Correlation of the Nighttime Visibility of Pavement Marking Tapes with Photometric Measurement

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A primary visual guide for a motor vehicle driver is the use of pavement markings on the centerline and edge line of the roadway. The nighttime visibility performance of these markings is predicted by a surrogate method of laboratory or field photometric measurement. There are currently several photometric systems in use that vary widely in geometric and precision capabilities. With the advent of modern pavement markings with a variety of retroreflective optical systems and surface characteristics, common retroreflective measurements in the laboratory and field have generally been found to lack correlation with the markings visibility performance of drivers. The nighttime visibility of new, dry centerline pavement markings as viewed from a stationary automobile and semitruck are compared with laboratory and field photometric measurements. The visibility results are compared with the photometric methods. The common test geometries used in the industry today are found to have poor correlation with driver visual perception at most distances. A laboratory test method has been developed with the hope of better characterizing actual pavement marking retroreflective performance. This test method measures products at the same photometric geometries at which a driver actually observes pavement markings. Excellent agreement between driver visual observation and this test method was obtained at multiple distances.

It has long been desirable to predict the brightness of pavement markings as seen by drivers with laboratory and field photometric measurements. With the miniaturization of electronics in the 1960s it became possible to manufacture portable retroreflectometers with optics approaching actual car/driver/road geometries for distances approaching 100 m (*1*). In practice, both entrance and observation angles needed to be increased to make these portable instruments durable and portable. Increasing these angles in comparison with actual road geometries was found to give acceptable results and proved useful for determining threshold values for retroreflectivity within narrow ranges of pavement marking product construction (i.e., new and worn paints and flat preformed pavement markings with 1.5 refractive index glass beads) (*2*). With the advent of modern pavement marking systems with greatly different product constructions, it has been our experience that these portable devices and common test methods do not correlate well with human perception.

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The purpose of this study was to compare pavement marking materials differing greatly in their retroreflective performance with human observers, standard retroreflective test methods, and new laboratory test methods incorporating actual road geometries. It was hoped that human perception of pavement marking performance could be predicted by laboratory and field photometric measurements.

HUMAN PERCEPTION OF PAVEMENT MARKING BRIGHTNESS

Night viewings were held on two consecutive nights in a dark rural setting. The first night 12 observers viewed pavement markings from a Ford Taurus. All 12 observers held a valid driver's license, and none had any visual problems when questioned. The test began at 9:30 p.m. under cloudy skies and a full moon. The test concluded at 3:30 a.m. with partly cloudy skies. The Taurus's headlights were aligned the date of the test. Two subjects viewed the markings at a time. The first subject sat in the driver's seat, and the second sat directly behind with his head next to the driver's. Both viewers' eye positions were recorded relative to the dimensions of the car. Five of the 12 viewers were female. Three were over 50 years old, and three viewers were under 30. Eight of the observers wore eye glasses.

The second night of viewing was performed using a Mack semitruck. Ten subjects from the car viewing and two alternates were chosen as subjects. The test began at 9:30 p.m. with clear skies and a full moon. Two subjects viewed the samples at a time. Both subjects shared the driver's seat. Eye position measurements were taken for each subject.

Pavement marking samples 10 cm wide by 3.05 m long were viewed, two at a time. Each sample of pavement marking was applied to 0.2-cm aluminum panels of the same dimension. The two samples were viewed 10 cm apart on top of a 0.3-m-wide by 3.2-m-long viewing table with a black colored matte surface finish. The table stood 3.8 cm above the road surface. The function of the table was to keep both samples optically flat and level.

The samples were viewed at distances of 12.2, 24.4, 48.8, and 73.2 m; distances are measured from the leading edge of the stripe to the headlight. The maximum distance was chosen such that one of the markings would not be visible to some of the subjects. The samples were viewed as centerline markings. The middle of the viewing table was centered 3.7 m from the right edge of the road. Both the car and the truck were parked between the centerline and edge line. All other road markings were obliterated within the test distances and for 50 m beyond the furthest samples.

