Relative Luminance of Retroreflective Raised Pavement Markers and Pavement Marking Stripes on Simulated Rural Two-Lane Roads

John A. Molino
SAIC/FHWA
6300 Georgetown Pike, F-215
McLean, VA 22101
Phone (202) 493 3381; Fax (202) 493-3390
John.A.Molino@saic.com

Kenneth S. Opiela
FHWA
6300 Georgetown Pike, T-301
McLean, VA 22101
Phone (202) 493-3371; Fax (202) 493-3417
Kenneth.Opiela@fhwa.dot.gov

Carl K. Andersen
FHWA
6300 Georgetown Pike, T-301
McLean, VA 22101
Phone (202) 493-3366; Fax (202) 493-3417
Carl.Andersen@fhwa.dot.gov

M. Joseph Moyer
FHWA
6300 Georgetown Pike, T-210
McLean, VA 22101
Phone (202) 493-3370; Fax (202) 493-3417
Joe.Moyer@fhwa.dot.gov

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ABSTRACT

The Federal Highway Administration’s (FHWA) Turner Fairbank Highway Research Center (TFHRC) is undertaking a research program to study the visibility of retroreflective raised pavement markers (RRPMs). The focus of the initial effort is to determine the relative luminance of RRPMs and pavement markings (PMs) needed to produce adequate guidance on rural two-lane roadways at night. A driving simulator was used to test 36 research participants as they drove simulated roadways containing various combinations of RRPMs and PMs. The luminance of the simulated roadway delineation ranged from 0.07 to 4.1 candelas per square meter. The primary driver performance measure was curve recognition distance. For the various RRPM and PM luminance conditions mean curve recognition distances ranged from 19.0 meters (62.3 feet) to 68.4 meters (224 feet), with a grand mean of 43.0 meters (141 feet). Regression analyses produced predictive equations to estimate the mean curve recognition distance from the luminance of RRPMs acting alone or of PMs acting alone. Trading ratios were computed for PM luminance with and without RRPMs present on the road. A conservative empirical estimate of 0.52 was computed for such a trading ratio based on the data from the current experiment. This value compared favorably with independent estimates of 0.54 and 0.55 based on an earlier analytical approach. Thus the current experiment confirmed with empirical data earlier estimates that it might be possible to reduce the luminance of PMs on rural two-lane roads by about 45 percent when appropriate RRPMs are installed.
INTRODUCTION

The Federal Highway Administration’s (FHWA) Turner Fairbank Highway Research Center (TFHRC) is conducting a multi-staged research program to study human factors issues associated with the use of retroreflective raised pavement markers (RRPMs). Over the long term, this program will address various applications of RRPMs, the potential for enhancements to these devices, and assessments of their relative role in delineation systems. The current paper describes an initial effort aimed at determining the importance of the relative luminance for RRPMs and for pavement marking (PM) stripes for providing basic roadway visibility at night. A question arose from efforts to establish minimum retroreflectivity requirements for pavement markings: How much can the retroreflectivity of roadway PMs be reduced if RRPMs of a certain retroreflectivity are installed on the road?

Neither RRPMs nor PMs are inherently luminous sources. They both reflect incident light from the vehicle headlamps back to the driver. Thus tradeoffs in the relative effectiveness of RRPMs and PMs (either paints or tapes) are usually expressed in terms of changes in the coefficient of retroreflectivity. In a driving simulator with a projection screen the RRPMs and the PMs are both rendered as extended luminous sources. In this case the RRPMs and PMs are best compared in terms of their relative luminance. In the current paper, for the sake of simplicity RRPMs and PMs are measured and compared in terms of their luminance. The term “luminance” is applied to measurements of RRPMs and PMs alike, although when referring to RRPMs in real environments “luminance” should be read as “luminous intensity.” In the simulator, point sources of light cannot be easily reproduced by a projector and screen.

