on four unlighted 1-mi-long tangent sections of a four-lane interstate highway (Interstate 70 between Ohio State Routes 37 and 79) with a lane width of 12 ft, and on four unlighted right 240-ft radius clover-leaf type entrance/exit ramps (at the intersection of Interstate 70 and Ohio State Route 79) with a lane width of 16 ft, at night and under dry and light rain conditions. Eleven young licensed test drivers who were in good health, had about 20/20 uncorrected vision, and were paid participated in this night driving study. The subjects drove an instrumented car (VW 412, automatic transmission, type 4000 low beams) equipped with an in-car television eye scanning recording system and other electronic equipment. For a more detailed description of the experimental apparatus see the report by Zwahlen (*4*). Each driver drove the ramps and tangent sections in the same order two times.

Figure 7 shows the relative number of eye fixations that occurred in each 1-degree × 1-degree cell within the viewing area for the tangent sections of a four-lane highway. More fixations are focused in the 1-degree × 1-degree cell that is centered 0.5° to the right of the focus of expansion and 0.5°

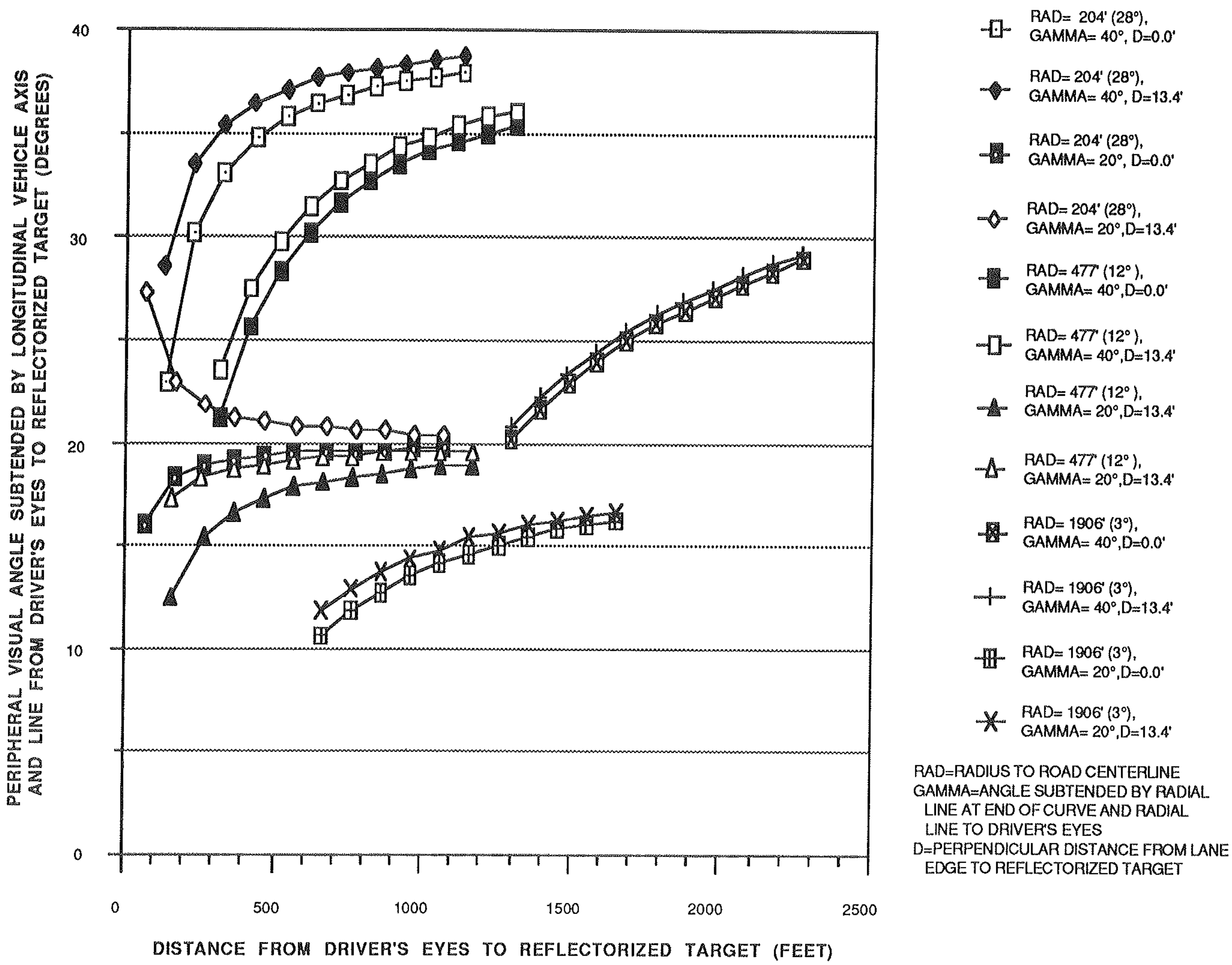

FIGURE 5 Peripheral detection angles for the curve-tangent section for a right curve of a highway for various distances, curve radii, curve position angles, and lateral distances.

below the horizon and focus of expansion than in any other cell. In fact, this cell contains 13.5 percent of the eye fixations made by the test drivers. The average of the horizontal eye fixation distribution for the sample size of 11,780 eye fixations is approximately 0.84° to the right of the focus of expansion with a standard deviation of 1.92°.

