Driver Lateral Control Performance as a Function of Delineation

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This project consisted of determining the optimal spacings for Raised Reflective Pavement Markers (RRPMs) along tangent sections and on interchange ramps of Interstate highways. Theoretical optimal spacings were first determined by using photometric calculations for the tangent sections, assuming clear and slightly degraded atmospheric conditions (rain intensity of 1 in./hr), and by using geometric calculations for the interchange ramps to determine the maximum driver viewing distance. As a result, optimal RRPM spacings of 25 and 120 ft were recommended for field evaluation for interchange ramps and tangent sections, respectively. Also included in this project was a test driver study using an instrumented vehicle to evaluate the recommended optimal RRPM spacings on dry and wet pavement in clear and slightly degraded atmospheric conditions. The tests were conducted at night on four unlit tangent sections (each 1 mi long) and on four unlit interchange ramps (each about 1,000 ft long with a 24 degree curve) of Interstate 70, east of Columbus, Ohio. Vehicle lateral lane position and speed maintenance were measured and analyzed for different RRPM spacings (for tangent sections at 60, 120, and 240 ft along the lane line, and no RRPMs; for ramps at 12.5, 25, and 50 ft along the outer edge line, and no RRPMs). On the basis of the results of this study, a maximum RRPM spacing of 120 ft for the lane line is recommended for tangent sections on Interstate highways, whereas no RRPMs are recommended for interchange ramps along Interstate highways.

Over the past few years, the Ohio Department of Transportation has invested a significant amount of resources in the implementation of a large-scale snow-plowable raised reflective pavement marker (RRPM) program. Because of the resultant increase in lane delineation, especially during night driving on wet pavement, the RRPM program has been accepted by motorists. The list of studies that show that the use of RRPMs benefits driver safety and performance is long, but so far no studies have been conducted concerning the optimal spacing and placement of RRPMs relative to driver visual requirements and lateral lane position control performance.

Recommendations for the implementation of RRPM systems have been compiled by the Signal Products Division of the Amerace Corporation. Criteria were suggested for marker placement, basic concepts of the RRPM system, function of the markers, proposed marker system and application, and placement of the RRPMs relative to paint lines and pavement joints. Although these recommendations provide a general and basic set of guidelines for the consistent application of RRPMs, they do not suggest specific spatial positioning or distance between markers. Although they recommend that for given applications the RRPMs should be spaced N (N stands for normal distance), $N/2$, or $N/4$ ft apart, these spacings were arbitrarily assigned and were not justified in an objective manner.

Because of the high cost of RRPMs, especially in northern states such as Ohio, where snow-plowable RRPM types are required, determination of the optimal marker spacing is important in the development of a cost-effective RRPM program. It was the objective of this study to determine and justify optimal spacings and placement schemes for RRPMs along tangent sections and entrance and exit ramps of Interstate highways in terms of driver visual information needs and lateral lane position control performance. Optimal in this sense meant that the particular RRPM spacing and placement scheme would be such that driver performance and driver safety for a certain set of selected conditions were at the borderline between satisfactory and unsatisfactory to minimize the relatively high life cycle cost of the RRPMs.

RESEARCH APPROACH

An analytical optimization of the RRPM spacings was conducted. First, to determine the driver preview distance, photometric calculations for the tangent sections and geometric calculations for the ramp sections were performed. Second, the expected lateral lane deviation was calculated as a function of the number of RRPMs visible to the driver. From the lateral lane deviation, the minimum number of RRPMs necessary for satisfactory driver performance was determined to be four. After consideration of the distance within which RRPMs must be placed to be visually detected by the driver (from photometric calculations for tangent sections and geometric calculations for ramps) and the determined minimum number of four RRPMs that must be presented within that distance, optimal RRPM spacings of 120 and 25 ft for tangent sections and ramps, respectively, were recommended for field evaluation.

Driver performance, determined from maintenance of lateral lane position and vehicle speed, was then experimentally evaluated for 11 test drivers along four unlighted tangent sections and four unlighted ramps of an Interstate highway on dry and wet pavement. Each of the following RRPM spacing schemes was tested on different tangent sections and on different ramps: no RRPMs, twice the optimal distance between RRPMs, the optimal spacing, or one-half the optimal distance between RRPMs.

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ANALYTICAL OPTIMIZATION

Tangent Sections

Photometric Calculations and Assumptions

Analytical optimization of the RRPM spacings was performed first to determine the theoretical optimal spacings for RRPMs along tangent sections and entrance and exit ramps of Interstate highways. Photometric calculations were made to determine the amount of headlight beam illumination that is reflected back to the driver's eyes from an RRPM ahead of the car at night as a function of the distance from the driver's eyes to the RRPM. These calculations were based on Allard's law, using the inverse square law twice because the light first travels from the source (the headlamp) to the reflector (the RRPM) and then back to the receptor (the driver's eyes). To obtain accurate results, many of the calculations were done separately for right and left headlamp beams. The following factors were taken into account in the determination of the amount of the headlamp beam illumination that is reflected back to the driver's eyes:

1. Candela output pattern of the headlamps
2. Car beam positions, in relation to
3. Driver eye position
4. All of the preceding in relation to
   a. RRPM position on the road
   b. Orientation of RRPM reference axis
   c. Orientation of RRPM datum axis
5. Specific intensity of the RRPM determined by
   a. Observation angle
   b. Entrance angle
   c. Presentation angle
   d Rotation angle
6. Transmissivity of the atmosphere

In the photometric calculations, evaluation of the specific intensity of the RRPMs under consideration in terms of the presentation and rotation angles proved to be beyond the scope of this study because of the vast number of possible combinations. Thus the RRPM photometric performance was based on observation and entrance angles only. The photometric calculations were performed with an interactive microcomputer-based software package under the following assumptions:

1. To assure that the driver has a comfortable preview time and that a change in direction (left or right curve) will be detected in a timely manner, at least four RRPMs should be visible to the driver.

2. On a straight and level Interstate highway with two lanes in each direction, the RRPMs are placed on the lane line only because of the high cost of snow-plowable RRPMs.

3. If it is assumed that the car travels in the center of the right-hand lane, which is 12 ft wide, then an RRPM will be 6 ft to the left of the car's longitudinal centerline.