Previous Studies

Only limited efforts have been made to investigate the influence of improved pavement markings and RRPMs on driving behavior. There have been several analytical studies of driver luminance needs by Zwahlen, Schnell, Chrysler, Farber, and others (2,3,4,5,6,7). These studies and others have shown that RRPMs increase the preview time for drivers to aid them in the driving task, particularly when driver visibility is reduced in rain or fog. These studies provide a scientific basis for understanding the effect of differences in the visibility of PMs and RRPMs.

There are various means to conduct controlled driver behavior research. Driving simulators have proven to be useful in this regard, and several studies have employed them. Research by Allen, et al. in the late 1970’s investigated the effects of contrast and configuration of PMs on driver performance and behavior (8). The focus of this study for the FHWA was to determine how much the reflected luminance of yellow PMs could be reduced without degradation of their ability to provide necessary guidance to the driver. This effort utilized both driving simulation and field observation methods. It did not consider RRPMs, but demonstrated that a driving simulator could provide useful driver performance data. In another simulation study, McKnight et al. investigated the effects of line width and contrast on lane keeping (9). They found that both variables only had an effect at very low contrast ratios.

Research performed a decade later by Freedman et al. for the FHWA investigated the noticeability requirements for delineation on non-illuminated highways (10). This research investigated delineation systems (which included RRPMs) using static laboratory tests, an earlier version of the FHWA simulator, and field observations. The specific effects of RRPMs could not be isolated, yet other important insights were gained as well as experience in using the driving simulator for studies of RRPMs and PMs.

In a recent study by Bloomfield et al., the effects of spacing, reflectivity, and location of RRPMs were analyzed using a driving simulator (11). Twenty-four research participants were tested to determine whether changes in recognition distance, lane-keeping, and speed control could be observed as the spacing, placement, and/or reflectivity of the devices were changed. The results of that study showed that recognition distances for curves and intersections generally improved with closer spacing and increased luminance of RRPMs.
Luminance Trading Relationships

If RRPMs are installed on a given roadway, it is possible that the luminance requirements of the PMs could be reduced and still achieve adequate visibility on the road. Such a reduction in PM luminance requirements could save some of the costs of repainting or re-striping the PMs by extending the maintenance cycle without sacrificing public safety. The question is, if RRPMs of a certain luminance are installed, by how much may the luminance of the PMs be reduced and still achieve the same level of driving performance? Zwahlen (12) estimated the possible reduction in PM luminance that could be tolerated if RRPMs were installed on a road. He estimated this potential luminance trading relationship by using the Computer Aided Road-marking Visibility Evaluator (CARVE) model, and assuming preview times of 3.65 seconds for roadways without RRPMs and 2.0 seconds for roadways with RRPMs.

These estimates derived by Zwahlen were modified and incorporated, along with other considerations, into a set of suggested retroreflectivity values for determining the useful service life for pavement markings (13). Since for the appropriate geometry retroreflectivity and luminance are proportional, the retroreflectivity values suggested by Migletz et al. may be used to infer possible luminance trading ratios. These data lead to suggested ratios of PM luminance without RRPMs to PM luminance with RRPMs on non-freeway roads. For the yellow center lines these suggested ratios are 0.54 for lower speeds (<40 mph) and 0.55 for higher speeds (>45 mph), respectively. However, these estimates are based on analytical studies without adequate confirmation from empirical human performance data.

Note that the current experiment does not purport to establish potential reductions in the required coefficient of retroreflected luminance ($R_L$) for PMs, based upon some value of the coefficient of luminous intensity ($I_L$) for RRPMs. Rather, it provides insights into the interaction of the visual stimuli provided by PMs and RRPMs of varying luminance. Given the intricate geometries involved in measurements of $R_L$ and $I_L$, further research would be needed to establish a precise quantitative relationship between these two metrics and the luminance of the visual stimuli observed by the drivers in the current simulator experiment.