Figure 8 shows the relative number of eye fixations that occurred in each cell (1° horizontal, 0.95° vertical) within the viewing area for the 240-ft radius right curves. Comparing Figure 8 with Figure 7 for the tangent sections, the eye fixations are dispersed much more in the spatial distribution for the curves. In fact, the cell centered 14.5° to the right of the imaginary focus of expansion and 1.7° below the horizon or imaginary focus of expansion, which contains the most fixations, contains only 3.9 percent of the fixations made by the drivers as they negotiated the 240-ft radius right curves. The average of the horizontal eye fixation distribution for a sample size of 8,884 eye fixations is approximately 12.79° to the right of the imaginary focus of expansion with a standard deviation of 3.79°.

Because a driver's eye scanning behavior consists of a continuous string of discrete eye fixations, there is no way to predict exactly where a driver will look at any instant. There may be a very remote possibility that a driver will, by chance, look directly at an appearing target. However, looking at the spatial distribution of eye fixations it is very unlikely that this will occur, especially for a target that is located 10° or 20° away from the focus of expansion. Figure 7 shows that on tangent sections more than 80 percent of all eye fixations are within a relatively small rectangle extending from $-2°$ left to 3° right of the focus of expansion and from 2° below to 2° above the focus of expansion, or an area of 20° squared. To get some idea about how much the calculated peripheral visual angles should be adjusted to account for the observed horizontal eye fixation distributions, the average and the standard deviation of the horizontal eye fixation distribution were estimated for a 12° and for a 28° left and right curve. The estimates were based on the data presented in Figures 7 and 8, on computer-generated curve driving scene perspectives, and on the assumption that the eye fixation distributions for left curves