Four distinctly different commercially available white preformed pavement marking products were tested. The four products were chosen because of their different retroreflective characteristics and because they represented the range of retroreflectivity available with modern pavement marking systems. The products differed in the type of glass beads, the surface texture of the markings, and the use of a double focusing lens system. Two of the four products were duplicated for controls. Thus a total of six markings were used.

The markings were viewed statically in random pairs. Fourteen random pairings of the six lines at each location were viewed. Each distance had its own random order between the 14 pairs. The 14 random pairs viewed at each distance were selected so that it could be determined whether there was a difference between the left- and right-hand sides of the viewing table. Also, two samples at each location were displayed with their own replicates to check that the subjects rated them as equal.

The pairs were installed on the top of the viewing table and covered with a black felt cloth. The viewers then turned on the vehicle headlights and the samples were exposed for 2 sec. Each subject was allowed to write down the response while a new pair was installed.

After viewing the paired samples for 2 sec each subject was asked to write down whether the samples were equal in brightness, the right sample was brighter or much brighter than the left, or vice versa. If only one line was visible the subjects were asked to write that down. To analyze the data, a numerical weight rating of 0, ±1, ±2 was assigned to the ratings of equal, brighter, or much brighter, respectively. Negative numbers were used to designate the left sample being brighter; positive numbers represented the right sample being brighter.

The left and right samples and their numerical rating were entered into a data base along with personal information for each subject such as sex, age, whether the subject wore glasses, eye position information, and which group number the subject was in during the night. The data base could then be searched for any criteria chosen.

The data for each vehicle were analyzed to determine whether there was any difference between the left and right sample positions. For both vehicles it was determined that the maximum difference in rating values between the left and right sample positions was 0.5. Typically the difference between sample positions was less than 0.25. A similar analysis was performed to determine whether the replicate samples were the same. Again replicate samples always measured less than a 0.5 rating difference, typically less than 0.25. Rating values less than 0.25 to 0.5 have little difference.

The data were then analyzed for all subjects in each vehicle to determine visual differences between the four products. For this analysis the replicate samples for the products were considered to be the same material. Also, the left and right sample positions were considered to be equivalent. The four materials were ranked at each distance according to their paired differences. Table 1 gives the ranking of Products A, B, C, and D; a rank of 1 indicates the highest and 4 the lowest perceived brightness. The number in parentheses next to the product represents the average paired ranking difference versus the product of next lower ranking.

There are several important points regarding the rankings of the materials in Table 1. First, except at 73 m, there were differences in the relative rankings of materials when viewed between the car and truck. Product C ranks brighter than Product A in the truck at the two closest distances. In the car, Product A was brighter than Product C at the closer distances. Most important, depending on the distance the products were viewed in each vehicle, the relative rankings of the materials changed. The exception was Product B, which at all distances had the lowest perceived brightness. Each of the other three products changed its relative rankings.

Stated another way, the relative ranking of product brightness as seen by observers is a function of the distance the products are observed at and the type of vehicle being used. The implications of this are great. There is no single retroreflectivity measurement that can predict the relative performance of different pavement marking products at all distances used by a driver.

During the night viewing at 73 m in the Taurus, when Products B and C were viewed with Products A and D, 10 percent of the time the subjects only saw the brighter materials (A and D). This implies that the brightness of Products B and C is approaching a threshold value for automobile drivers at 73 m. In the semitruck all lines were visible at all distances.

TABLE 1 Product Rankings and Their Paired Differences

Vehicle	Distance	#1 Rank	#2 Rank	#3 Rank	#4 Rank
Taurus	12.2m	D (0.7)	A (0.2)	C (1.5)	B (0)
Taurus	24.4m	D (0.3)	A (1.1)	C (0.9)	B (0)
Taurus	48.8m	A (1.0)	D (1.7)	C (0.5)	B (0)
Taurus	73.2m	A (2.0)	D (1.2)	C (0.3)	B (0)
Truck	12.2m	D (0.0)	C (1.4)	A (0.7)	B (0)
Truck	24.4m	D (0.6)	C (0.2)	A (1.5)	B (0)
Truck	48.8m	D (0.2)	A (1.2)	C (1.2)	B (0)
Truck	73.2m	A (0.8)	D (1.4)	C (0.4)	B (0)

DEVELOPMENT OF LABORATORY RETROREFLECTIVITY TEST METHODS

The second aspect of this study was the development of laboratory retroreflectivity test methods to measure the coefficient of retroreflected luminance (specific luminance, or R_L) (ASTM D 4061-89) of pavement markings using the actual optical geometries from the night viewing.