METHOD

The current experiment was directed at empirically exploring the trading relationship between the luminous intensity of RRPMs and the luminance of PMs using human driving performance measures. The primary driver performance measure was curve recognition distance, although vehicle speed and vehicle lane position were also recorded. The experiment was conducted in a dark environment with dark adapted drivers, so the results should not be generalized to lighted roads, or to unlighted roads in areas with high ambient illumination.

Research Participants

Research participants were recruited from the area surrounding McLean, Virginia from newspaper advertisements, local bulletin boards, by word of mouth, and from a list of interested participants previously used in other FHWA studies. Each research participant possessed a valid U.S. driver’s license and passed a locally administered vision test. The criterion for passing the vision test was at least 20/40 visual acuity in each eye (corrected if necessary). The 36 research participants were divided into three age groups of 12 participants each: younger drivers (age 18 to 30 years), middle-age drivers (age 31 to 64 years) and older drivers (age 65 years and above). These age groups contained equal proportions of male and female participants (6 of each gender). The experiment took about 3 hours to complete. Each participant was paid $100 upon successful completion of the study. The experiment was conducted in a dark laboratory environment. Each research participant was dark adapted to the environment for at least...
15 minutes before driving in the simulator. Red photographic lighting that did not interfere with dark adaptation was provided for moving about the laboratory room during breaks.

Driving Simulator

The experiment was conducted in the FHWA fully interactive High Fidelity Highway Simulator (HYSIM) located at the TFHRC. The simulator consists of a 1998 Saturn SL sedan car cab mounted on an electronically actuated motion base. Since all driving scenarios involved straight driving at constant speed, the motion base was turned off for the current simulator experiment. A loudspeaker system provided engine and roadway noise. A curved projection screen in front of the car cab provided a potential 270-degree field of view of a simulated roadway environment. Since the perceptual task involved recognizing curves on a straight roadway segments, the horizontal field of view in the current experiment was limited to 88 degrees, with a vertical field of view that covered the entire windshield. A rear projection screen was provided for rear and side-view mirror scenes but was not employed in the current experiment. The computer graphics were created by an SGI ONYX2 Infinite Reality Engine, running Multigen Creator and Performer software. The visual scenes were projected by an Electrohome 9500 video projector with a resolution of 1920 X 1200 pixels refreshed at a 60-Hertz frame rate.

Roadway Scenarios

The visual scenarios consisted of straight segments of simulated roadways containing different delineation treatments. These roadway scenes usually led to curves. The research participants drove these scenarios at either 35 or 55 miles per hour. The simulated roadway was composed of a textured roadway surface with tire mark patterns and represented a two-lane rural highway with 12-foot lane widths. The roadway contained two kinds of curves: a 6 degree curve for the 55 mph condition and a 10 degree curve for the 35 mph condition. The RRPMs were vertically oriented yellow polygons about 4 inches wide and 2 inches high in scale. They had emissive material attributes and were located in a single row down the center of the two yellow roadway center lines. The RRPMs were spaced 80 feet apart in the tangent segments and 40 feet apart in the curves. The PMs were flat shaded polygons about 4 inches wide in scale. Both the RRPMs and the PMs were saturated colors, either yellow or white as appropriate.

From the high luminance to the low luminance conditions, the delineation treatments represented the brightest and dimmest polygons possible to generate with the current simulator hardware and software. The luminance levels for the RRPMs and PMs are shown in Table 1. A crude headlight illumination pattern was established for the PMs whereby the white right edge line had the highest relative luminance, the two yellow center lines had the next highest and the white left edge line had the least. This relative weighting simulated the right-side bias of proper headlight alignment. Since the yellow RRPMs and the yellow center lines form the focus of the trading relationships under investigation, the PM luminance refers to measurements of either center line (they were equal), and not of either edge line.