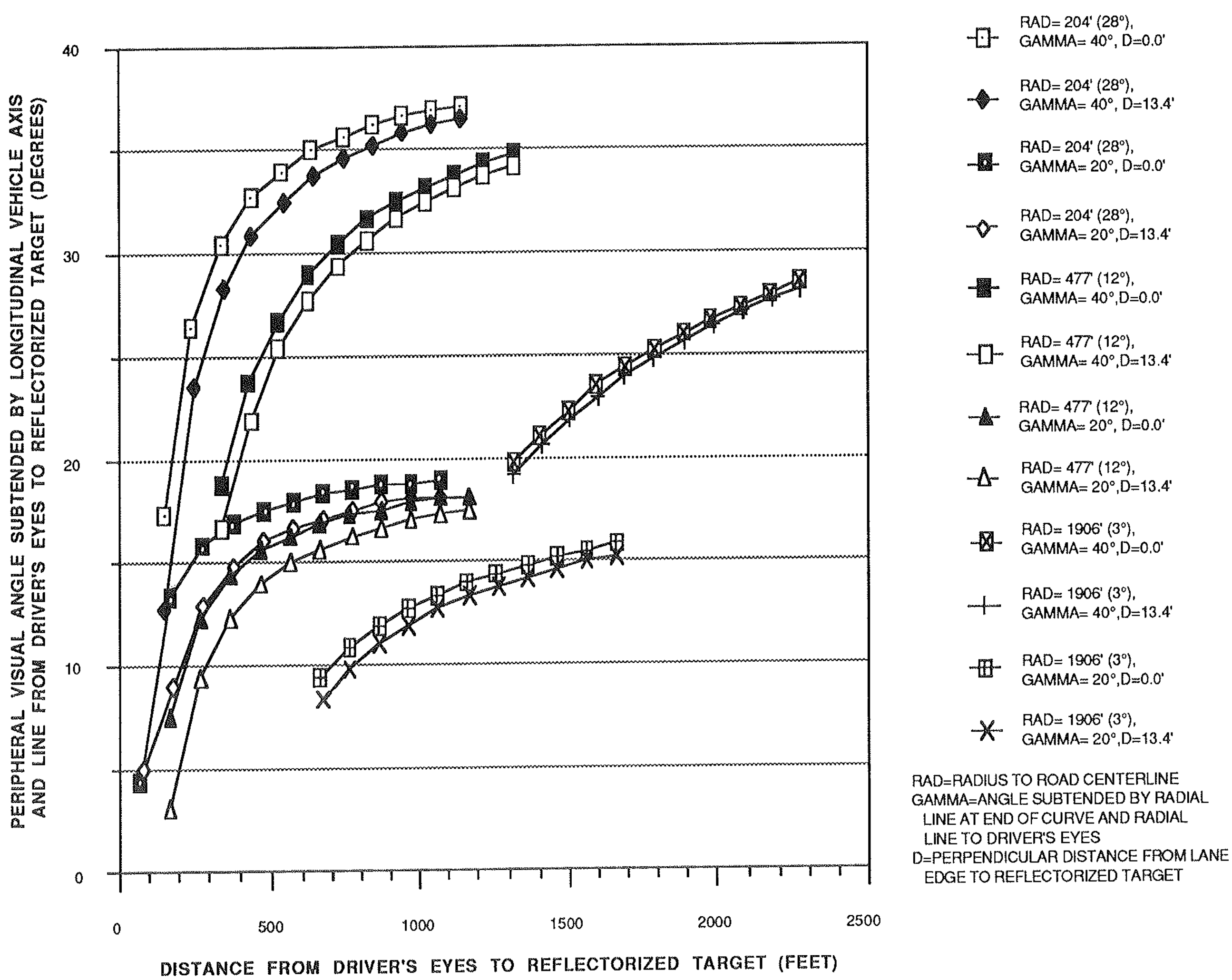

FIGURE 6 Peripheral detection angles for the curve-tangent section for a left curve of a highway for various distances, curve radii, curve position angles, and lateral distances.

are approximately symmetric and the same as for right curves. Three horizontal eye fixation location values were then selected (average, average minus one standard deviation, and average plus one standard deviation) to represent horizontal eye fixation locations for the instant when a target becomes first visible in a driver's field of view. Table 1 gives information about the calculated and adjusted peripheral visual detection angles. Table 1 was developed for a selected target distance of 500 ft (the euclidean distance from the driver's eyes to the target of interest). This distance corresponds roughly to the average peripheral visual detection distance minus one standard deviation for a 10° peripheral detection angle and near maximum low beam output (−3° car heading angle) as it was presented by Zwahlen (*1*). Further, Zwahlen (*3*) found average first look or eye fixation distances on curve warning signs on two-lane rural highways at night of about 500 ft. Looking at Figures 3 to 6, one can see that a target distance of less than 500 ft would result in an increase of the calculated peripheral detection angles in some cases and in a decrease of the calculated peripheral detection angles in other cases.

When adjusting the calculated peripheral angles for all tangent-curve sections, an average foveal eye fixation position of 0.84° to the right of the focus of expansion and a standard deviation of 1.92° were used. The curve-tangent sections for 12° right curves were adjusted for an estimated average horizontal foveal eye fixation position of 9.0° to the right of the imaginary focus of expansion and an estimated standard deviation of 3.3°. The curve-tangent sections for 28° right curves were adjusted for an estimated average horizontal foveal eye position of 13.6° to the right of the imaginary focus of expansion and an estimated standard deviation of 4.0°. The curve-tangent sections for 12° left curves were adjusted for an estimated average horizontal foveal eye fixation position of 7.2° to the left of the imaginary focus of expansion and an estimated standard deviation of 3.3°. The curve-tangent sections for 28-degree left curves were adjusted for an estimated average horizontal foveal eye position of 11.2° to the left of the imaginary focus of expansion and an estimated standard deviation of 4.0°. Only curves with 12° and 28° of curvature (radii of 204 and 477 ft, respectively) were selected because no calculated peripheral visual detection angles were available for curves with 3° of curvature (1,906-ft radius) at a distance of 500 ft.

Looking at Table 1, one can see that adjusting the calculated peripheral visual detection angles (based on the estimated average, the estimated average minus one estimated