4. Typical dimensions assumed for a small car and normal driver were 42 in. from the driver's eyes to the pavement in the vertical direction, 82 in. from the driver's eyes to the headlamps in the horizontal direction, 13.5 in. from the driver's eyes to the longitudinal centerline of the car, and headlamps spaced equidistant from the longitudinal centerline of the car at a distance of 24 in.

5. A uniform dark background with a luminance value of 0.01 foot-Lambert (fL) was assumed, corresponding to an illumination threshold value of 0.28493×10^{-8} foot candle (fc) for 98 percent detection of white point sources in the laboratory (clear, moonlight, and lower end of night driving range).

6. The headlamps and white RRPMs were assumed to be clean and operating at the prescribed output (100 percent), and the windshield was assumed to be clean, with a transmission factor of 1.

7. Finally, rain intensity of 1 in./hr was assumed.

Figure 1, compiled from U.S. Weather Bureau statistics *(1)*, shows the probability over an average 30-day period between

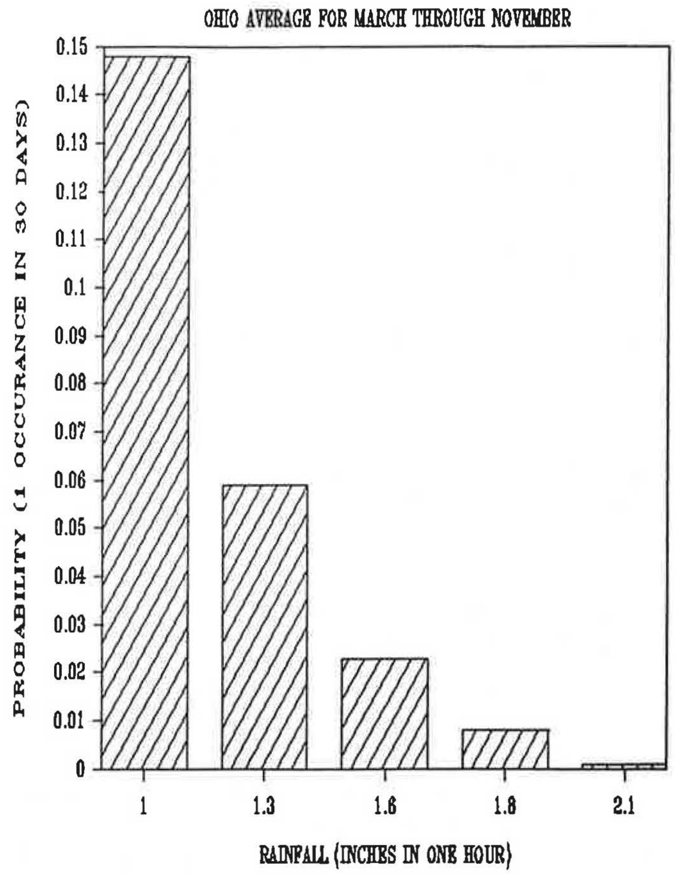

FIGURE 1 Probability of having a given average rainfall intensity for 1 hr over a 30-day period.

March and November (inclusive) for given amounts of rain in a 1-hr period. From the figure it can be seen that the probability of a rain shower within a 30-day period decreases rapidly as average rain intensities become heavier than 1 in./hr. For example, rainfall of 2.1 in./hr can only be expected once every 25 years, and rainfall of 2.6 in./hr can only be expected once every 100 years. Much as the civil engineers who design bridges and drainage systems for Interstate highways must draw a line in considering high-intensity rainfall and its duration to keep highway costs reasonable, so must highway engineers draw a line in considering the implementation of driver safety and performance devices on these highways. In the event of extremely intensive rainfall, it must be assumed that the driver adjusts speed and driving strategies accordingly. From Figure 2, using the relationships of Allen et al. *(2)*, transmissivity values of 0.89 and 0.99 for rain intensity of 1 in./hr and for clear atmospheric conditions, respectively, are obtained.

Recommended Spacing and Discussion

To provide a framework in which the small illumination values in foot-candles at a driver's eyes can be compared one-to-one

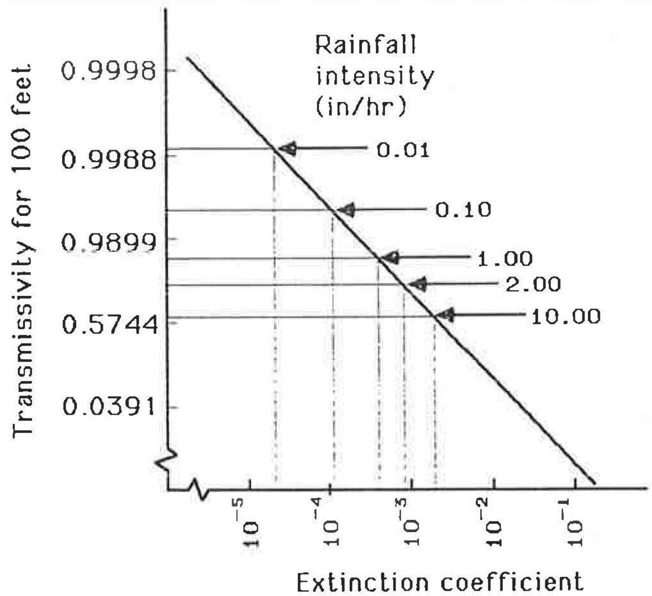

FIGURE 2 Extinction coefficients and transmissivities for given rainfall intensities.

with visual backgrounds that have different luminance levels and to relate the results to human visual detection performance, the results are expressed as multiples of threshold values—the number of times exceeding the normal human visual illumination threshold for 98 percent detection of a white point source. This concept was discussed by Zwahlen *(3)*, who suggested that for unexpected objects a threshold multiple of 1,000 will assure timely detection. In the case of RRPMs, where the driver has some idea about the location of the next RRPM and in many cases may actually be looking for it, a threshold multiple of about 30 can be considered adequate.