As previously mentioned, the driver's eye height and distance behind the headlight were measured for each observer in the car and truck. The height of the center of the headlight above the ground was 66 cm for the Taurus and 114 cm for the Mack Truck. The eye height above the center of the headlight averaged 47 cm ± 2.8 cm for the Taurus and 112 cm ± 2.8 cm for the truck. The displacement of the eye behind the headlight averaged 225 cm ± 4.6 cm for the Taurus and 92 cm ± 2.0 cm for the truck.

These vehicle dimensions were used to calculate the photometric geometries during the night viewing. Table 2 gives the calculated angles using intrinsic geometry (ASTM E 808-91) to the center of each stripe for both vehicles.

The right-hand column of Table 2 gives the illuminance of each vehicle's headlight at each distance. This is the intensity of light striking an object from the vehicle headlight at that distance. A photometric range was used to make the measurements (*3*).

Measurements of R_L (coefficient of retroreflected luminance) were then made at the angles of Table 2 using a photometric range. The results for both vehicles are presented in Table 3.

The measurements of R_L in Table 3 were then multiplied by the illuminance of the headlight at each geometry in Table 2. The data for each headlight were then added together to obtain the total luminance (L) of each marking as seen by the driver. The results are given in Table 4.

Table 4 indicates the same changes in relative rankings as a function of distance as the night viewing data in Table 1. Only at 12 m in the car did the luminance measurements fail to order the materials as seen by the night viewing subjects, yet even here agreement is reasonable. It is very likely that because 12 m is such a short distance to view pavement marking materials, factors other than R_L may be influencing the driver's perception. It is also possible that because the luminance is so high at close observation distances, the eye is essentially desensitized and unable to detect differences in retroreflectivity.

Despite the truck's being disadvantaged in terms of observation angle, at large distances the observers in the truck had equal or higher retroreflected light available. This was shown by the fact that no subject viewed only one of the test lines at any distance. The reason for this appeared to be related to the intensity of the headlights on the truck.

As mentioned previously, several of the subjects were unable to view Products B and C at 73 m in the car. Using Table 4 it appears that a luminance value of 50 to 60 mcd/m² is close to a threshold value for pavement marking visibility.

TABLE 2 Intrinsic Angles for a Ford Taurus and a Mack Truck

INTRINSIC ANGLES FOR A FORD TAURUS						
Distance (meters)	Headlight	Observation (Deg)	Entrance (Deg)	Presentation (Deg)	Orientation (Deg)	Headlight Illumination (Lux)
12.2	Left	1.33	87.47	-4.44	-174.9	4.60
12.2	Right	5.07	87.50	74.36	-169.9	4.07
24.3	Left	0.87	88.66	-16.33	-177.3	0.873
24.4	Right	2.58	88.66	70.57	-174.6	1.02
48.8	Left	0.52	89.30	-21.36	-178.6	0.185
48.8	Right	1.29	89.31	67.90	-177.2	0.211
73.2	Left	0.37	89.53	-22.91	-179.1	0.0874
73.2	Right	0.86	89.53	66.87	-178.1	0.0771
INTRINSIC ANGLES FOR A MACK TRUCK						
12.2	Left	4.05	85.46	3.84	-175.6	1.42
12.2	Right	7.81	85.53	57.94	-169.2	0.969
24.4	Left	2.30	87.59	1.97	-177.7	2.17
24.4	Right	4.21	87.6	56.55	-174.3	1.83
48.8	Left	1.23	88.76	1.00	-178.8	0.379
48.8	Right	2.18	88.76	55.57	-177.0	0.384
73.2	Left	0.84	89.16	0.67	-179.2	0.152
73.2	Right	1.47	89.16	55.19	-178.0	0.123