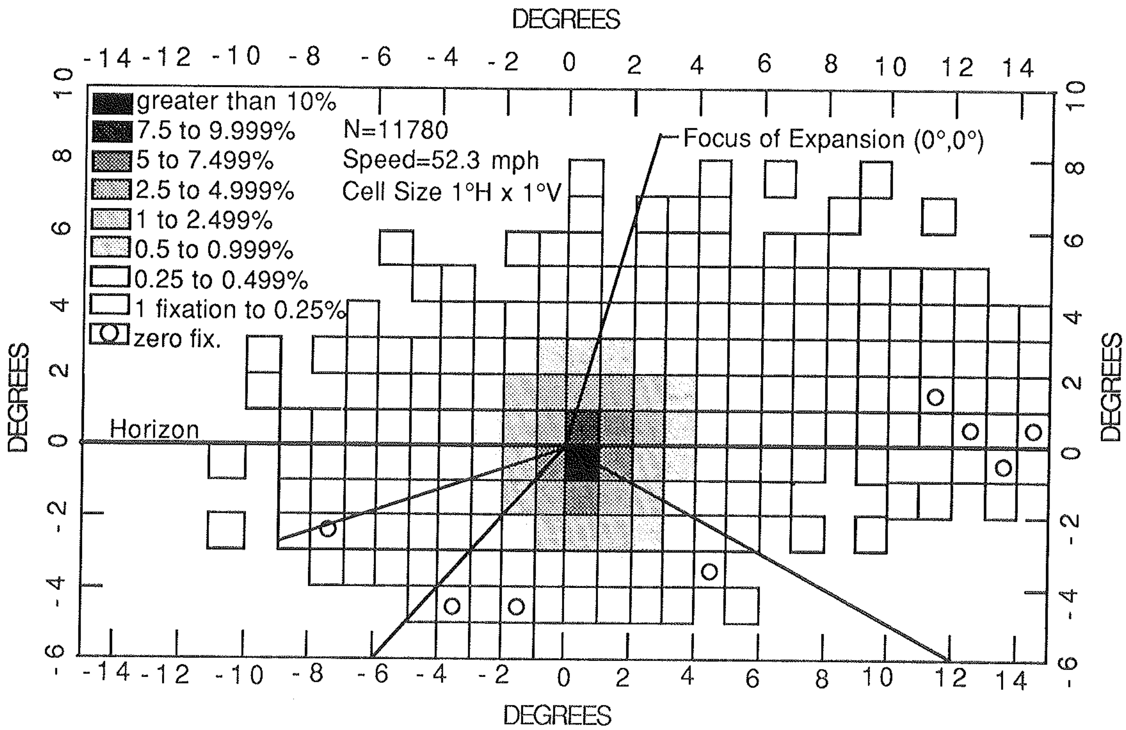

FIGURE 7 Driver eye fixation pattern for tangent sections of a four-lane interstate highway at night (11 subjects, 91 runs, 13.3 percent of all eye fixations on vehicles ahead).

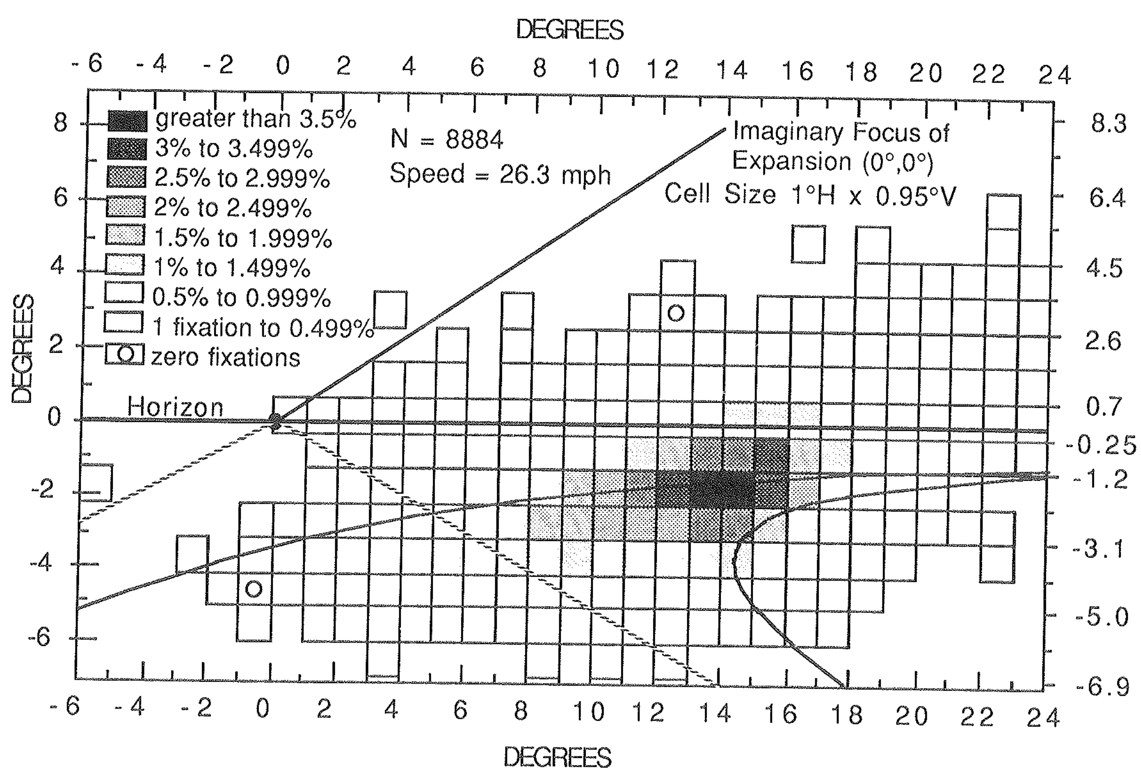

FIGURE 8 Driver eye fixation pattern for 240-ft radius right-curved entrance/exit ramps at night (11 subjects, 153 runs, 0.7 percent of all eye fixations on vehicles ahead).

