Division of Research staff, for the collection of data at inconvenient locations and times of day.

REFERENCES

1. T. D. Davis. *Construction Zone Safety and Delineation Study*. Report FHWA/NJ-83/005. FHWA, U.S. Department of Transportation, 1983.
2. C. W. Niessner. *Construction Zone Delineation (RPM)*. Report FHWA-TS-78-222. FHWA, U.S. Department of Transportation, 1978.
3. L. J. Lanz. *Road Marking Material, Second Interim Report*. Mississippi State Highway Department, Jackson, 1973.

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

Evaluation of Temporary Pavement Marking Patterns in Work Zones: Proving-Ground Studies

CONRAD L. DUDEK, R. DALE HUCHINGSON, AND DONALD L. WOODS

Results of proving-ground studies for evaluation of temporary pavement markings for work zones are summarized. The objective was to investigate 10 candidate temporary marking treatments: one base treatment consisted of 4-ft stripes with 36-ft gaps, and nine other candidate marking treatments employed variations in stripe length, gap length, and reflective and nonreflective raised pavement markers (RPMs). The initial studies were conducted during dry-weather, daytime conditions. Based on the findings of the daytime studies, the base treatment and the best six of the nine other marking treatments were evaluated during nighttime, dry-weather conditions employing the same procedures and experimental design. The studies were conducted on the test track at the Texas A&M Research and Extension Center, with a demographically balanced sample of drivers individually driving an instrumented test vehicle. Measures of effectiveness included speed and distance data, erratic maneuver data, and subjective evaluations of treatment effectiveness. The nighttime studies aimed to determine whether the daytime findings were applicable to dry-weather, nighttime driving conditions. The approach was to essentially replicate the daytime study procedures with a matched, but different sample of drivers. The six markings selected were three with striping patterns and three RPM configurations. Daytime treatments deleted were those with 1- and 2-ft stripes, long (48- and 38-ft) gaps, or both.

In highway work zones traffic is often required to use different parts of the roadway for short periods of time, which necessitates changes in path delineation. For example, a significant portion of highway maintenance activities involves pavement overlay work. This type of work frequently requires more than one layer of pavement, and traffic is permitted to operate on the roadway between the times the first and last layers are laid. Therefore, there is a need to delineate pathways (lanes) through work zones for motorists, particularly for nighttime and adverse weather driving conditions.

There are basically two schools of thought: (a) to simply use the Manual on Uniform Traffic Control Devices (MUTCD) standard markings, resulting in the expenditure of considerable time and materials, which seems impractical for conditions where the marking would be in use for a short period of time, and (b) to use temporary and possibly an abbreviated marking pattern. Research is needed to develop a cost-effective temporary pavement-marking pattern for use in highway work zones.

Proving-ground studies were conducted to evaluate 10 candidate temporary pavement marking treatments: one base treatment consisting of 4-ft stripes with 36-ft gaps, and nine other candidate marking treatments. Studies were first conducted during daytime, dry weather conditions. The six best or most promising treatments, along with the base treatment, were then studied during nighttime, dry weather conditions.

APPROACH FOR DAYTIME STUDIES

Objectives and Scope

The objective of this series of studies was to investigate 10 candidate temporary pavement marking treatments for use at work zones by determining the effects of each on various measures of driving effectiveness during daytime, dry weather conditions. The markings consisted of a set of low-profile markings (LPMs) and raised pavement markings (RPMs) applicable to work zones.

Texas Transportation Institute, Texas A&M University, College Station, Tex. 77843-3135.

The optimal markings recommended were based on the best overall driving performance in negotiating a series of four horizontal curves on a test track located at the Texas A&M Research and Extension Center. The controlled field study consisted of drivers individually driving the test track course in both directions, thereby negotiating a total of eight test curves.

Experimental Plan

The daytime experiment consisted of three stages:

1. A pilot study to determine which of two entry speed strategies (cruise control and noncruise control) would likely result in the most useful test data.
2. A baseline study with the same control treatment (4-ft stripe with 36-ft gap) applied to all four curves of the test track. This study was conducted to determine if there were curve differences irrespective of treatment differences. Although the horizontal test curves were identical in degree of curvature, features near the curves could possibly affect the drivers' performance. Therefore, it was necessary to establish baseline data before application of treatments to the curves.
3. The main study consisted of a comparison of 10 marking pattern treatments: the baseline (control) treatment and nine other candidate treatments.