Two simulated lighting conditions represented a dark overcast Night Scene and a totally Black Background. The Night Scene had no direct illumination, a dark green textured grass ground, a gray/black textured road, a dark blue sky, and a visible horizon line. The Black Background was totally dark. It had no visible features whatsoever besides the roadway delineation, either RRPMs or PMs, or both. The tangent straight roadway segments were 9, 11, 13 and 15 seconds long at the instructed driving speed. They were uniformly distributed over the range from 9 to 15 seconds with an average of 12 seconds.

Procedure

A certain combination of RRPM and/or PM luminance was simulated on a rural two-lane roadway segment. This roadway segment began as a straight (tangent) roadway segment that, in most cases, turned either to the right or to the left after a short distance. The research participant drove the simulator vehicle
along this simulated straight roadway until she/he detected a curve and could recognize whether the curve turned to the right or to the left. At that point the research participant pressed one of two response buttons located on the steering wheel in the car cab. One button was located on the right side of the steering wheel and the other button was located on the left side, at approximately the 10 and 2 o’clock positions. The participant pressed the button that corresponded to the perceived direction of the curve ahead.

At the instant the research participant pressed one button or the other, the scenario shifted to the next trial. Next, the research participant drove down a new straight roadway segment, in most cases with a curve located some random distance down the roadway. If the research participant failed to recognize the curve before the center of mass of the vehicle was over the beginning of the curved road segment, the current roadway segment automatically switched to the next segment as described above. A 0.3 second tone was presented each time the roadway segment was switched for whatever reason. The tone was high pitched if the participant’s response was correct, and low pitched if the response was incorrect. There were a few roadway segments that did not lead to any curve. These served as blank trials. In these cases, the scenario changed to the next roadway segment without any response from the research participant once the simulator vehicle reached the end of the tangent roadway segment.

**Experimental Design**

A single block of experimental conditions consisted of 16 different combinations of luminous intensity levels for the RRPMs and luminance levels for the PMs. The 16 combinations were derived from the matrix formed by crossing None, Low, Medium and High luminance levels for the RRPMs and the PMs. In addition, there were two varieties of pavement markings. In one variety, there was a double yellow centerline down the center and a single white edge line on each side of the roadway. In the other variety there was only a double yellow centerline and no markings on the roadway edges. Thus, there were a total of 16 X 2 (or 32) roadway delineation treatments in the current experiment. Each block of 32 roadway delineation treatments was presented by one of four combinations of environmental lighting and instructed driving speed. The environmental lighting conditions consisted of the Night Scene and the Black Background described above. The instructed driving speeds were either 35 or 55 miles per hour.

The “None” condition for PMs applied only to the yellow center lines in cases where there were white edge lines present. In PM-None conditions, the white edge lines were present at High, Medium and Low luminance levels corresponding to the accompanying intensity categories of the RRPMs, when RRPMs were present. In the None-None condition, where RRPMs were not present, edge lines were present but only at the Low luminance level. Thus, the luminance of the edge lines was always yoked to the luminance of other roadway delineation elements, and was not varied independently like the luminance of the RRPMs and PMs.

Altogether, there were 32 roadway delineation treatments and four driving parameters in the experiment -- a total of 128 conditions. Each research participant was presented with each experimental condition two times for a total of 256 trials. In addition, there was one blank trial with no curve out of every 16 trials, resulting in a total of 272 trials for each participant in the experiment. The trials were organized into blocks of 68 trials at a given combination of speed and lighting condition. Thus each research participant completed four blocks of 68 trials, plus a block of 68 practice trials at the beginning of the experiment.

**Calibrations**

The luminance of the RRPMs, PMs and background was measured by means of a Pritchard PR 880 Photometer. The Photometer calibration was traceable to the National Institutes of Science and Technology. RRPMs and PMs were measured at the near position on the roadway where they were large in size in comparison to the 0.125-degree aperture in the Photometer. The average results of these calibrations for the luminance of the RRPMs and PMs may be found in Table 1. The mean PM luminance
measurements refer to the center lines, not to the edge lines. The average luminance of the roadway surface was about 0.0074 candelas per square meter, yielding a contrast ratio of about 10 to 1 with the lowest luminance level of pavement marking (0.07 candelas per square meter).