TABLE 1 CALCULATED AND ADJUSTED PERIPHERAL VISUAL ANGLES FOR 500-FT VIEWING DISTANCE

Degree of Curvature	Beta/ Gamma (degrees)	Target Position[a] (*D1*)(ft)	Peripheral Visual Angle: Calculated (degrees)	Adjusted (degrees): X^b	$X - S^c$	$X + S^d$
Tangent Right						
12	40	0.0	13.5	12.7	14.6	10.8
12	40	13.4	14.7	13.9	15.8	12.0
28	40	0.0	6.0	5.2	7.1	3.3
28	40	13.4	7.2	6.4	8.3	4.5
Curve Right						
12	20	0.0	17.5	8.5	11.8	5.2
12	20	13.4	19.1	10.1	13.4	6.8
28	20	0.0	19.4	5.8	9.8	1.8
28	20	13.4	21.0	7.4	11.4	3.4
Tangent Left						
12	40	0.0	−12.5	−13.3	−11.4	−15.2
12	40	13.4	−11.3	−12.1	−10.2	−14.0
28	40	0.0	−5.0	−5.8	−3.9	−7.7
28	40	13.4	−3.8	−4.6	−2.7	−6.5
Curve Left						
12	20	0.0	−15.8	−8.6	−5.3	−11.9
12	20	13.4	−14.2	−7.0	−3.7	−10.3
28	20	0.0	−17.7	−6.5	−2.5	−10.5
28	20	13.4	−16.2	−5.0	−1.0	−9.0

[a]Target position is from the right edge of the highway.
[b]Adjusted using the estimated average of the horizontal eye fixation distribution.
[c]Adjusted using the estimated average minus one estimated standard deviation of the horizontal eye fixation distribution.
[d]Adjusted using the estimated average plus one estimated standard deviation of the horizontal eye fixation distribution.

standard deviation, and the estimated average plus one estimated standard deviation of the horizontal eye fixation distribution data) resulted in considerable decreases of the magnitude of the angles for about one half of all the cases (curve left and right). For the other half (tangent), the magnitude of the angles was only slightly reduced. However, it should be noted that the magnitude of many of these angles remains relatively large after adjustment.

PERIPHERAL VISUAL DETECTION CAPABILITIES

An experiment was conducted to assess the conspicuity of a suprathreshold reflective target at night in the field. Some aspects of this study have been reported in Zwahlen (*1*). Two separate groups of subjects were used to study the effects of two different beam output conditions (high candlepower values and moderate candlepower values in the direction of the reflectorized target) and the relative stability and reliability of the experimental results. The first group had 7 subjects (5 males, 2 females) with an average age of 21.1 yrs (standard deviation of 0.9 yrs). This group of subjects had an average of 5.6 yrs driving experience during which they drove an average of 5,000 mi per yr, with standard deviations of 1.9 yrs and 3,000 mi per yr. The second group had 7 subjects (3 males, 4 females) with an average age of 23.5 yrs (standard deviation of 1.7 yrs). The second group had an average of 7.1 yrs driving experience during which they drove an average of 8,700 mi per yr, with standard deviations of 2.2 yrs and 3,300 mi per yr. All of the subjects had normal visual acuity and volunteered their time as subjects. Each subject served as his or her own control.

A 1979 Ford Fairmont was used as the experimental car for the first group of subjects. The headlamps (H4656) were 24 in. above the ground and had a horizontal center-to-center distance of 48 in. The actual established location of the hottest spot for the left low beam was 2° to the right and 2° down. The actual established location of the hottest spot for the right low beam was 1.5° to the right and 1.7° down. The electrical system of the car operated at an average of 13.3 volts. The average distance from the longitudinal vertical center plane of the car to the subject's sagittal plane while in the driver position was 14 in. The average horizontal distance from the headlamps to the subject's eyes was 89 in. and the average subject eye height was 45 in. above the ground.

A 1979 Ford LTD II was the experimental car for the second group of subjects. Its headlamps (GE 4562) were 29 in. above the ground with a vertical center-to-center distance of 46 in. The actual established location of the hottest spot for the left low beam was 2° to the right and 2° down. The actual established location of the hottest spot for the right low beam was 1.5° to the right and 1.7° down. The electrical system of the car operated at an average of 14.1 volts. The distance from the headlamps to the subject's eyes was 97 in. and the average subject eye height was 43 in. above the ground.