Figure 3 shows the results of the computer analysis of the quantity of illumination reflected back from the RRPM to the driver's eyes both for clear atmospheric conditions and rain intensity of 1 in./hr, at given threshold multiples, as a function of the RRPM distance ahead of the car. The candela output pattern for 6,052 low-beam headlamps aimed 2 degrees down and 2 degrees to the right was used for a driver driving in the right lane. The maximum distance for a threshold multiple of about 30 under a rain intensity of 1 in./hr is 480 ft with a threshold multiple of 29.6. By using the assumption of four RRPMs visible to the driver, the resultant RRPM spacing is 120 ft. The corresponding threshold multiple for clear atmospheric conditions for an RRPM at 480 ft is 79. If the specific intensity value of a new RRPM is reduced by 50 percent to account for wear during its life cycle and if the less

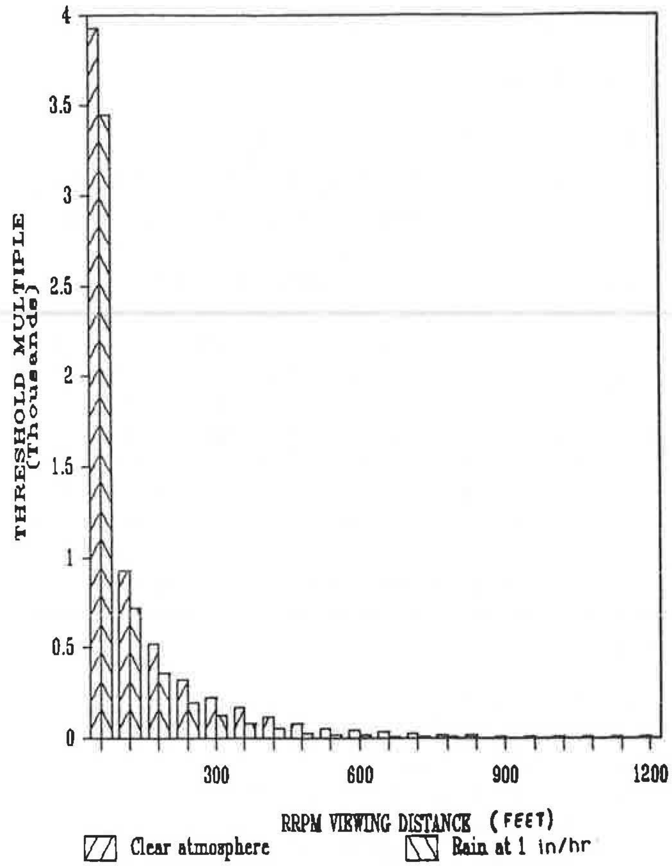

FIGURE 3 Threshold multiples of illumination reflected back to the driver's eyes from RRPMs at given distances.

than 100 percent efficiency of the headlamps and windshield are taken into account, threshold multiples of about 10 and 30 for rain intensity of 1 in./hr and for clear atmospheric conditions, respectively, are obtained. The threshold multiples are considerably higher for high beams and slightly higher for a driver driving in the left lane (because the headlamps are aimed 2 degrees to the right for a typical output pattern). Thus for clear atmospheric conditions with an RRPM spacing of 120 ft the suggested threshold multiple is met under conditions that are far below optimal for the fourth RRPM away from the car. The threshold multiple for the third RRPM away from the car is more than two times greater than that of the fourth RRPM away from the car, and three RRPMs provide a driver with a minimum level of visual cues for preview, perception of upcoming curves, and lateral control. Further, this optimization ignores the increased luminance levels of the wet pavement due to headlamps of oncoming vehicle traffic. Under those conditions, luminance levels can be so high that they completely mask the reflective stimulus of even new RRPMs.

Ramps

Calculation of Maximum Preview Distance

Entrance and exit ramps found on cloverleaf-type interchanges on Interstate highways are typically 16 ft wide and have a radius of about 240 ft, corresponding to a 24 degree curve. Because of the effect of this curvature, the illumination distance of the roadway and the RRPMs on the outer edge line of the pavement in front of the car is limited to about 130 ft. Therefore, the placement and spacing of RRPMs along the outer edge line of entrance and exit ramps reduce to geometric rather than photometric calculations because the threshold multiples at 130 ft are high (see Figure 3).

A major assumption concerning the geometric determination of the optimal RRPM spacing along exit and entrance ramps was that a solid body of grass or snow 1 to 2 ft high existed on both sides of the pavement. Thus, the driver's view of the curve is limited by the inner edge line of the curve, as shown in Figure 4. On the basis of this assumption, placement of the RRPMs along the outer edge of the ramp provides the driver with a considerably longer arc, which is exposed to a direct line of sight, resulting in a longer preview time of the curve ahead as well as an improved and easier-to-perceive general outline of the curve ahead.

The direct lines of sight from the front of the car to the outer edge line for the right curve and the left curve while the RRPM is illuminated by both beams are 119 and 115 ft, respectively. Under the assumption that four RRPMs should be within the view of the driver to provide adequate preview and both lateral and directional control visual cues, RRPM placement on the outer edge line with an optimal spacing of 25 ft was selected for field evaluation. Again, if one of the RRPMs is missing within the series of four RRPMs available in the driver's direct field of view, three RRPMs will still be visible, constituting a minimum number of single point sources to allow some preview and perception of the curvature ahead.

To improve their photometric performance, each RRPM should be turned in such a way that the angle between the tangent line of the outer edge line and the reference axis of the RRPM is 15 degrees. With this orientation, the front surface of the RRPM is just about perpendicular to the driver's line of sight, which intersects the outer edge line at a distance of 100 ft in front of the car.

CALCULATION OF LATERAL LANE POSITION STANDARD DEVIATION USING A MODIFIED EMPIRICAL MODEL

The model for determining lateral lane position standard deviation developed under simulated driving conditions by Systems Technology Inc. of Hawthorne, Calif. (STI), for painted road lines was modified to obtain lateral lane position standard deviations for point sources. Derivation of Equation 1 was given by Zwahlen *(4)*.

$$SD = A_0 + A_1 * U_0 + A_2 * (1/N + 0.05) * K_s \quad (1)$$

where

SD = lateral lane position standard deviation (ft);
A_0 = constant = −0.08;
A_1 = constant = 0.021;
U_0 = speed (mph);
A_2 = constant = 0.36 for straight road, 0.72 for curves;
N = number of RRPMs visible;
K_s = delineation symmetry factor = 1 for delineation on both lane edges, 2 for no right lane edge delineation.

