

Detectability of Pavement Markings Under Stationary and Dynamic Conditions as a Function of Retroreflective Brightness

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With the availability of pavement marking systems having varying reflective performance, the brightness a road surface marking must have to provide safe and effective guidance has remained undefined. This work studied minimum reflective brightness needed for a pavement marking to be visible to a driver as a function of distance of the marking from a vehicle. Six pavement marking products having a wide range of retroreflective brightness performance were viewed as isolated center skip lines from stationary vehicles at distances from 30 to 250 m in a dark rural setting. Product detectability for each viewer/marking combination was determined. Also, seven pavement marking products were viewed from moving vehicles with a driver approach speed of 24 kph. Detection distances for each driver/marking combination were determined. Retroreflective brightness of the products as a function of distance was measured at geometries corresponding to the vehicle-driver distances of the experiment. Detectability of pavement markings depends on the viewing conditions. A correlation could be seen between detectability of pavement markings and product brightness and viewing distance. The nature of this correlation was different when the experiment was changed from a stationary viewing to one with a moving vehicle with shorter detectability distances for the same marking in a moving vehicle.

There has long been interest in the description of the minimum brightness requirements for retroreflective pavement markings (1-3). Recently that interest has been renewed (4,5). It has been shown that photometric measurements of pavement marking brightness made under geometric conditions approximating those of driver visual observations at a range of viewing distances correlate well with driver visual perception (5,6).

With the availability of pavement marking systems having varying reflective performance, the retroreflective brightness needed for a road surface marking to provide safe and effective guidance has remained undefined. A better understanding of the minimum reflective brightness for a pavement marking to be visible to a driver as a function of distance of the marking from a vehicle was needed. The approach in this work involved the determination of pavement marking detectability as a function of distance and the coefficient of retroreflected luminance at the distances of detection.

EXPERIMENTAL APPROACHES

Two different viewing experiments were conducted to assess minimum brightness for pavement marking detectability. In the first

experiment, drivers viewed different pavement markings at a fixed set of distances from a stationary vehicle. In the second study, drivers approached pavement markings in a moving vehicle and the marking detectability distance was noted.

Night viewings were held on two consecutive nights in the summer of 1993. A test roadway with black asphalt pavement in a dark rural setting was used. Tests began after dark at about 10:00 p.m. The sky was dark, overcast, and moonless. Samples were illuminated with standard low-beam headlamps. The vehicle type used in the viewings was a 1993 Ford Taurus 4-door sedan.

Retroreflective properties of the marking materials were characterized before the viewing experiments to ensure that the selection of test samples represented a wide range of retroreflective performance. The reflective brightness of the materials at each detection distance was calculated from the photometric data.

Photometric Measurements

Retroreflectivity of the test pavement markings was measured in a laboratory photometric range similarly to ASTM D 4061-89 using actual optical geometries calculated to correspond to the night viewing conditions as described by Hedblom et al. (5). For this experiment the measurement was simplified by using a two-dimensional geometry. The presentation and orientation angles were set at 0 and -180 degrees, respectively, and the headlamp illumination, marking, and driver eye position were all in the same plane.

Measurement geometries were calculated for drivers in a 1993 Ford Taurus for distances from 30.5 to 167.6 m from vehicle to center line target for both left and right headlights. Table 1 shows the geometries at which the coefficient of retroreflected luminance, R_L , was measured.

Brightness was measured at each geometry for seven pavement marking products used in the night viewing experiments. These measurements are presented graphically as a function of distance in Figure 1 for the driver-left headlight-two-dimensional geometry.

Night Viewings

A set of 23 driver viewers and a 1993 Ford Taurus 4-door sedan were assembled for the stationary viewings. Three automobiles (all 1993 Ford Taurus sedans) and 19 observers were used for the dynamic viewings (moving vehicle). All vehicle headlights were aligned before the viewing.

TABLE 1 Simplified Two-Dimensional Geometries as a Function of Distance for Left and Right Headlights

Distance (m)	Angles in Degrees for:			
	Left Headlight		Right Headlight	
	Entrance	Observation	Entrance	Observation
30.5	88.6	0.95	88.6	2
45.7	89.1	0.67	89.1	1.86
50.0	89.2	0.63	89.2	1.72
61.0	89.3	0.52	89.3	1.37
76.2	89.5	0.42	89.5	1.08
79.9	89.5	0.4	89.5	1.04
91.4	89.6	0.35	89.6	0.9
106.7	89.6	0.31	89.6	0.76
121.9	89.7	0.27	89.7	0.67
137.2	89.7	0.24	89.7	0.59
152.4	89.7	0.21	89.7	0.53
167.6	89.8	0.2	89.8	0.48

All viewers held valid driver's licenses from the state of Minnesota or Wisconsin and most had "good" vision. Four of the 23 viewers were women. Six were 50 to 60 years old and eight were under 30. Eight of the observers wore corrective lenses. Visual acuity of the test subjects was measured on an orthorater using the Snellen test. Comparison of the test subject data with the general population (7) is presented in Table 2.