TABLE 3 Coefficient of Retroreflected Luminance ($mcd/m^2/lx$)

			Preformed Tape Sample			
Vehicle	Distance	Headlight	A	B	C	D
Taurus	12.2m	Left	784	364	997	908
Taurus	12.2m	Right	193	244	257	341
Taurus	24.4m	Left	796	347	665	755
Taurus	24.4m	Right	357	305	334	571
Taurus	48.8m	Left	1080	308	412	619
Taurus	48.8m	Right	736	371	379	728
Taurus	73.2m	Left	1330	269	308	516
Taurus	73.2m	Right	1100	422	418	791
Truck	12.2m	Left	270	189	450	393
Truck	12.2m	Right	117	153	184	190
Truck	24.4m	Left	477	245	584	558
Truck	24.4m	Right	217	214	294	337
Truck	48.8m	Left	700	292	572	640
Truck	48.8m	Right	399	271	373	542
Truck	73.2m	Left	868	310	518	630
Truck	73.2m	Right	596	313	380	606

TABLE 4 Luminance of Pavement Marking Samples (mcd/m^2)

		Preformed Tape Sample			
Vehicle	Distance	A	B	C	D
Taurus	12.2m	4390	2670	5640	5570
Taurus	24.4m	1060	615	921	1240
Taurus	48.8m	354	135	157	282
Taurus	73.2m	200	56.0	59.2	106
Truck	12.2m	497	417	818	743
Truck	24.4m	1430	923	1804	1830
Truck	48.8m	418	215	360	450
Truck	73.2m	205	85.3	125	170

In an effort to quantify the correlation, the common logarithm of the luminance value for each product in Table 4 was plotted against the cumulative rankings from Table 1. For example, the log(luminance) of Products B, C, A, and D for the car at 12.2 m was plotted against the cumulative rankings of 0, 0 + 1.5, 0 + 1.5 + 0.2, and 0 + 1.5 + 0.2 + 0.7. The results for the car and truck are presented in Figures 1 and 2, respectively. A correlation was taken to exist if the luminance of the marking increased as the cumulative ranking increased, that is, if the graph had a continuously positive slope. No mathematical analysis of the data was performed, and no mathematical relationship was assumed. As can be seen, excellent correlation exists for both vehicles at 24.4 m and beyond. At 12.2 m for the truck the overall rankings as predicted by luminance values matches with subject perception, but the correlation is not as strong as at the greater distances. At 12.2 m in the car the correlation is poorest.

CORRELATION OF VISUAL OBSERVATIONS TO COMMON TEST GEOMETRIES

The third purpose of this experiment was to compare the nighttime visual observations with commonly used retroreflectivity test geometries. Table 5 gives the photometric angles of the various test methods used in the industry throughout the world. The test geometries given represent common laboratory test methods as well as geometries used in portable instrumentation.