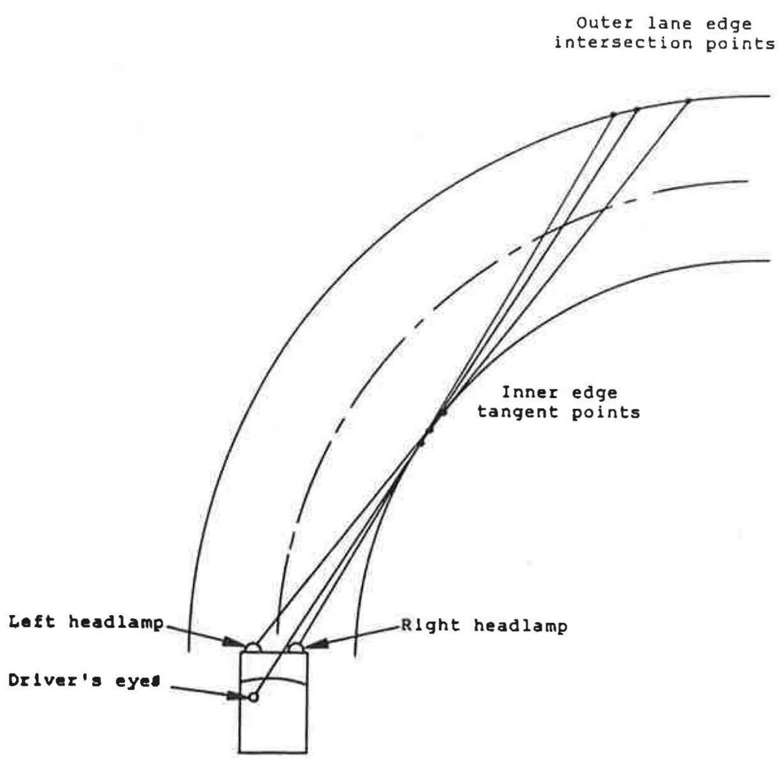

FIGURE 4 Driver's field of view on an Interstate highway ramp as used for geometric calculations.

Figure 5 shows that the largest portion of the lateral lane position standard deviation is due to the speed factor. Also, the reduction in lateral lane position standard deviation due to increasing the number of RRPMs visible to the driver is small for numbers greater than four. The decrease in lateral lane position standard deviation due to delineation on both lane edges compared to that of having delineation only on the right edge line is modest and would not justify tripling the life cycle cost of the RRPM program on a typical tangent section of an Interstate highway.

The modified STI model may also be used to examine lateral position standard deviation on entrance and exit ramps of Interstate highways. For example, for driving through a ramp (24 degree curvature) at 25 mph with an RRPM spacing of 25 ft, lateral lane position standard deviation is expected to be about 0.66 ft. Because this value appears much too small, considering the difficulty involved in driving at a constant radius through a 24 degree curve, the modified STI model may not provide usable data for the ramps or 24 degree curves.

Visibility and detection calculations for tangent sections indicate that under clear atmospheric conditions, a Stimsonite RRPM should be visible to a driver at 480 ft under low-beam conditions. For this reason, an RRPM spacing of 120 ft was recommended for field testing. Results of the modified STI model indicate that lateral lane position standard deviation should not decrease significantly when reducing the spacing from 120 to 60 ft. On the basis of the visibility and detection calculations, geometric and direct line-of-sight considerations, and results of the modified STI model, RRPM spacings of 120 ft for Interstate highway tangent sections and 25 ft for entrance and exit ramps are technically feasible and reasonable and were therefore recommended for field testing.

TEST DRIVER STUDY

General Information

The objective of the test driver study was to measure driver performance in terms of the maintenance of lateral lane position and speed to validate the recommended RRPM placements and spacings. Of primary interest were the effects of the placement and spacing schemes on the measures of driver performance during rain and while the pavement was wet.

Subjects

Eleven subjects were used as test drivers for this study, with eight tested during rain or while the pavement was wet; four subjects were tested on dry pavement. One of the subjects was tested for both conditions. The "wet and rain" group (*N* = 8, 5 males, 3 females) had an average age of 22.3 years (*SD* = 2.3 years) and an average of 6 years of driving experience of about 6,000 mi/year. The "dry" group (*N* = 4, all females) had an

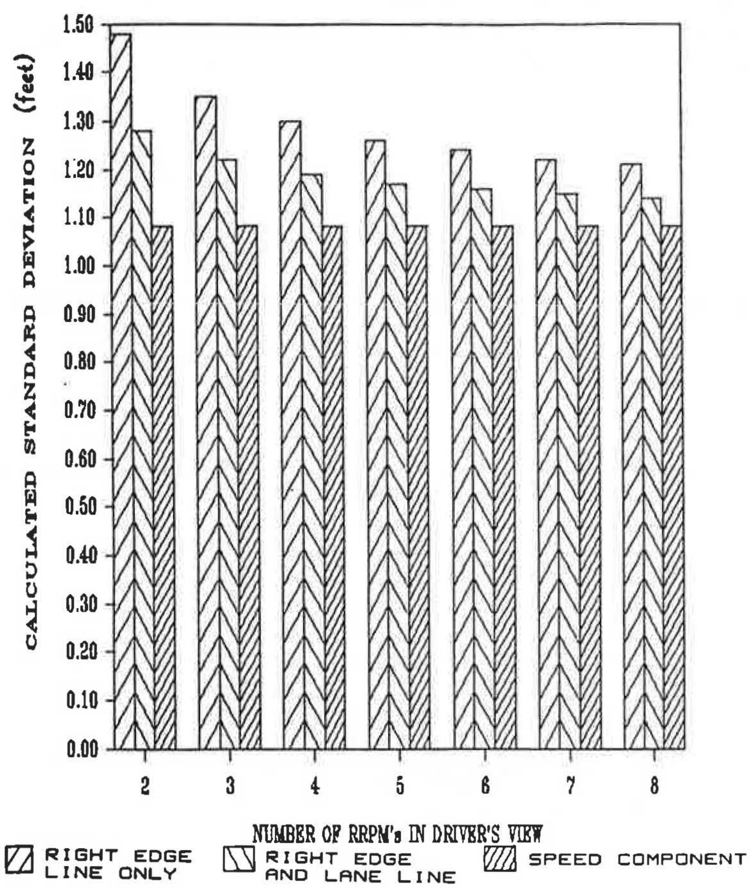

FIGURE 5 Standard deviations of lateral lane positions predicted by the modified STI model for tangent sections.

average age of 19.3 years (*SD* = 1.7 years) and an average of 3.5 years of driving experience of about 4,000 mi/year). All test drivers were in good health, had about 20/20 uncorrected (no eyeglasses or contact lenses) visual acuity, and were paid to participate in the experiment.