In order to document the overall stability of the projection system, detailed calibrations were made at the beginning and end of the experiment. Multiple luminance measurements were taken at different locations on the projection screen and averaged. The transmissivity of the windshield was not included in reported luminance values. Thus all reported luminance values should be reduced by about 33 percent to obtain the luminance as measured at the eye of the driver. A separate survey photometer was employed every day to measure projector performance and stability over the duration of the testing.

RESULTS

The overall results of the experiment are shown in Table 2, which summarizes 9,216 measurements. The mean curve recognition distance in meters is given along with the standard error of the mean (in parentheses). Each mean represents the central tendency of 576 measurements across all research participants -- both lighting environments and instructed driving speeds. The small standard errors indicate that differences in mean curve recognition of more than about 4 meters are likely to be significant. Blank trials have been eliminated since no curves were present. The range over all measurements was from 0 meters for a minimum (missed the curve) to 539 meters (1,725 feet) for a maximum (probably a guess or an error). The grand mean over the entire matrix was 43.0 meters (141 feet). The data was also analyzed eliminating all missed curves, errors and guesses. In this instance, a guess was defined as any curve recognition distance of greater than 180 meters, which is the maximum distance at which the best-trained observer on the laboratory staff could recognize a curve under optimal (bright) conditions. These analyses on cleansed data were only slightly different from the analyses performed on all of the data. With 9,216 measurements the data proved highly resistant to noise, and subsequent analyses were performed on the entire data set without any cleansing.

Primary Effects

An analysis of variance on all of the curve recognition data revealed statistically significant main effects for PM luminance ($F(3,6) = 52.37, p<0.001$), RRPM luminance ($F(3,6) = 32.61, p<0.001$), and the age group (young, middle or old) of the research participants ($F(2,9) = 17.65, p<0.001$). There were several statistically significant interactions, but all of these accounted for a much smaller proportion of the variance than the main effects and were difficult to interpret. For all statistical tests, the alpha level was 0.05.

For both RRPM and PM luminance, higher luminance levels were associated with longer curve recognition distances. Examination of the None conditions reveals that the PM luminance had a somewhat stronger effect on recognition distance than the RRPM luminance. The shortest mean curve recognition distance was of 19 meters (62 feet) was for the None-None condition, where there were no RRPMs or PMs to guide the driver. The longest mean distance was 68.4 meters (224 feet) for the High-High condition, where both the RRPMs and the PMs were at their highest luminance (brightest) levels. Examination of the entire Table reveals an additive effect of RRPM and PM luminance, establishing the basis for possible trading relationships between the two variables with fractional coefficients applied to one or both of the contributing factors. The nature of the RRPM and PM luminance effects is portrayed in Figures 1 and 2. Figure 1 shows the RRPM luminance effect with PM luminance as the parameter. Figure 2 shows the PM luminance effect with RRPM luminance as the parameter. Error bars represent 95 per cent confidence intervals around each mean. The luminance levels are expressed as common logarithms, with zero being assigned a value of minus two. This value was close to the average luminance of the roadway without any delineation (-2.13 log candelas per square meter). The logarithmic
transformation was consistent with the general ratio nature of sensory processes, and reduced variance in subsequent regression analyses.

The effect of the age group of the participants was examined by conducting three separate analyses of variance, one for each age group. As expected the RRPM and PM luminance produced strong and significant effects for all three age groups. Overall, in matrices analogous to Table 1, the younger age group had the longest mean curve recognition distances, ranging from 23.69 to 80.28 meters; the older age group had the next longest mean distances, ranging from 17.93 to 64.40 meters; and the middle-age group had the shortest mean distances, ranging from 15.38 to 60.36 meters. The grand means for each of the three matrices were computed along with the 95 percent confidence intervals around those means. The results provided further insight into the magnitude of this age effect. In order of decreasing mean curve recognition distance, for the younger participants the grand mean was 51.69 meters (50.66<M<52.71); for the older participants it was 40.25 meters (38.57<M<41.92); and for the middle-age participants it was 37.05 meters (35.95<M<38.15). Thus the younger participants had greater curve recognition distances than the older and middle-age participants, whose means were close and whose standard errors almost overlapped. This result was expected given the anticipated more sensitive sensory and perceptual capabilities of the younger group, as confirmed on their individual visual acuity tests administered before the current experiment.