A black bicycle was used as the target vehicle. A white license plate was mounted on the front of the bicycle so that the horizontal center of the license plate was 26.8 in. above the paved surface and its reflecting surface made an angle of $-10°$ with the transverse axis of the bicycle to simulate a vehicle parked at a slight angle along the highway. The 6-in. × 12-in. license plate had a reflectivity of 24 CIL (measured 23.5 cd/fc at 0.2° observation angle and $-4°$ entrance angle).

A 75-ft wide, 2,000-ft long section of an abandoned concrete runway located at the edge of the city of Athens, Ohio, was used as the experimental site. A two-lane state highway with moderate traffic was located parallel to and approximately 200 ft away from the runway. A number of luminaires, a few advertising signs, and other light sources were in the subject's field of view, mainly in the left peripheral field. Typical luminance ranges for the 75-ft wide concrete runway surface under low beam illumination were 0.006 to 0.016 fL at 150 ft in the front of the vehicle; 0.004 to 0.009 fL at 300 ft; 0.002 to 0.009 fL at 600 ft; and sky above horizon 0.004 to 0.01 fL, haze, no stars, and no moon (Pritchard photometer, 1° aperture for 150 ft; 20 min aperture for 300 ft, 600 ft, and sky measurements).

There were three approach paths parallel to the runway axis. The front centers of the experimental cars were placed at the zero distance line, vertically above the center line of the runway. Looking forward from the car, Path 1 was 12.5 ft to the left of the runway center line, Path 2 was 6.25 ft to the right of the runway center line, and Path 3 was 25 ft to the right of the runway center line. The inclusion of three paths in the experiment was intended to introduce some uncertainty about the lateral location of the approaching target. The car was then positioned on the runway so that it was heading 3° to the left of the center of the runway ($-3°$ car heading angle) for Group 1 or 10° to the right of the center of the runway (10° car heading angle) for Group 2. The $-3°$ car heading angle produced close to maximum low beam candlepower values in the direction of the reflectorized target and the 10-degree car heading angle produced considerably lower low beam candlepower values in the direction of the reflectorized target. Stakes were placed radially 500 ft away from the car at angles of $-30°$, $-20°$, $-10°$, 0°, 10°, 20°, and 30° with respect to the runway center line to indicate where one movable red dim light (3 ft above the ground) should be positioned as a fixation point to be used by the subjects.

During the experiment, a group of dark-clothed experimenters were positioned at various locations along the side of the runway. Using a flashlight, they signaled the beginning of each trial to an experimenter sitting in the passenger seat of the stationary experimental car. Another experimenter sitting in the car recorded the time of each trial, car voltage, weather conditions, and the subject's responses. The engine of the experimental car was kept idling throughout the experiment. When the experimenter in the car received the signal that the bicycle rider was ready for an approach and the measurement crew was off the runway, the subject was asked to fixate on the dim red light positioned 500 ft ahead of the car at one of the seven selected detection angles. The subject was then instructed to turn on the low beams and be prepared to detect the approaching license plate while continuously fixating his or her eyes on the dim red light. The bicycle rider would approach the stationary car along one of the three approach paths at a constant speed of approximately 10 mph. As soon as the subject had the initial sensation of detection of the target, he or she would switch immediately from low to high beams and keep them on for a few seconds. When the bicycle rider perceived the high beams, he or she would drop a small sandbag on the runway to indicate the detection distance. The measurement crew would then measure the detection distance, pick up the sandbag, and return it to the bicycle rider.

The measurement crew would signal the experimenter in the car indicating the beginning of the next trial after everyone had cleared the runway, the bicycle rider had moved back to the end of the runway, and the bicycle was positioned perpendicular to the runway center line on the correct approach path for the next trial. The correct approach path of the bicycle with the target and fixation point position was checked by the experimenter in the car. Six practice trials were carried out for each subject. This was then followed by the 63 actual trials (7 detection angles × 3 paths × 3 approaches). The experiment required approximately 1 hr and 20 min to complete for each subject.

The independent variables for this experiment were the seven detection angles ($-30°$, $-20°$, $-10°$, 0°, 10°, 20°, and 30° with respect to the runway center line) and the two car heading angles ($-3°$ to the left and 10° to the right). The dependent variable was the detection distance measured in feet. The order of presentation of the peripheral detection angles was according to a latin square design (7 angles, 7 subjects). The 9 observations for each angle (3 paths × 3 replications) were blocked (3 blocks, each path assigned in random order once within each block).