Stationary Experiment

Pavement marking samples 0.1 m wide by 3.0 m long were prepared for viewing. Each sample of pavement marking was applied to alu-

minum panels 0.2 cm thick of the same dimension with the leading edge of the aluminum panel masked with black colored matte finished tape. The samples were viewed on top of a viewing table 0.3 m wide by 3.2 m long with a matte black surface finish. The table stood 3.8 cm above the road surface. The function of the table was to keep the samples optically flat and level.

The samples were viewed at distances of 30, 50, 80, 120, 160, 200, and 250 m from the front of the vehicle to the leading edge of the marking. Markings were presented as isolated centerlines 3.7 m from the right edge of the road. Markings were viewed from the driver position of a stationary vehicle parked centered in the lane between the centerline and edge of the road. All other markings on the road surface were obliterated for the course of the experiment.

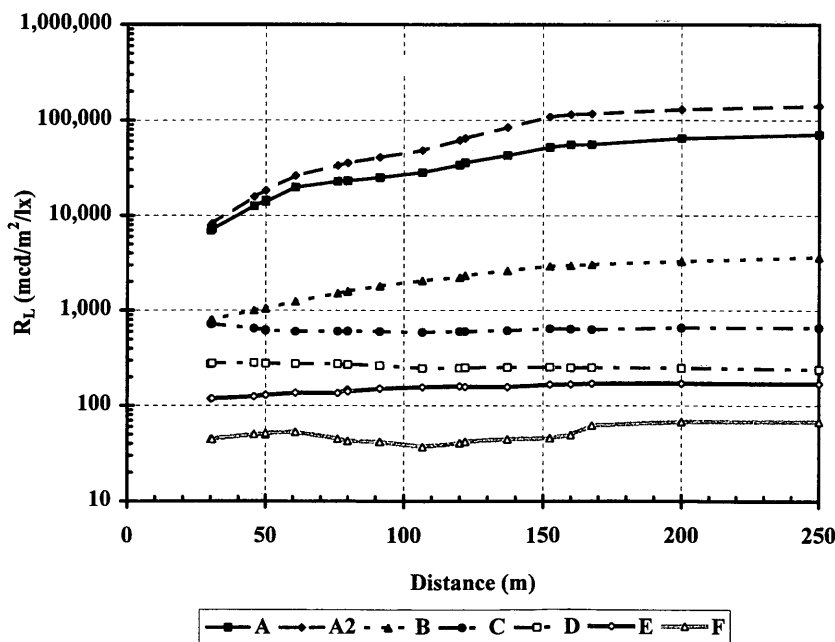


FIGURE 1 Coefficient of retroreflected luminance, R_L , with distance for seven marking products measured for distances of 30 to 250 m using a two-dimensional left headlight geometry.

TABLE 2 Comparison of Viewers to Standard Population

Best Binocular Visual Acuity with Corrected Lenses

	% of Population below Visual Acuity			
	20/20	20/25	20/30	20/40
	Experiment	37.5	18.8	6.3
U.S. 1977 (7)	26.8	12.9	6.9	3.5

Six distinctly different white preformed pavement marking products (A, B, C, D, E, and F) were tested representing a wide range of retroreflective characteristics as indicated in Figure 1. The materials included experimental products designed for this work having higher and lower retroreflectivities than those normally commercially available to extend the range of the experiment.

Samples were viewed one at a time at each distance. A replicate of at least one of the six samples was included at each distance. A blank of either no sample present or one that had not been visible to any of the viewers at a shorter distance was presented at each distance. Each distance had its own randomized sample presentation order.

Individual samples were installed on the top of the viewing table and covered with a black cloth. The viewers then turned on the vehicle headlights (low beam) and the test sample was exposed for 2 sec. The sample was then covered and the headlights extinguished. After viewing the test area for 2 sec, each subject was asked to write down whether a sample was visible or not visible. For each product at each distance the number of positive sightings of samples and the number of presentations were counted. Table 3 shows the percent of positive sightings of samples for each product at each distance. Figure 2 shows the same data in graphic form for each product at each distance.