Secondary Effects

With curve recognition distance as the dependent variable, additional analyses revealed that the effects of environmental lighting (Night Scene vs Black Background), instructed driving speed (35 vs 55 miles per hour) and white edge lines (With Edge Lines vs Without Edge Lines) were all small and/or not statistically significant. With vehicle speed as the dependent variable, instructed driving speed had a powerful and statistically significant effect (F (1,2) = 1272, p<0.001), as might be expected, but all other major independent variables (RRPM luminance, PM luminance and age group) had a small and/or not statistically significant effect. In this case vehicle speed was measured as the single sample of speed at the instance of the curve recognition response on each trial. Since the participants never drove through the curved segment of the roadway in the current experiment, speed refers to driver performance in the tangent section of the roadway, not in the curve. When instructed to drive at 35 miles per hour, the sample of participants drove at an average speed of 36.3 miles per hour. When instructed to drive at 55 miles per hour, they drove at an average speed of 55.9 miles per hour.

Lateral lane position was measured as the normal (90 degree) distance from the center line of the road to the center of gravity of the vehicle in meters, again sampled only once per trial at the instance of the curve recognition response. Thus, as with speed, lateral position refers to driver performance in the tangent section of the roadway, not in the curve. The grand mean for lateral lane position was 1.85 meters, which, for a roadway width of 3.66 meters (12 feet), placed the vehicle on the average almost exactly in the middle of the travel lane (1.83 meters). With lateral lane position as the dependent variable, the presence or absence of edge lines had the strongest effect (F (1,9200) = 195.2, p<0.001), the PM luminance had the next strongest effect (F (3,9200) = 37.26, p<0.001), and all other major independent variables (RRPM luminance, environmental lighting and age group) had a small and/or not statistically significant effect. Without edge lines the mean lane position was 1.93 meters, substantially to the right of the center of the lane. With edge lines it was 1.77 meters, slightly to the left of the center of the lane. The data for PM luminance revealed a steady progression of mean lane positions: None = 1.75, Low = 1.86, Medium = 1.88 and High = 1.91 meters. This progression was in the opposite direction from the edge line effect, however. The higher the PM luminance, providing more guidance to the driver, the more the mean lane position migrated to the right. In summary, the lateral position data revealed that the presence of edge lines contributed significantly toward improved lane keeping performance along the tangent roadway sections.
Regression Analyses

Regression analyses were conducted on the curve recognition distance data provided by the 36 research participants in the current experiment. In order to isolate the effects of each of the primary dependent variables (RRPM luminance and PM luminance) acting alone, regression lines were fit to the data in Figures 1 and 2 for the None condition of the parameter separating the curves. The logarithmic transform described above was employed on the luminance measurements to minimize variability and to conform to other psychophysical data. The None-None condition was eliminated from the regression analyses since no pavement marking at all represents a possible discontinuity in the luminance function for pavement delineation, and since the logarithmic value of zero luminance for delineation was arbitrarily set to minus two. Thus in Figures 1 and 2 only the data represented by the right most three points on the lowest curve in each plot were incorporated in the regression analyses.