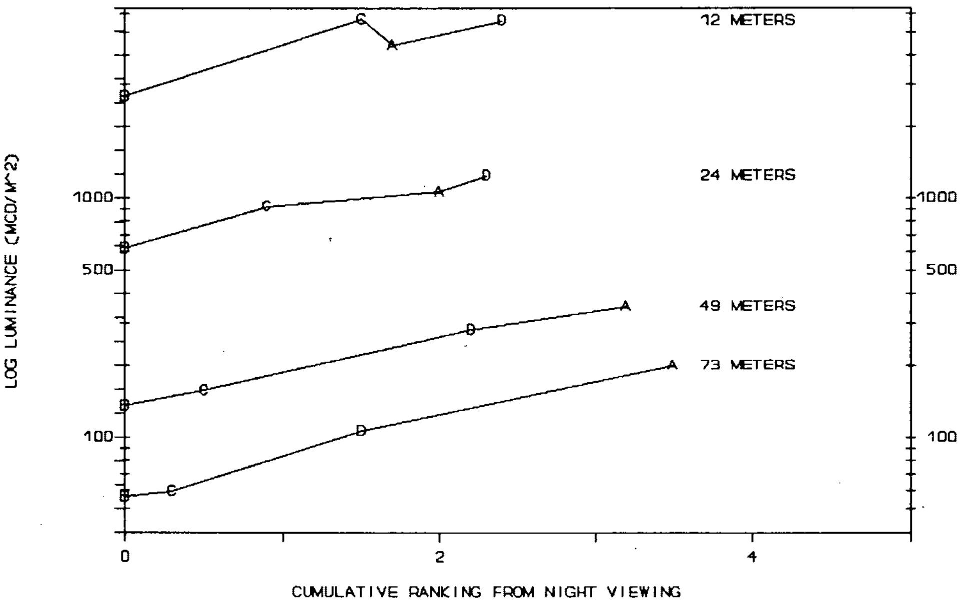

FIGURE 1 **Correlation of luminance with cumulative ranking for a Taurus.**

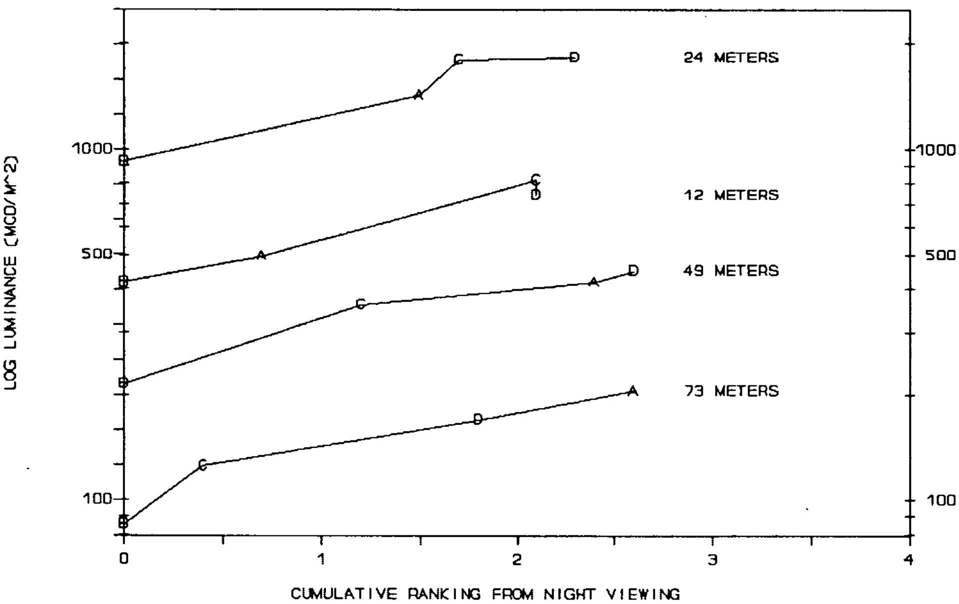

FIGURE 2 **Correlation of luminance with cumulative ranking for a Mack Truck.**

Table 6 gives the values of R_L at the photometric angles of Table 5 for each of the four products used in the night viewing. The samples were measured in a photometric range.

Graphs similar to Figures 1 and 2 were prepared for each of the common test geometries to determine whether there was a relationship to the visual observations. A geometry was stated to correlate with observation if measurement values of products increased as product ranking increased, that is, if the slope of the graph was continuously positive. Table 7 summarizes at what distance a specific test geometry correlated with the visual observations of Table 1. A question mark following a specific distance means that the correlation was not perfect; that is, the order of the products as measured by R_L at that geometry did not exactly match the order as ranked by the observers. No geometry correlated well at both short and long distances for either vehicle. In general, only one geometry correlated well at long distances for both vehicles. That geometry has an entrance angle of 89.3 degrees and an observation angle of 0.63 degrees.