TABLE 3 Percentage of Positive Sightings of Pavement Marking Products with Distance Viewed under Stationary Conditions

distance (m)	Product						
	A	B	C	D	E	F	G
30	100	100	100	100	98	96	0
50	100	100	97	91	91	87	4
80	100	91	96	83	54	13	13
120	92	96	33	22	20	13	0
160	87	39	2	0	4	0	8
200	91	30	0	0	0	0	0
250	52	0	0	0	0	0	0

Dynamic Experiment

As in the stationary viewing experiment, pavement marking samples 0.1 m wide by 3.0 m long were prepared for viewing and mounted on top of a viewing table (described earlier) for each viewing run for each sample.

Pavement markings were viewed one at a time as isolated center skip lines by subjects driving a Ford Taurus sedan traveling along a straight section of test road. Samples were placed at center line locations randomly within a 70-m section of the test roadway. Ambient conditions were dark overcast, moonless sky, rural setting with black asphalt pavement as described above.

Seven different pavement marking samples were viewed in the dynamic experiment. Photometric data for the seven samples as a function of distance are indicated in Figure 1. A blank in which no sample was present on the viewing table was also included.

The drivers approached the marking at a speed of 24 kph with low beam headlights illuminated. When drivers decided that they had detected the pavement marking, a passenger in the vehicle was

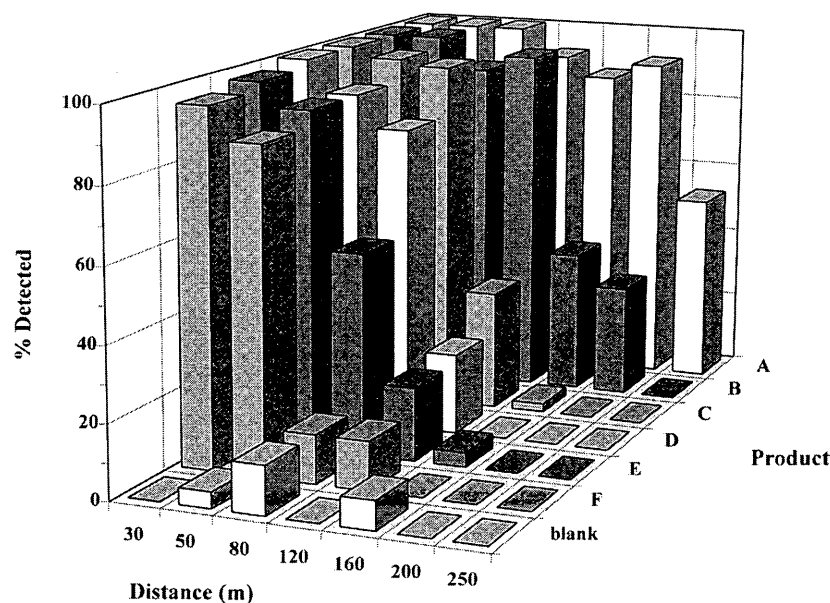


FIGURE 2 Percentage of positive sightings of pavement marking products with distance viewed under stationary conditions.

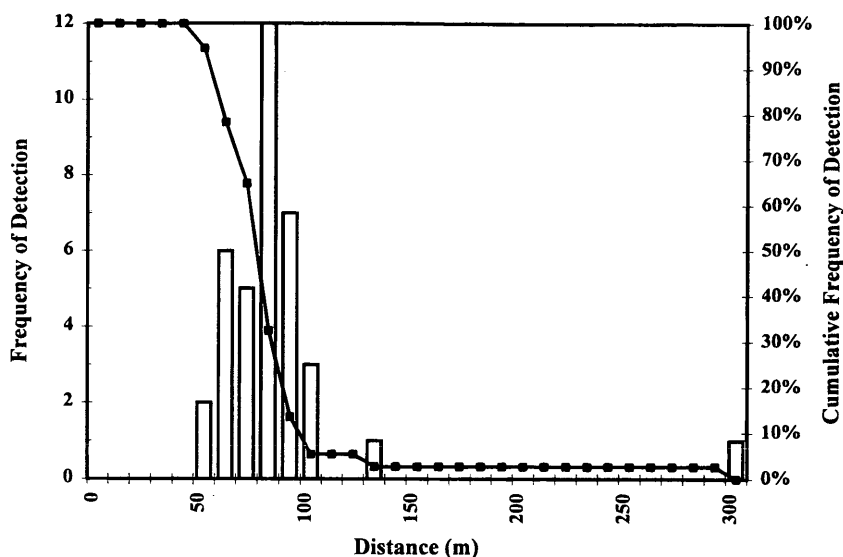


FIGURE 3 Detection distances of Product C under dynamic conditions.

informed and a reflectorized bean bag was immediately dropped from the moving vehicle. Workers along the side of the test roadway retrieved the bean bag and measured the distance from the car to the marking at the time of detection. Detection distances for Product C are shown in histogram form in Figure 3. Table 4 shows detection distance distributions for all seven products.