The detection distances obtained for each of the three approach paths were combined because paired t-tests indicated that almost all differences among the three paths were not statistically significant at the 0.05 level. The combined results are in Figure 9, which shows averages and standard deviations for the detection distances as functions of the peripheral visual detection angle. From Figure 9, one can see that the average detection distances decrease considerably as the peripheral visual detection angle increases. At a peripheral visual detection angle of 10° the average detection distance was between 54.2 and 59.2 percent of the average foveal detection distance for the -3-degree car heading angle and between 47.3 and 55.6 percent of the average foveal detection distance for the 10° car heading angle. At a peripheral visual detection angle of 20° the average peripheral detection distances were between 35.7 and 36.0 percent of the average foveal detection distance for the $-3°$ car heading angle and between 35.6 and 37.9 percent of the average foveal detection distance for the 10° car heading angle. At a peripheral angle of 30° the average peripheral detection distances were between 25.1 and 27.0 percent of the average foveal detection distance for the $-3°$ car heading angle and between 28.2 and 32.6 percent of the average foveal detection distance for the 10° car heading angle. As expected, the average detection distances obtained for the 10° car heading angle, or the much

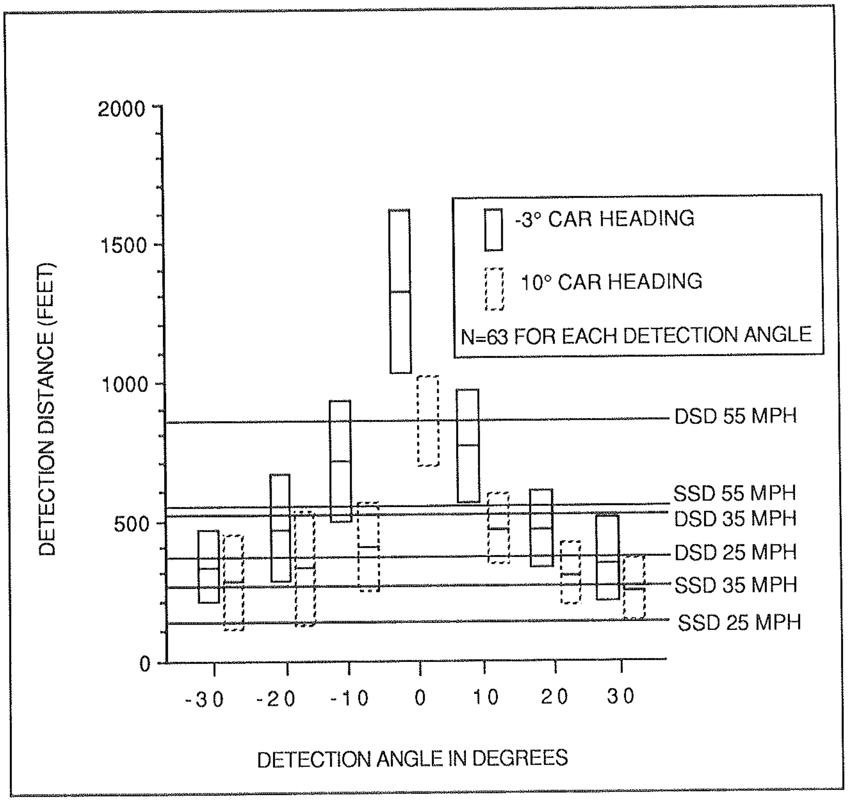

FIGURE 9 Averages and standard deviations of the measured peripheral visual detection distances for a −3-degree and 10-degree car heading angle compared with selected stopping sight distances and lower values of selected decision sight distance ranges.

lower candlepower values of the low beams, are considerably shorter than the average detection distances obtained for the −3° car heading angle.

The average detection distances obtained in this study and shown in Figure 9 can be further evaluated from a safety point of view. Comparing the peripheral detection distances with a recommended stopping sight distance of 563 ft for a speed of 55 mph, only the average detection distances for the foveal and the 10° peripheral detection angles exceed the recommended stopping sight distance for the −3° car heading angle. If the recommended stopping sight distance of 563 ft for a speed of 55 mph is compared to the average detection distance for the 10° car heading angle, then the recommended stopping sight distance is larger than all of the average detection distances except the average detection distance for the 0° (foveal) detection angle. If the idealized average detection distances obtained in this study are reduced by 50 percent to adjust for driver alertness and expectancy, older drivers, information acquisition and information processing load while driving, somewhat degraded environmental visual conditions, dirty windshield, and dirty headlamps, then only the 50 percent reduced average detection distance for the 0° peripheral angle (foveal detection) for the −3° car heading angle exceeds the stopping sight distance for a speed of 55 mph. Comparing the average detection distances acquired for the −3° car heading angle after they are reduced by 50 percent with a stopping sight distance of 263 ft for a speed of 35 mph, the reduced average detection distances are larger than the stopping sight distance for only the foveal detection and the 10-degree peripheral visual detection angles. Further, comparing the average detection distances acquired for the 10° car heading angle, only the reduced average detection distances for the 0° peripheral visual detection angle are larger than the stopping sight distance. In fact, once the average detection distances are reduced by 50 percent they are so small that for the 10° car heading angle the reduced average detection distances for the 30° peripheral angles are approximately equal to or slightly smaller than the stopping sight distance of 137 ft for a speed of 25 mph.