Experimental Equipment

An instrumented car (VW 412, automatic transmission, 4-door, with Type 4000 low beams) with a lane-tracking device and other electronic sensors and equipment was used. The car and equipment are described in detail in Report FHWA/OH–84/003, entitled "Warning Signs and Advisory Speed Signs—Reevaluation of Practice" *(5)*.

Experimental Test Site

Figure 6 shows the layout of the test site and the RRPM placements on each section. The unlighted tangent sections were located on Interstate 70 (I–70) east of Columbus, Ohio, between SR 37 and SR 79. The four unlighted entrance and exit ramps were located at the I–70 and SR 79 interchange. The first mile eastbound on I–70 upon entering from SR 37 was the tangent section with an RRPM spacing of 240 ft, and the next mile eastbound had no RRPMs. The eastbound I–70 exit ramp to SR 79 north (slight upgrade) had RRPMs spaced 25 ft apart, whereas the westbound I–70 entrance ramp from SR 79 north (slight downgrade) had no RRPMs. The westbound I–70 exit ramp to SR 79 south (slight upgrade) had RRPMs spaced at 12.5 ft, whereas the eastbound I–70 entrance ramp from SR 79 south had RRPMs spaced 50 ft apart. The first mile on I–70 west after the I–70 and SR 79 interchange was the tangent section with RRPM spacing of 120 ft, followed by the final tangent section with RRPM spacing of 60 ft.

To create more representative test conditions, all of the Stimsonite RRPMs were cut in half to obtain 50 percent of the initial reflectivity of 4.5 cd/fc with an observation angle of 0.20 degrees and an entrance angle of −4 degrees to represent RRPMs that have been in service for a length of time; only halves were glued to the pavement. White RRPM halves were used with spacings of either 240, 120, or 60 ft on the lane lines of the appropriate tangent sections, whereas yellow or amber RRPM halves were used on the outer edge of the ramps with spacings of 50, 25, or 12.5 ft. Each RRPM half on the ramps was turned 15 degrees with respect to the tangent at the lane edge, as described in the section on analytical optimization of RRPM placements and spacings for entrance and exit ramps.

The painted right edge lines along the tangent sections and the yellow painted edge lines along the ramps were, at best, in fair condition. The post delineators along the tangent sections and the ramps were in good condition throughout the experimental data collection period, which lasted for 2 years. All lane markings, RRPMs, and post delineators along the tangent sections and ramps were periodically inspected, and missing or broken post delineators were replaced. Zwahlen *(4)* presented a record of the inspected RRPMs as to those that were missing or had lost their useful reflective property. The traffic on the tangent sections of I–70 was usually heavy during the experimental runs, resulting in a loss of certain collected data because of short car and truck following distances.

Experimental Design

The independent variable for the tangent sections and the ramps was the RRPM spacing. The tangent sections had spacings of 240, 120, or 60 ft, or had no RRPMs; the ramps had spacings of 50, 25, or 12.5 ft, or had no RRPMs. The dependent variables were two measures of driver performance: standard deviation of the lateral lane position deviation and speed maintained by the driver over each test section.

Each driver served as his or her own control and drove all four tangent sections and all four ramps in the same order. Each subject drove the test course twice (Loop 1 and Loop 2), and the ramps with RRPM spacings of 25 ft and no RRPMs were driven twice on each loop to return to the tangent sections. For all test drivers to become familiar with the test car, each test

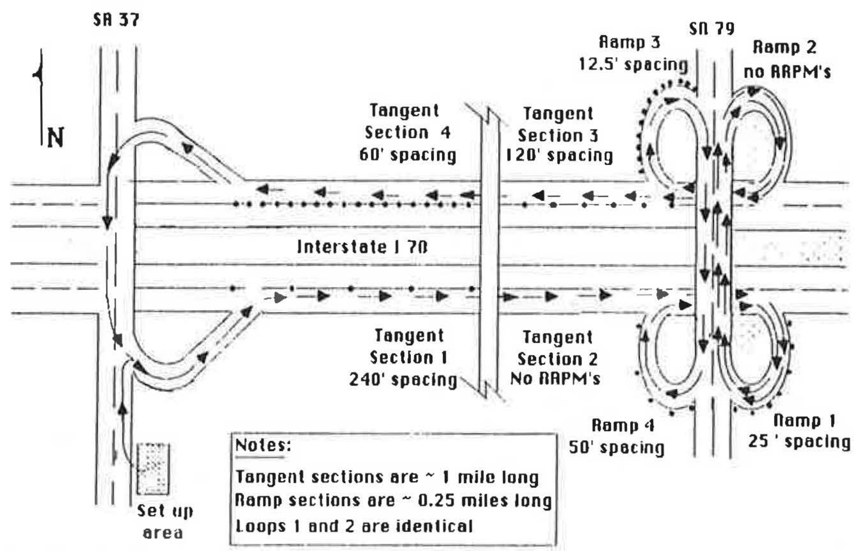

FIGURE 6 Experimental test site showing route and RRPM placement.

driver was required to drive the test car in the Athens, Ohio, area or from Athens to the test site, or both. Although the objective of the study was to collect data during rain, some data was collected after the rain had stopped and the roadway had dried to allow comparison of data from the "wet and rain" and "dry" groups. At a few times during the testing, the rainfall became too intense for the lane tracking camera to detect the edge lines, and the data collected during those times could not be analyzed.

Results and Discussion

In analyzing the data from the driver test study, results from the individual test drivers were examined to determine whether consistent or statistically significant differences existed between the subjects or between Loop 1 and Loop 2 data. After no consistent or statistically significant differences were found, the data were then combined for the purpose of comparing the measures of driver performance on portions of the test track with different RRPM spacings.