RESULTS AND DISCUSSION

Age, gender, and the use of corrective lenses by the observers had no distinguishably consistent effect within the sample of observers used in this study. The vision of the test subjects was not different from that estimated for an average population of drivers in the United States (see Table 2). In the dynamic experiment, any effects caused by the three different test vehicles were not distinguishable from the observer variability.

Measurement

From the photometric measurements made at geometries corresponding to distances from 30 to 167 m, reflectivities for intermediate distances were interpolated. Reflectivities at shorter and longer distances were approximated by graphic extrapolation of the available data set. A graph of the extrapolated R_L data is shown in Figure 4.

Stationary Experiment

The distribution of marking detectability as a function of viewer/target distance and product retroreflective brightness was examined. Figure 2 presents the percent of positive sightings of each product at each distance. Figure 5 shows the coefficient of retroreflected luminance, R_L (mcd/m²/lx) for each product at each distance measured using a left-headlight, two-dimensional geometry. A comparison of Figures 2 and 5 shows that although R_L is maintained, and in some cases actually increased with viewing distance, the detectability of a given marking material diminished at greater distances.

TABLE 4 Experimental Detection Distances in Meters of Pavement Markings Products Viewed Under Dynamic Conditions at 24 kph

Product						
A2	A	B	C	D	E	F
99.1	67.1	44.2	45.7	33.5	33.5	12.2
146.3	111.3	83.8	45.7	44.2	44.2	13.7
149.4	114.3	89.9	51.8	53.3	53.3	18.3
163.1	115.8	91.4	53.3	53.3	53.3	19.8
184.4	118.9	100.6	54.9	54.9	54.9	27.4
184.4	118.9	100.6	57.9	54.9	54.9	30.5
211.8	121.9	103.6	57.9	56.4	56.4	30.5
221.0	125.0	105.2	57.9	61.0	61.0	32.0
225.6	134.1	108.2	62.5	65.5	65.5	33.5
246.9	143.3	121.9	64.0	67.1	67.1	44.2
248.4	146.3	125.0	64.0	67.1	67.1	50.3
262.1	147.8	128.0	68.6	70.1	70.1	51.8
285.0	149.4	128.0	68.6	70.1	70.1	53.3
286.5	152.4	131.1	70.1	71.6	71.6	56.4
298.7	152.4	134.1	71.6	82.3	82.3	59.4
420.6	153.9	134.1	71.6	88.4	88.4	64.0
423.7	158.5	140.2	71.6	93.0	93.0	64.0
975.4	173.7	144.8	71.6	99.1	99.1	64.0
		149.4	71.6	99.1	99.1	
			76.2			
			76.2			
			76.2			
			76.2			
			76.2			
			77.7			
			80.8			
			82.3			
			83.8			
			85.3			
			85.3			
			88.4			
			88.4			
			94.5			
			94.5			
			96.0			
			125.0			
			298.7			

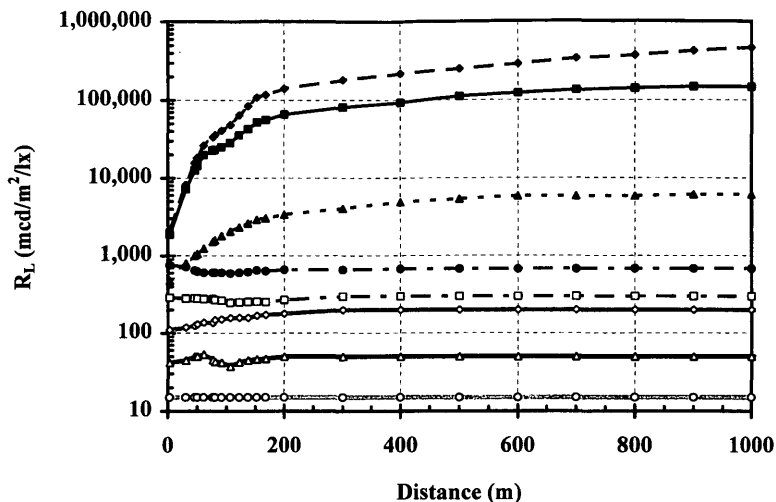


FIGURE 4 Coefficient of retroreflected luminance, R_L , with distance for seven marking products extrapolated to 1,000 m.