McGee et al. (*6*) recommended decision sight distances, i.e., the distances a driver needs to perceive a potentially hazardous situation and react efficiently to the impending danger, of 375 to 525 ft for a speed of 25 mph, 525 to 725 ft for a speed of 35 mph, and 875 to 1,150 ft for a speed of 55 mph. Comparing the smaller of each of these distances with the detection distances obtained in this study, the average detection distances are greater than the minimum decision sight distance for a design speed of 55 mph for only the foveal detection angle with the −3° car heading angle (near optimal low beam candlepower conditions). As the peripheral visual detection angle is increased, the average detection distances decline so rapidly that for the relatively small peripheral detection angle of 10° the average detection distances for 10° car heading angle are less than the decision sight distance for a speed of 35 mph. The average detection distances for a peripheral detection angle of 30° are as much as 130 ft less than the decision sight distance for a speed of 25 mph. If the decision sight distances are compared to the detection distances reduced by 50 percent, then the decision sight distance for a speed of 55 mph is larger than all of the 50 percent reduced average detection distances for both the $-3°$ and 10° car heading angles. Comparing the decision sight distances for a speed of 25 mph to the average detection distances reduced by 50 percent, only the detection distance for the 0° visual detection angle for the 10° car heading angle is larger than the decision sight distance for a speed of 25 mph. Similarly, only the average detection distances obtained for the 0° and 10° peripheral visual detection angles for the $-3°$ car heading angle are equal to or larger than the minimum decision sight distance for a speed of 25 mph. The much shorter 10° car heading detection distance results might be more applicable to the peripheral visual detection of a reflectorized target in the highway environment than the $-3°$ car heading detection distance results. The longitudinal direction of the car and its beams is such that the candlepower values of the beams in the direction of the reflectorized target are probably reduced considerably in a situation where a reflectorized target first appears in a driver's peripheral visual field.

Zwahlen (*7*) has shown that the multiples of threshold that a driver needs to detect a reflectorized target, such as a bicycle pedal, increase very rapidly as the peripheral visual detection angle is increased. The multiples of threshold are proportional to the specific intensity of a reflectorized target. Therefore, if, for a given peripheral visual detection angle, an average detection distance equal to the average foveal detection distance is desired, the specific intensity or reflectivity of the retroreflective target would have to increase appropriately, assuming the environmental and beam conditions remain the same.

Paired *t*-tests were performed to determine whether or not the average peripheral detection distances for the left side (peripheral visual detection angles of $-30°$, $-20°$, and $-10°$) could be assumed to be equal to the corresponding average peripheral detection distances for the right side (peripheral visual detection angles of 10°, 20°, and 30°). For both the $-3°$ and the 10° car heading angles, the average peripheral detection distances for the 10-degree peripheral visual detection angle for the left side were about 9.2 to 17.6 percent shorter (statistically significant at the 0.05 level) than the average peripheral detection distances for the right side. This can be partially explained by noting that there was a highway with moderate traffic located about 200 ft away on the left parallel to the airport runway. Therefore, there were more light sources (luminaires, advertising signs, etc.) in the left peripheral field of view (less uniform dark background). The average peripheral detection distances for the 20° and 30° peripheral visual detection angles were of about equal magnitude and were not statistically different.

CONCLUSIONS

Using Ohio as an example, it has been shown that curve-tangent and tangent-curve sections occur fairly frequently along two-lane rural highways, especially in hilly regions. Therefore, relatively large peripheral visual detection angles (up to 15° or more from a driver's foveal eye fixation point or line of sight) could be quite common for reflectorized targets that become visible for the first time in the periphery of a driver's visual field. The field study to assess the peripheral visual detection capability of drivers at night, or the conspicuity of suprathreshold reflectorized targets, produced visual detection distances with nearly ideal subjects under fairly ideal and well-controlled conditions. The results show that the peripheral visual detection ability, or the detection distances for suprathreshold reflectorized targets, decrease considerably as the peripheral visual detection angle increases. The decrease of the visual detection distances in the periphery can, however, be offset by increasing the reflectivity or specific intensity of the retroreflective target. It is, therefore, recommended that in cases where a reflectorized target will become visible for the first time most likely in the periphery of a driver's visual field and where there is a need for early detection, the reflectivity of the target should be increased to assure timely recognition, information processing, and decision making, and appropriate control actions.

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