From the aforementioned regression analyses, two predictive equations were developed to estimate the mean curve recognition distance from the luminance of either the RRPMs or the PMs acting independently on the roadway, i.e. where only RRPMs or only PMs are employed on the road, but not both. The predictive equation for estimating mean curve recognition distance when yellow RRPMs of a certain luminance are employed down the center of the roadway is

\[ \text{Recognition Distance in meters} = 13.26 \times \log(\text{RRPM Luminance in cd/m}^2) + 37.44. \]

Similarly, the predictive equation for estimating mean curve recognition distance when yellow PMs of a certain luminance are employed down the center of the roadway is

\[ \text{Recognition Distance in meters} = 30.89 \times \log(\text{PM Luminance in cd/m}^2) + 63.22. \]

From the slopes of these two predictive equations it is apparent that the PMs were more effective than the RRPMs in enhancing curve recognition distance in the current experiment. This result may seem inconsistent when one considers that the luminance levels of the RRPMs were between 3 and 10 times greater than the corresponding luminance levels of the PMs (see Table 1). However, the continuous PM stripes present a much greater luminous surface area than the small (2-inch x 4-inch) RRPMs spaced every 80 feet (every 40 feet in the curves). Thus, for the relatively low absolute levels of luminance and the restricted dynamic range of luminance that could be obtained in the simulator, the apparent superiority of the PMs over the RRPMs could be a reasonable outcome.

Luminance Trading Relationships

The predictive equations above, along with the data in Table 2 showing the combined effects of RRPMs and PMs acting together, may be used to determine quantitative luminance trading relationships between the two types of roadway delineation guidance. One of these potential trading relationships is particularly relevant for practical concerns in RRPM deployment. As indicated earlier, based on the work of Zwahlen (12), suggested ratios of PM luminance without RRPMs to PM luminance with RRPMs are 0.54 to 0.55 for yellow center lines on non-freeway roads. These ratios represent a possible reduction of PM luminance of about 45 percent with the addition of RRPMs to the roadway.

Equivalent ratios of PM luminance were computed from the results of the current experiment. The procedure was as follows: For each relevant cell in the original data matrix in Table 2 where there were combinations of PMs and RRPMs operating together, the curve recognition distance for the combined stimulus was identified. By using the second of the two predictive equations above, the PM luminance for the equivalent curve recognition distance was computed for the case where only PMs were operating. The PM luminance when acting in combination with the RRPM was then compared with this PM luminance when acting alone to yield the estimated ratio.
The results are shown in Table 3. From a practical perspective, the only cells that are relevant are those cells in the lower right section of the matrix, excluding the last row. In this lower right section, below the diagonal and excluding the last row, the RRPM luminance levels are relatively high and the PM luminance levels are somewhat lower. This is the situation of practical concern where relatively new RRPMs with high luminance values permit a reduction to lower luminance values for the PMs. The two cells for High RRPM and Medium and Low PM luminance levels are certainly relevant. They yield ratios of 0.23 and 0.21, less than half of the 0.54 and 0.55 ratios suggested earlier. This situation indicates that the PM luminance could be reduced by about 78 percent, instead of 45 percent as suggested earlier. However, this last column in the matrix represents cases with the highest RRPM luminance, characteristic of new, bright RRPMs. In fact the luminance of RRPMs diminishes considerably after only a few months of service (13). Thus a more conservative choice would be the Medium RRPM and the Low PM condition, which yielded a ratio of 0.52, extremely close to the ratios suggested earlier. This Medium RRPM trading ratio was also computed separately from the data for each age group. The results were: younger = 0.56, middle-age = 0.54 and older = 0.46. There was not much difference in the trading ratios for the younger and middle-age groups. However, in an unexpected outcome, the older participants could tolerate a somewhat more severe reduction in PM luminance of about 54 percent. In this case the conservative value would be the one required by the younger and middle-age groups.

DISCUSSION

The current experiment achieved its goal of empirically exploring the trading relationship between the luminous intensity of RRPMs and the luminance of PMs using human driving performance measures. Curve recognition distance in simulated driving scenarios served as the primary performance measure. The experimental methodology had the advantage of being able to test a large number of stimulus combinations in a short time (average trial duration = 12 seconds) under extremely controlled and repeatable laboratory circumstances. In a period of five weeks 9,792 trials were run, including blank trials. Stable mean curve recognition distances were determined with extremely small standard errors. The data also proved highly resistant to errors and noise. Previous trading ratio estimates were confirmed on how much the PM luminance requirements might be relaxed if RRPMs were installed on the road.