Figure 6 shows (a) a three-dimensional contour plot of the percent of positive sightings mapped onto brightness R_L and distance and (b) a projection contour viewing the surface from directly above the brightness-distance plane. The contours on the surface represent 5th percentile intervals of marking detectability. For example, the contour line corresponding to the 75th percentile means that at the set of brightnesses and distances along this curve, 75 percent of the observers could see the marking and 25 percent of them could not see the marking. As brightness of a marking is increased, its detectability improves. For a marking of given luminance, detectability improves at shorter distances.

Relations presented in a CIE publication (8) predicted the visibility distance of road markings having a given coefficient of retroreflected luminance. The measurement geometry of R_L is unclear from the text. For the work presented here, R_L was measured in the laboratory at geometries corresponding to the actual viewing conditions of the experiment.

Figure 7 presents the 5th, 25th, 50th, 75th, and 95th percentiles of marking detectability interpolated from the data of the stationary experiment in a 2-dimensional graph of visibility distance versus R_L . This graph is similar in format to that of Figure 2.2 of the CIE publication (9). Included in Figure 7 are data taken from the curve in the CIE publication for comparison with the data in this paper. The CIE curve covers a much narrower range of R_L values. It falls close to the 75th and 50th percentile detectability curves for the stationary experiment and has similar curvature to the percentile contours obtained from this work.

Dynamic Experiment

The distribution of marking detectability as a function of viewer/target distance and product retroreflected brightness was examined. Figure 8 is an example of a plot of product brightness with distance

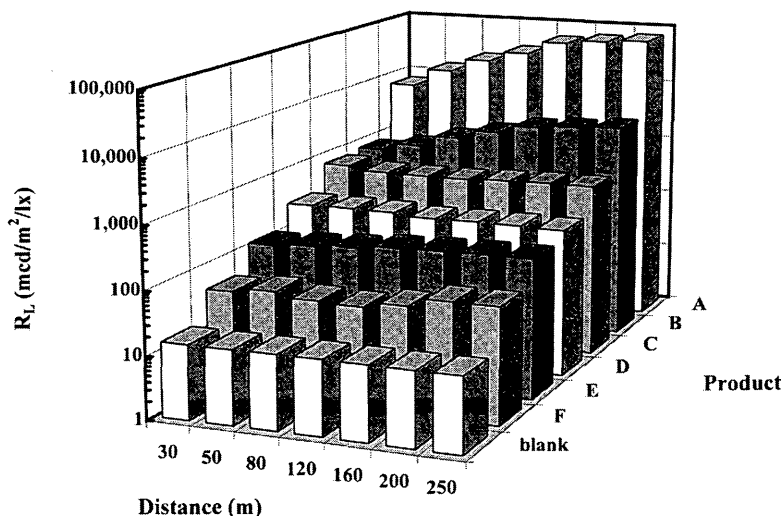


FIGURE 5 Coefficient of retroreflected luminance, R_L , for each product and distance in the stationary viewing experiment.