The first measure of driver performance considered was the effect of different RRPM spacings on vehicle speed. Figures 7 and 8 show the average vehicle speeds and standard deviations on ramps and tangent sections, respectively, for portions of the test track with different RRPM spacings and the "wet and rain" and "dry" groups of test drivers. Figure 7 shows a slightly higher average vehicle speed for the RRPM spacing of 25 ft on the ramps and a slightly smaller standard deviation in vehicle speed on the second pass of the ramp where no RRPMs were present. These differences, however, are not statistically significant at a probability level of 0.05.

Figure 8 shows that the shorter RRPM spacing (60 ft) appears to result in a slightly higher average vehicle speed and that, with no RRPMs present, the variance in the vehicle speed appears to be smaller on the tangent sections. However, these differences are also not statistically significant at a level of .05. Thus the RRPM spacing does not appear to affect the driver's ability to achieve or maintain the safe and desired vehicle speed on either the ramps or tangent sections of the test track.

The other measure of driver performance considered was the lateral lane position of the vehicle over portions of the test track with different RRPM spacings. Figure 9 shows the average lateral lane position of the test vehicle on the entrance and exit ramps for the different RRPM spacings for both the "wet and rain" and "dry" groups of test drivers. The calculated optimal RRPM spacing of 25 ft appears to result in an average lateral lane position closer to the center of the lane (6 ft) on the ramps. However, the differences between this average and the average obtained when using the other RRPM spacings are not statistically significant at a level of 0.05.

Figure 10 shows the average standard deviation of the lateral lane position for each of the RRPM spacings tested on the entrance and exit ramps for both the "wet and rain" and "dry" groups of test drivers. This measure of driver performance does not vary greatly among ramps with different RRPM spacings. In fact, at a level of 0.05 there are no significant differences in the standard deviations of lateral lane position between any of the RRPM spacings on the entrance and exit ramps for either the "wet and rain" or "dry" groups.

Figure 11 shows the average lateral lane positions of the test vehicle for the different RRPM spacings on the tangent sections of the test track for both the "wet and rain" and "dry" groups of test drivers. The average lateral lane position is smaller for the tangent section with an RRPM spacing of 60 ft than for the sections with other spacings. In fact, at a level of 0.05 the lateral lane position is statistically smaller for the RRPM spacing of 60 ft than for the other spacings, indicating an average lateral lane position closer to the right edge line, for the "wet and rain" group, the "dry" group, and both groups combined. Thus a slight but consistent shift toward the right edge line of about 0.44 ft exists in the lateral lane position for

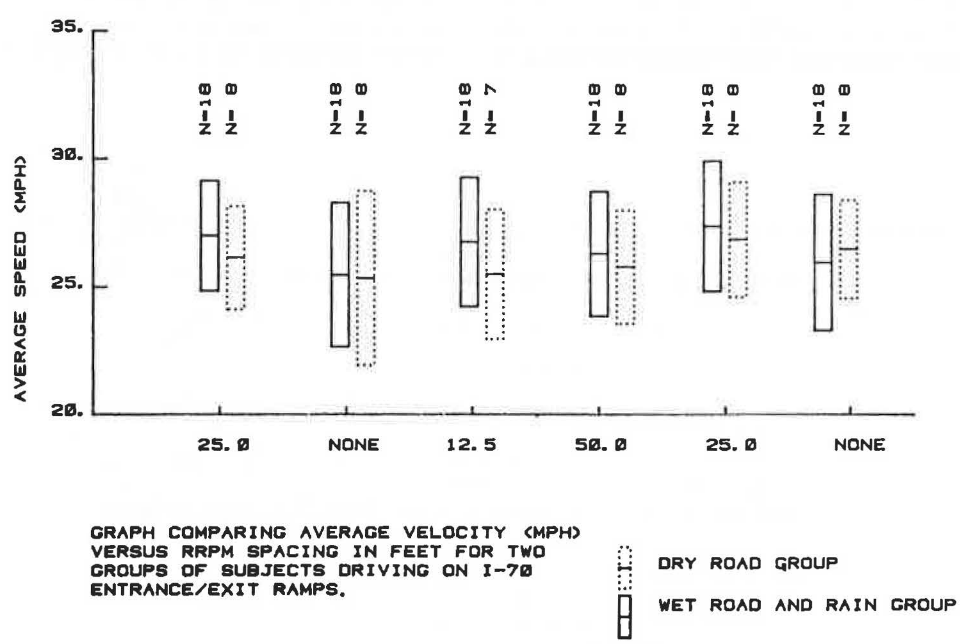

FIGURE 7 Comparison of average vehicle speeds for different RRPM spacings on ramps.

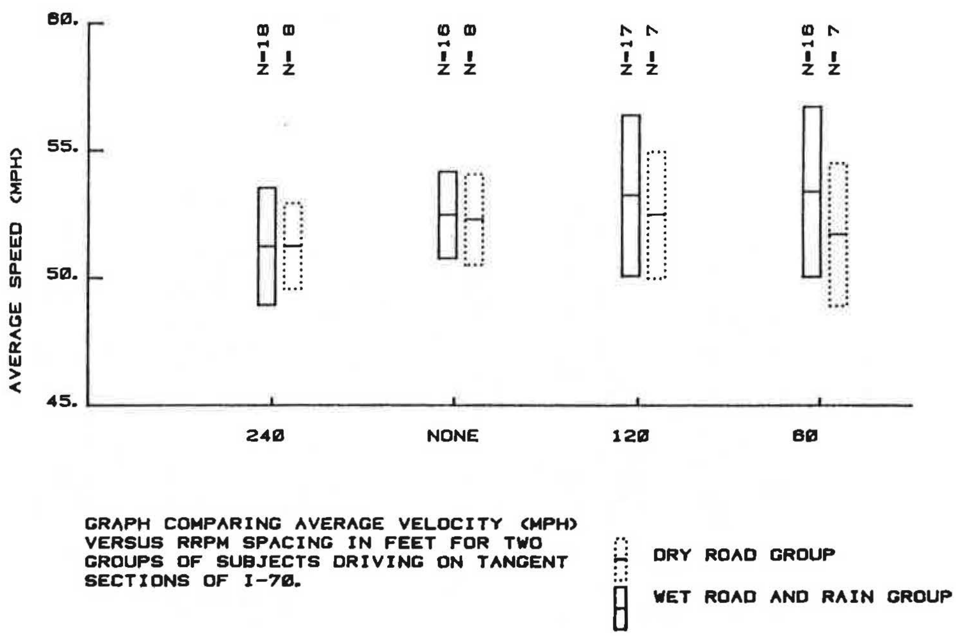

FIGURE 8 Comparison of average vehicle speeds for different RRPM spacings on tangent sections.