The same simulator technology which offered these strong advantages presented a number of fundamental limitations as well. For a psychophysical experiment on visibility at night one major deficit was the extremely limited visual dynamic range of the simulator and its inability to recreate intense point sources of light similar to real RRPMs. At a distance of 45.7 meters (150 feet), close to the grand mean curve recognition distance of 43.0 meters (141 feet) found in the current experiment, new RRPMs might be expected to produce a luminance of about 41.2 candelas per square meter, and new PM strip material (3M5730), a luminance of about 0.836 candelas per square meter (14). The corresponding Medium luminance values used in the current experiment were 1.39 and 0.10 candelas per square meter, much lower than those likely to be found in the field. Even the High luminance values used in the current experiment of 4.06 and 0.61 candelas per square meter, respectively, were below luminance estimates for RRPMs and PMs at about 150 feet in the field, although the PMs came close.

Thus the luminance values tested in the current experiment were much lower than those likely to be found in the field, especially for the RRPMs. Relative determinations such as the computation of certain trading ratios may be feasible under such circumstances. However, these low upper luminance limits seriously restrict inferences from absolute luminance values observed in the current experiment to their effects on driver behavior in real situations. Thus the absolute curve recognition distances in the current experiment may not correspond to those obtained with RRPMs and PMs of Low, Medium and High retroreflectivity in the field. However, with the application of appropriate scale factors obtained from parallel field studies, the relative tradeoffs in luminance obtained in the laboratory may be adjusted to predict actual effects on driver behavior in real environments. Therefore a parallel field study was conducted to validate some of the simulator data collected in the current experiment, and to develop scale...
factors to relate the current laboratory data to practical highway applications. The data from this field study are presently being analyzed.

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REFERENCES


TABLES AND FIGURES

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3. Table 3 PM Luminance Trading Ratios (Luminance with RRPMs / Luminance without RRPMs)
4. Figure 1. Curve recognition distance as a function of log RRPM luminance, with log PM luminance as the parameter.
5. Figure 2. Curve recognition distance as a function of log PM luminance, with log RRPM luminance as the parameter.
Table 1 Mean Luminance Values in cd/m²

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</tbody>
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* Arbitrarily set at 0.01 and –2.0 to conform to background luminance.
### Table 2 Mean Curve Recognition Distances in Meters and (Standard Errors of the Mean)

<table>
<thead>
<tr>
<th>PM Luminance</th>
<th>RRPM Luminance</th>
<th>None</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td></td>
<td>56.46 (1.49)</td>
<td>55.65 (1.26)</td>
<td>60.68 (1.24)</td>
<td>68.35 (1.54)</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>33.62 (1.22)</td>
<td>38.86 (1.47)</td>
<td>45.79 (1.68)</td>
<td>51.97 (1.30)</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td>27.08 (1.26)</td>
<td>31.60 (1.33)</td>
<td>36.91 (1.21)</td>
<td>49.18 (1.59)</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>19.00 (1.67)</td>
<td>29.81 (2.33)</td>
<td>34.15 (2.10)</td>
<td>48.81 (1.72)</td>
</tr>
</tbody>
</table>
Table 3 PM Luminance Trading Ratios (Luminance with RRPMs / Luminance without RRPMs)

<table>
<thead>
<tr>
<th>PM Luminance</th>
<th>RRPM Luminance</th>
<th>None</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.42</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td>0.37</td>
<td></td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td>0.77</td>
<td>0.52</td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Curve recognition distance as a function of log RRPM luminance, with log PM luminance as the parameter.
Figure 2. Curve recognition distance as a function of log PM luminance, with log RRPM luminance at the parameter.