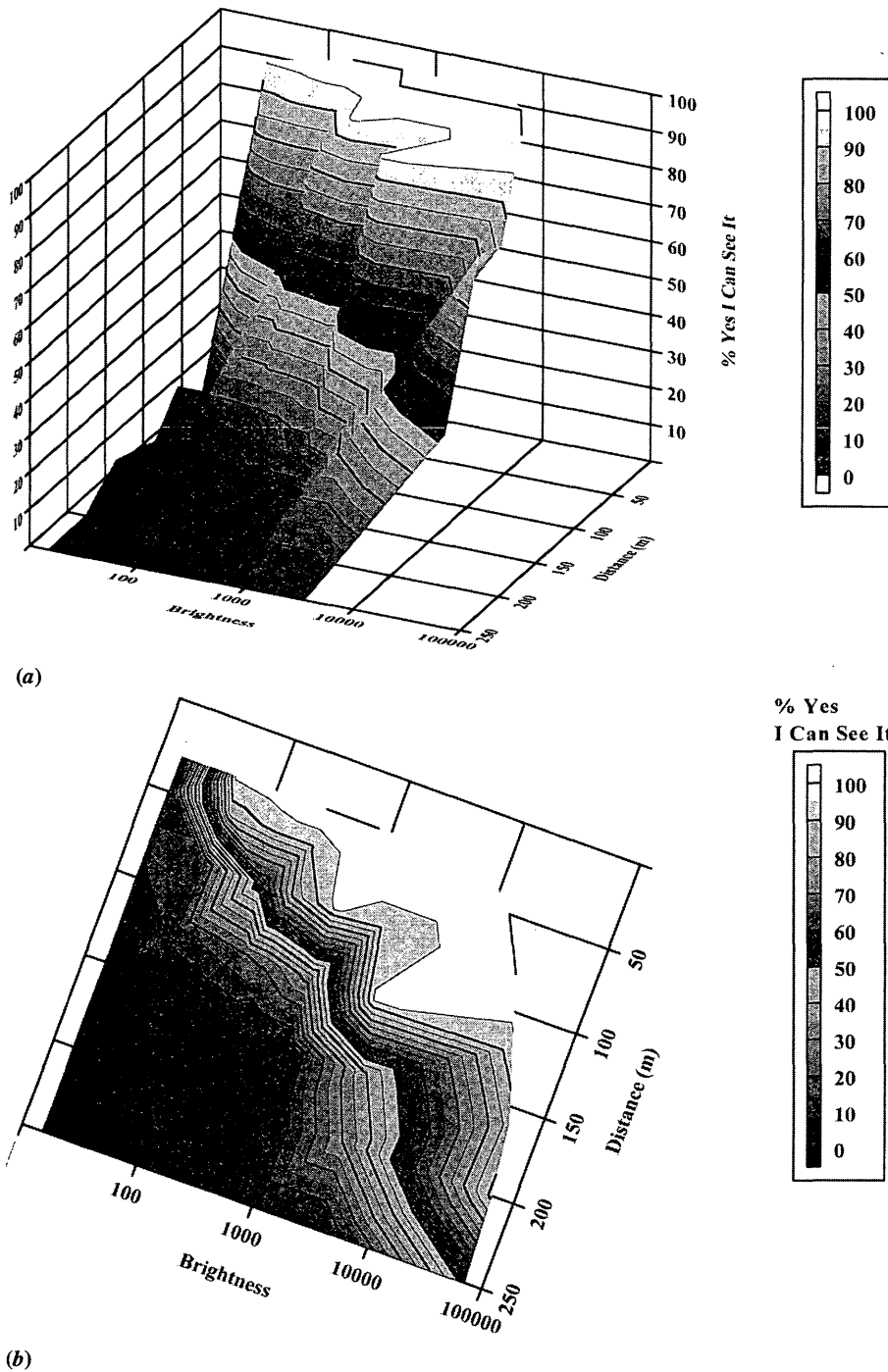


FIGURE 6 (a) Three-dimensional contour of the percentage of positive sightings of pavement marking products viewed under stationary conditions mapped onto coefficient of retroreflected luminance, R_L , and distance; (b) two-dimension projection of the same contour viewed from directly above the R_L distance plane.

for each observer's detection of Product C. The points on the graph correspond to each detection of C by the various observers at different distances and the brightness of the marking at each set of viewing conditions. This can be obtained through comparison of the histogram for Product C in Figure 3 and the extrapolated R_L values from Figure 4.

Figure 9 shows the cumulative frequency of detection with distance from 0 to 250 m for each product in the dynamic experiment.

These data were used to calculate the 5th, 25th, 50th, 75th, and 95th percentiles of marking detectability with distance and brightness for the dynamic data. These curves are presented in a plot of visibility distance versus coefficient of retroreflected luminance in Figure 10.

Comparison of Figures 7 and 10 shows that the detectability contours for the dynamic experiment are shifted to shorter-visibility distances than for the stationary experiment. Also this shift is not linear. The shift for the less-bright samples appears to be about