CONCLUSIONS

Four different white pavement marking tapes were viewed by 12 subjects as isolated center skip lines at 12.2, 24.4, 48.8, and 73.2 m from the front of an automobile and semitruck

TABLE 5 Commonly Used Pavement Marking Test Geometries

	Intrinsic Geometry (Degrees)			
Instrument/ Test Method	Entrance (Beta)	Observation (Alpha)	Presentation (Gamma)	Orientation (Omega)
ASTM D 4061-89	86.0	0.2	0.0	180
ASTM D 4061-89	86.0	0.5	0.0	180
Ecolux	86.5	1.0	0.0	180
Mirolux	86.5	1.5	0.0	180
ART LLR IV	88.5	1.0	0.0	180
CEN	88.8	1.05	0.0	180
LTL800	89.3	0.63	0.0	180

TABLE 6 Coefficient of Retroreflected Luminance at Common Geometries

Intrinsic Geometry (Degrees)				Preformed Pavement Marking Sample			
Beta	Alpha	Gamma	Omega	A	B	C	D
86.0	0.2	0.0	180	1820	726	3950	2310
86.0	0.5	0.0	180	1400	586	2790	1830
86.5	1.0	0.0	180	1010	479	1720	1420
86.5	1.5	0.0	180	781	394	1240	1150
88.5	1.0	0.0	180	900	473	1060	1050
88.8	1.05	0.0	180	869	444	900	957
89.3	0.63	0.0	180	1170	571	887	1080

TABLE 7 Correlation of Common Geometries with Observed Ranking

Intrinsic Geometry (Degrees)				Distance that Correlates (meters)	
Beta	Alpha	Gamma	Omega	Taurus	Truck
86.0	0.2	0.0	180	none	none
86.0	0.5	0.0	180	none	none
86.5	1.0	0.0	180	none	12?
86.5	1.5	0.0	180	none	12
88.5	1.0	0.0	180	none	12,24?
88.8	1.05	0.0	180	12?	24
89.3	0.63	0.0	180	49,73	49?73

cab. Differences between the brightness of the four products were observed. The relative rankings of the four products from brightest to dimmest were found to be a function of both distance and vehicle type.

The retroreflectivity of the four pavement marking tapes was measured using common test method geometries. The four tapes were found to have greatly different retroreflectivities depending on the method or equipment used. The relative product rankings of retroreflectivity by many test methods was found not to correlate with the relative brightness rankings assigned by the subjects. Whereas a few of the common retroreflectivity test methods produced rankings similar to those of the subjects at specific distances, no one method was effective at ranking the relative product brightness under all viewing conditions.

Because of the changes in order of ranking of the products with distance and vehicle type, it appears that current instrumental methods are inadequate for ranking retroreflective differences between different classes of products. Current instrumental methods for measuring retroreflective brightness may have some value in monitoring variability within a single product, as well as monitoring changes in that product's performance throughout its useful life; however, this remains to be established.

When laboratory darkroom measurements of pavement marking retroreflectivity were made at actual driver geometries at the distances used in the human viewing experiment, excellent correlation was observed. It is now possible to predict relative brightness performance of unworn pavement marking stripes under static viewing conditions with laboratory measurements at appropriate geometries.

ACKNOWLEDGMENTS

The authors of this paper would like to express sincere appreciation to the 12 subjects who participated in the night viewing experiment. The authors are particularly indebted to the following for all their help during the experiment and in the subsequent analysis and generation of data: Tony Dang, Mary Anne Dibelka, Sithya Khieu, and Trent McKay.

REFERENCES

1. T. L. Harrington and M. D. Johnson. An Improved Instrument for Measurement of Pavement Marking Reflective Performance. *Highway Research Board Bulletin 336*, HRB, National Research Council, Washington, D.C., 1962.
2. J. L. Ethen and H. L. Woltman. Minimum Retroreflectance for Nighttime Visibility of Pavement Markings. In *Transportation Research Record 1093*, TRB, National Research Council, Washington, D.C., 1986, pp. 43–47.
3. N. L. Johnson. The Photometry of Retroreflectors Using a Computer-Controlled Four-Axis Goniometer. *Color Research and Application*, Vol. 7, No. 4, 1982, pp. 319–326.

Publication of this paper sponsored by Committee on Coatings, Signing and Marking Materials.