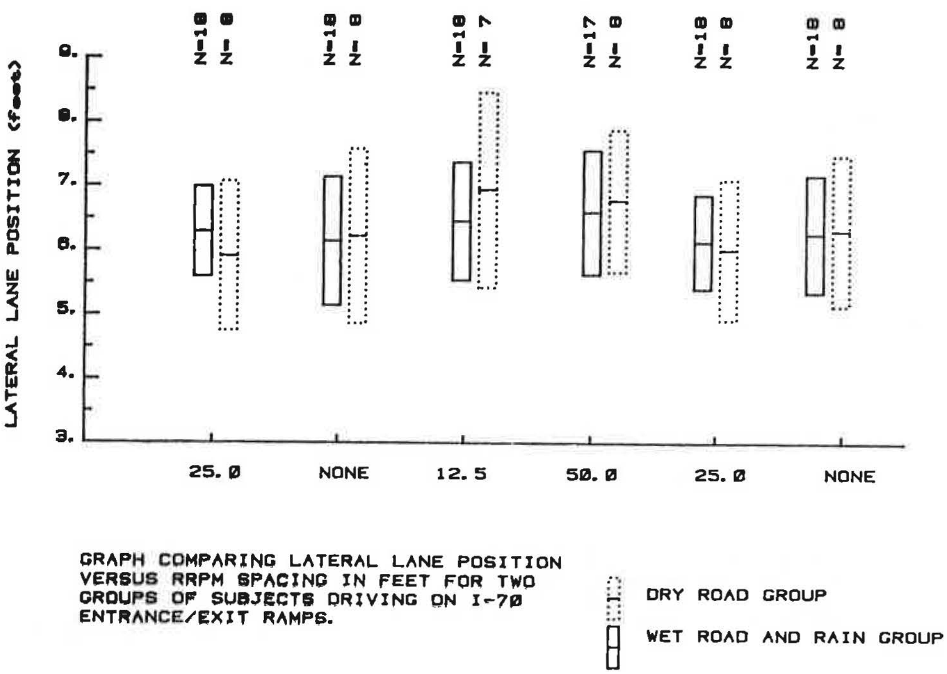

FIGURE 9 Average lateral lane positions on ramps for different RRPM spacings.

the RRPM spacing of 60 ft compared to the spacing of 120 ft for the "wet and rain" and the combined groups of test drivers.

Figure 12 shows a comparison of the average standard deviation of the lateral lane position for the different RRPM spacings over the tangent sections of the test track for both the "wet and rain" and "dry" groups of test drivers. The average standard deviation of the lateral lane position for the RRPM spacing of 60 ft compared to the other spacings is smaller for the "wet and rain" group. The difference of about 0.13 ft compared to the average lateral lane position over the section with an RRPM spacing of 120 ft is statistically significant at a level of 0.05 for the "wet and rain" group and for both groups combined.

Finally, the lateral lane position standard deviation averages for the ramps with an average ramp speed of about 26.5 mph, are about 0.5 ft larger than those for the tangent sections, in complete disagreement with the results obtained using the modified STI model. The lateral lane position standard deviation for the tangent sections for all RRPM treatments is about 0.9 ft, whereas the expected standard deviation value obtained from the modified STI model due solely to the speed effect is 1.08 ft. Thus these results also disagree with the calculated values using the modified STI model.

The "wet and rain" group was tested under conditions of light-to-moderate rainfall intensities (considerably less than 1/2

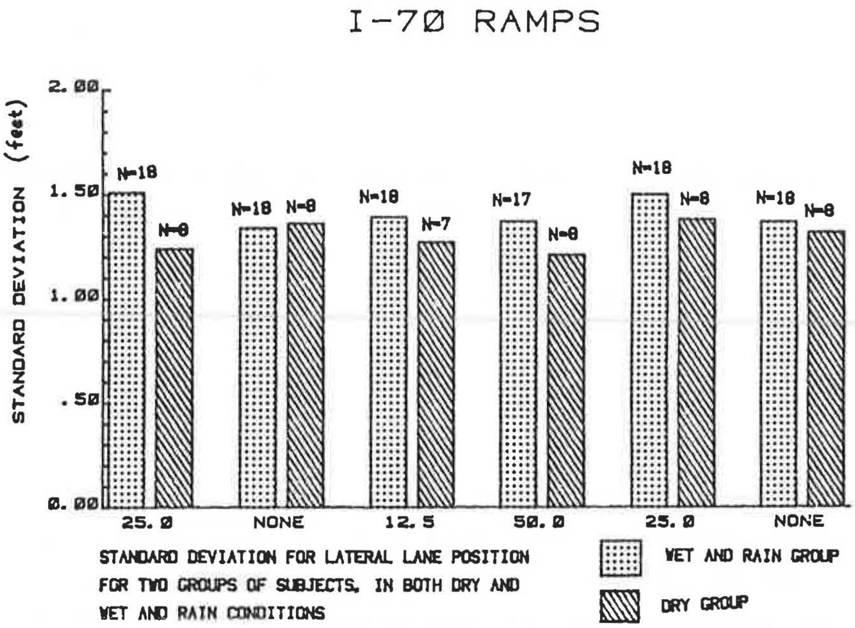

FIGURE 10 Standard deviations of average lateral lane positions on ramps for different RRPM spacings.