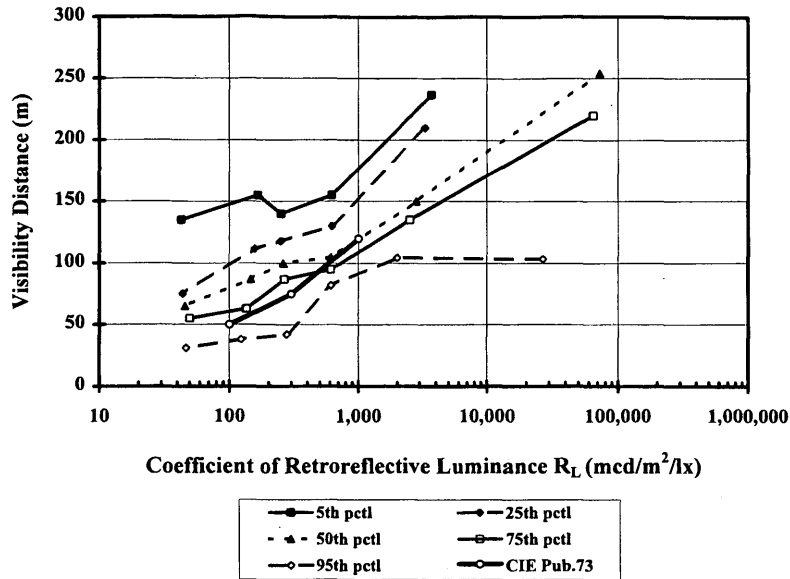


FIGURE 7 Marking visibility distance (5th, 25th, 50th, 75th, and 95th) percentiles with R_L under stationary viewing conditions.

20 m for the moving vehicle experiment relative to the stationary experiment. For brighter materials, for example, in the 10,000 to 100,000 $mcd/m^2/lx$ range, the shift could be as much as 100 m or more.

The curvature of the contours of detectability appears to be different for stationary compared with dynamic conditions. There was a stronger increase in detection distance with increased brightness for the stationary experiment than for the dynamic experiment. From this limited data set, there appears to be a decrease in visibility distance on the order of 40 percent changing from a stationary vehicle to one moving at about 24 kph.

Assuming a vehicle traveling speed of 24 kph with an estimated delay time of about 1 sec for driver reaction time, statement by dri-

ver to passenger and dropping of the reflective bean bag marker by the passenger, and falling to the ground and an inertial roll of the marker of less than about 1.5 m, a lag distance based solely on mechanical aspects of the experiment would be 11 m or less. The shift in detectability distance seems to be more complex than simple physical delay. In both the stationary and dynamic experiments, the observers were well trained to know approximately when and where to look to detect a marking. The complexity of the driving task at speeds as slow as 24 kph may be a contributor to this shift.

Figure 10 also includes the curve for the predicted visibility with distance from a CIE publication (9). The CIE prediction appears to cross more of the detectability contours for the dynamic experiment than for the stationary experiment. The CIE data are not consistent

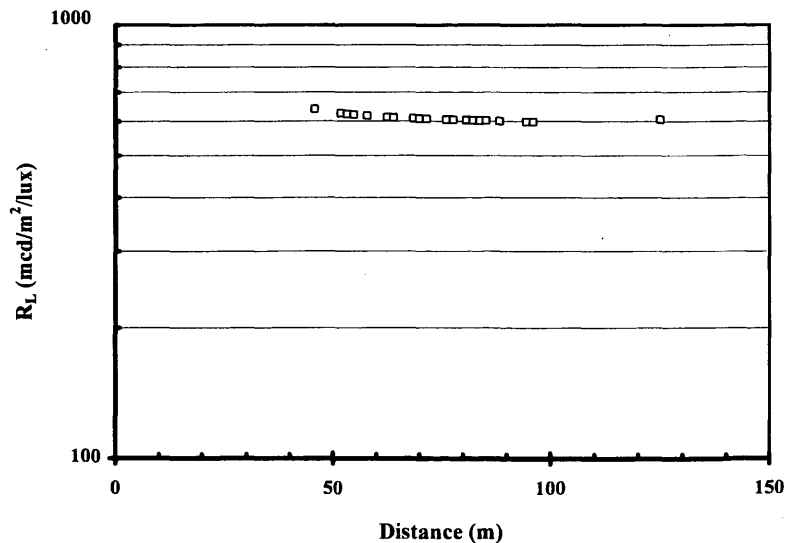


FIGURE 8 Product brightness with distance for each observer's detection of product C.

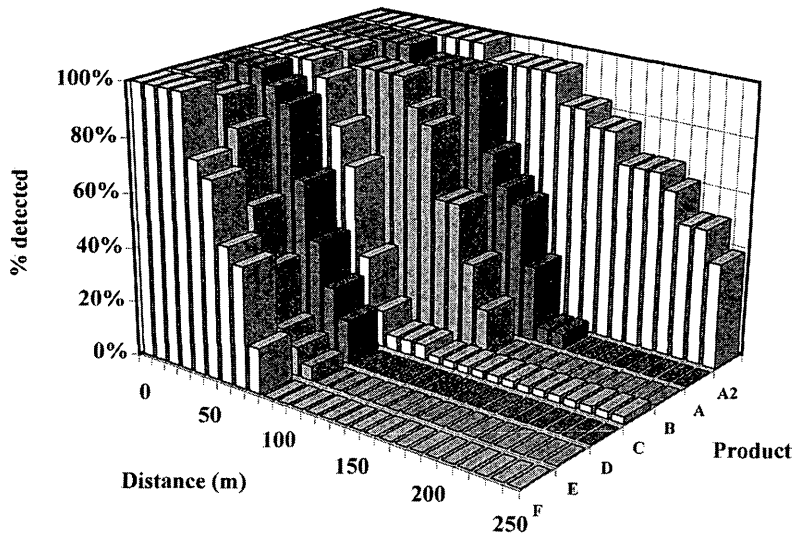


FIGURE 9 Cumulative frequency of detection for each product from 0 to 250 m for the dynamic viewing experiment.