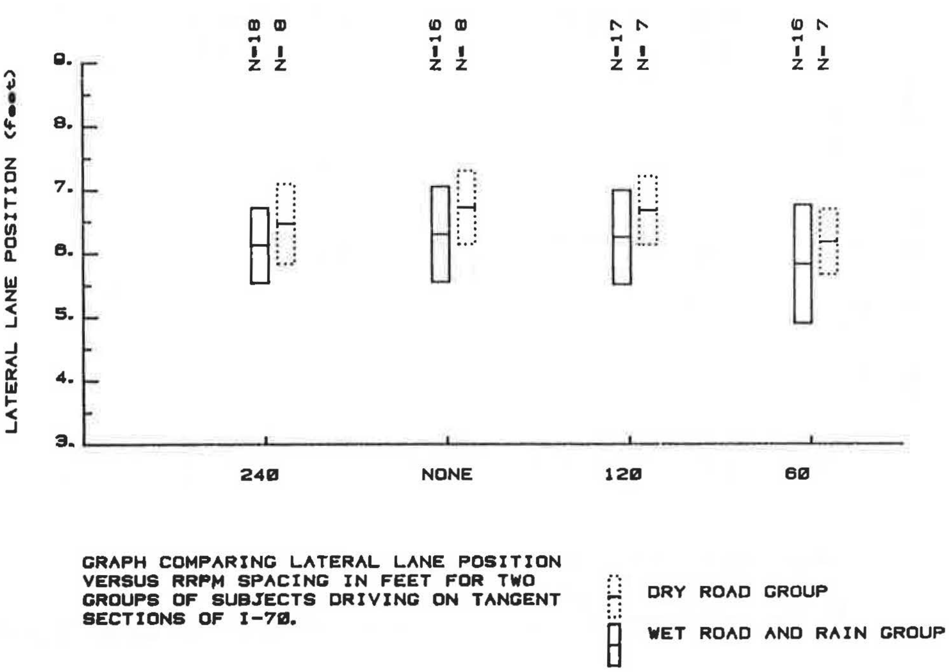

FIGURE 11 Average lateral lane position on tangent sections for different RRPM spacings.

in./hr). Thus the calculated optimal RRPM spacings were not tested for highly degraded visibility conditions. However, the probability of extremely-high-intensity rainfall is very small in Ohio, as was shown in Figure 1. In the event of such rainfall, even the painted edge lines and lane lines immediately in front of the car can become so obscured that the driver cannot detect them. To accommodate these extreme conditions, the RRPMs would be placed at such small distances apart that any RRPM installation would be economically infeasible. Thus, to keep the cost of RRPM programs in Ohio reasonable, the calculated optimal RRPM spacings were evaluated for conditions of slightly degraded visibility only. In times of very highly degraded visibility due to extremely-high-intensity rainfall, drivers must adjust their speed and driving strategies.

Paired *t*-tests were performed using the individual subject averages and standard deviations to compare differences in the measures of driver performance obtained when using different RRPM spacings on ramps and tangent sections of Interstate highways. No consistent or statistically significant differences between the measures of driver performance were found when using any of the RRPM spacings on the entrance and exit ramps in either "wet and rain" or "dry" pavement conditions.

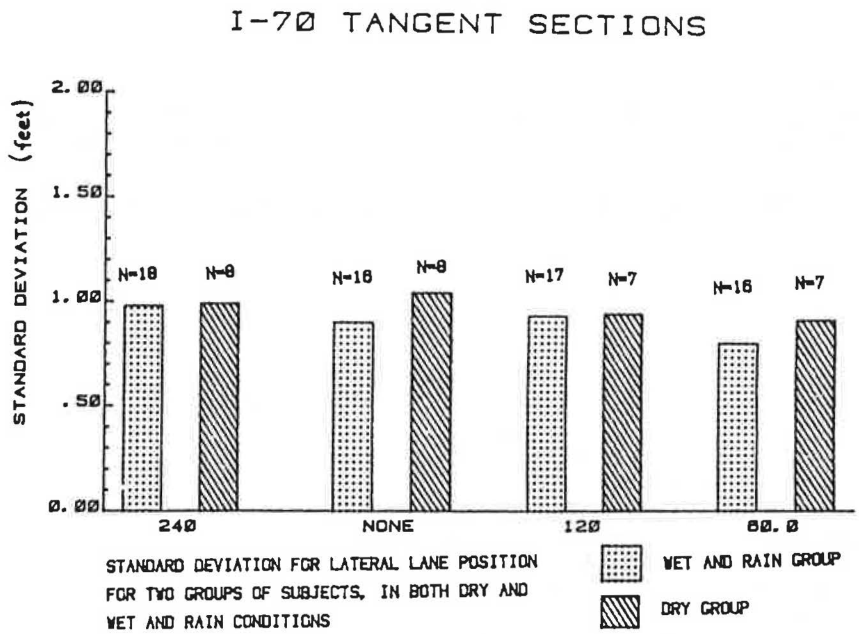

FIGURE 12 Standard deviations of average lateral lane positions on tangent sections for different RRPM spacings.

On the tangent sections, two measures of driver performance appeared to be slightly sensitive to the RRPM spacings (statistically significant at a level of 0.05). First, there was a slight but consistent shift of about 0.44 ft toward the right edge line in the average lateral lane position for the RRPM spacing of 60 ft compared to the spacing of 120 ft for the "wet and rain" group, the "dry" group, and the two groups combined. Second, the lateral lane position standard deviation was smaller by about 0.13 ft for the RRPM spacing of 60 ft, compared to the spacing of 120 ft for the "wet and rain" group and for both groups combined. However, this marginal improvement in the lateral lane position standard deviation for the RRPM spacing of 60 ft compared to the spacing of 120 ft along tangent sections of Interstate highways does not justify doubling the life cycle cost of the RRPM installation. Because of the differences in the experimental results and the calculated values obtained using the modified STI model, the applicability of this model should be further investigated by using data from actual driving experiments rather than from simulator experiments.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the results of this study, it is concluded that for conditions of light-to-medium rainfall intensity an acceptable level of driver performance can be achieved with an RRPM spacing of 120 ft along the lane lines of Interstate highway tangent sections. The installation of RRPMs on the outer edge lines of cloverleaf-type interchanges of Interstate highways does not improve driver performance in any consistent, practical, or statistically significant manner. Because of the relatively short visibility distance of about 100 ft on a ramp compared to about 480 ft on a tangent section and the lower driving speed on exit and entrance ramps, it appears that adequate driving performance with no RRPMs can be expected even under somewhat degraded weather conditions on ramps.

These conclusions are based on experimental evidence obtained for conditions of slightly degraded visibility due to light-to-moderate rainfall and in glare caused by headlamps and tail lamps of vehicles. Because extremely-high-intensity rainfall is a very rare occurrence, it is probably not economically feasible to design RRPM installations for such events.

It is recommended that a maximum RRPM spacing of 120 ft be used for tangent sections of Interstate highways. Placement of RRPMs on the outer edge lines of cloverleaf-type interchanges on these highways is not recommended.

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