with the dynamic portion of this work. This could be partially because of the difference in reflectivity measurement geometry. Perhaps, more importantly, it could be the result of the differences in detectability that occur when the observers are driving a moving vehicle.

Recent work in the area of pavement marking detection distances has also been done by Zwahlen and Schnell (4). Their work used a range of commercially available markings with different brightness performance. They did not have data available at the time for the coefficient of retroreflected luminance at geometries corresponding to their viewing conditions. Photometric measurements have been made for one of the products they used, and the data points for 5th, 25th, 50th, 75th, and 95th percentiles are included on the graph of visibility distance with coefficient of retroreflected luminance in Figure 10. With

the appropriate measures of R_L now available, it can be seen that their moving vehicle experiment at a similar speed agrees well with this work in describing effects of marking brightness on detection distance.

CONCLUSIONS

Measurement of the brightness of retroreflective markings at geometries corresponding to actual driver viewing conditions has provided a better understanding of minimum brightness requirements for detectability of pavement markings. As expected, brighter markings were detectable at greater distances from observer to marking in both stationary and dynamic viewing experiments.

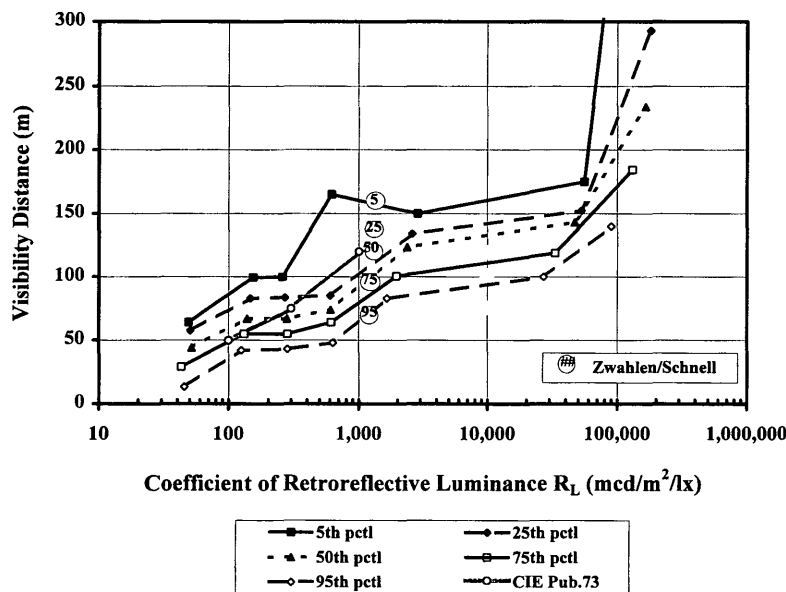


FIGURE 10 Percentiles of marking visibility distance (5th, 25th, 50th, 75th, and 95th) with R_L under dynamic viewing conditions.

Detectability of pavement markings depends on the viewing conditions. A correlation could be seen between detectability of pavement markings and product brightness and viewing distance. The nature of this correlation was different when the experiment was changed from a stationary viewing to viewing the same set of products from a moving vehicle. Both the detectability distances and the dependence of detectability on distance and brightness changed with the added complication of vehicle movement. A speed of as little as 24 kph was sufficient to significantly shift marking detectability to shorter distances.

Marking detectability also depends strongly on the viewers themselves. For example, the visibility distance for a marking with a value of R_L of about 120 mcd/m²/lx at 30 m ranged from less than 30 m to more than 160 m for the stationary experiment and from 20 to 95 m for the dynamic experiment. These ranges were obtained using trained viewers who knew approximately when and where to observe a specific type of object.

Minimum brightness requirements for detectability of pavement markings in actual road use are subject to the safety needs of the driving environment in question. Many factors, including vehicle speed, the background surround and contrast, and the consequences of not being able to detect a road surface marking need to be considered when defining such limits for a particular driving scenario. More effort will be required to fully understand these effects on marking detectability to define meaningful minimum brightness levels.

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