A description for each of the 10 treatments follows. Treatment 1 was the control condition. The other treatments consisted of both LPMs and RPMs with LPM variations in stripe length and gap length, and combinations of reflective and nonreflective RPMs.

- Treatment 1: 4-ft stripes (4-in. wide) with 36-ft gaps. (Control condition).
- Treatment 2: 2-ft stripes (4-in. wide) with 38-ft gaps.
- Treatment 3: 8-ft stripes (4-in. wide) with 32-ft gaps.
- Treatment 4: 2-ft stripes (4-in. wide) with 18-ft gaps.
- Treatment 5: four nonreflective RPMs at $3\frac{1}{3}$-ft intervals with 30-ft gaps and reflective marker centered in alternate gaps at 80-ft intervals.
- Treatment 6: three nonreflective and one reflective RPM at $3\frac{1}{3}$-ft intervals with 30-ft gaps.
- Treatment 7: 2-ft stripes (4 in.) with 48-ft gaps.
- Treatment 8: Treatment 2 and RPMs at 80-ft intervals.
- Treatment 9: two nonreflective RPMs at 4-ft intervals with 36-ft gaps and one reflective RPM centered in each 36-ft gap.
- Treatment 10: 1-ft stripes (4 in.) with 19-ft gaps.

Treatments 1-6 and 9 were day and night studies. All of the stripes and RPMs were yellow.

The experimental plan for the main study involved dividing the nine marking treatments into three sets (A, B, and C). Each set consisted of three randomly assigned treatments and the control condition from the baseline study. For example, the Set A study included three temporary treatments and the control. During Set B and Set C studies, three different treatments were tested along with the control treatment in each study.

Table 1 gives the curve treatment sets. The experiment used a matched group design, with matched but different driver subjects assigned to each set. The decision to use matched groups was based on the unusual length of administration time required to have each driver exposed to each treatment. Also, possible learning or fatigue effects could have biased the results. Sixteen subjects were assigned to each set. They encountered three treatments and the control (base) condition in random order.

TABLE 1 ASSIGNMENT OF TREATMENTS TO CURVES AND SETS FOR DAYTIME STUDIES

	Treatment by Curve No.			
	1	2	3	4
Base	1	1	1	1
Set A	2	5	3	1
Set B	4	6	7	1
Set C	10	9	8	1

Test Subjects

Because the findings of the research were to be generalized to the U.S. driving population, a sample of driver subjects was selected based on demographic data on current drivers. Subjects were to be representative of the U.S. driving population in terms of age, sex, education, and driving experience. All were to hold a current driver's license and at least corrected 20/40 visual acuity.

In the matched group design, subjects in each set were assigned to ensure equivalency on the relevant subject characteristics. There were 48 subjects in the main study, 16 in the base study, and 5 in the pilot study. No subject was used more than one time.

Test Track

Figure 1 shows the test track at the Texas A&M Research and Extension Center located at an old air force base. The 6-mi test track included several horizontal curves. Four of the curves (1, 2, 3, and 4) were specifically designed for 50-mph speeds and were used as the test curves. Traffic control devices were installed adjacent to the test track at locations where speed reductions and stops were desirable. No devices were installed near the test curves.

The test track is a two-lane, two-way highway with 11-ft lanes. An 11-ft lane width was used in order to take advantage of part of an existing test track. Also, it reflects geometric standards common for construction and maintenance operations. A standard centerline was used and edgelines were placed on the outside of both lanes throughout the entire truck except near the four test curves. The temporary pavement marking treatment began and the edgelines were dropped on the tangent sections in both directions of travel 500 ft before the beginning of each test curve. The pavement marking treatment extended through the curve and was discontinued with the addition of the normal centerline and edgeline on the tangent section 500 ft beyond the point of tangency of the curve. The removal of the edgeline before the curve allowed for a transition between the tangent section and the test curve. If drivers reacted to the edgeline drop, it was surmised that the reaction would take place within the 500-ft tangent section before the curve. Therefore, the speed reductions in the curves could be attributed to the motorists' guiding ability on the temporary pavement marking treatment and not to the edgeline drop.

Curve	Curve Length (ft.)	Left Tangent (ft.)	Right Tangent (ft.)
1	1636	1200	1100
2	818	2600	1000
3	818	3600	1400
4	754	1100	900

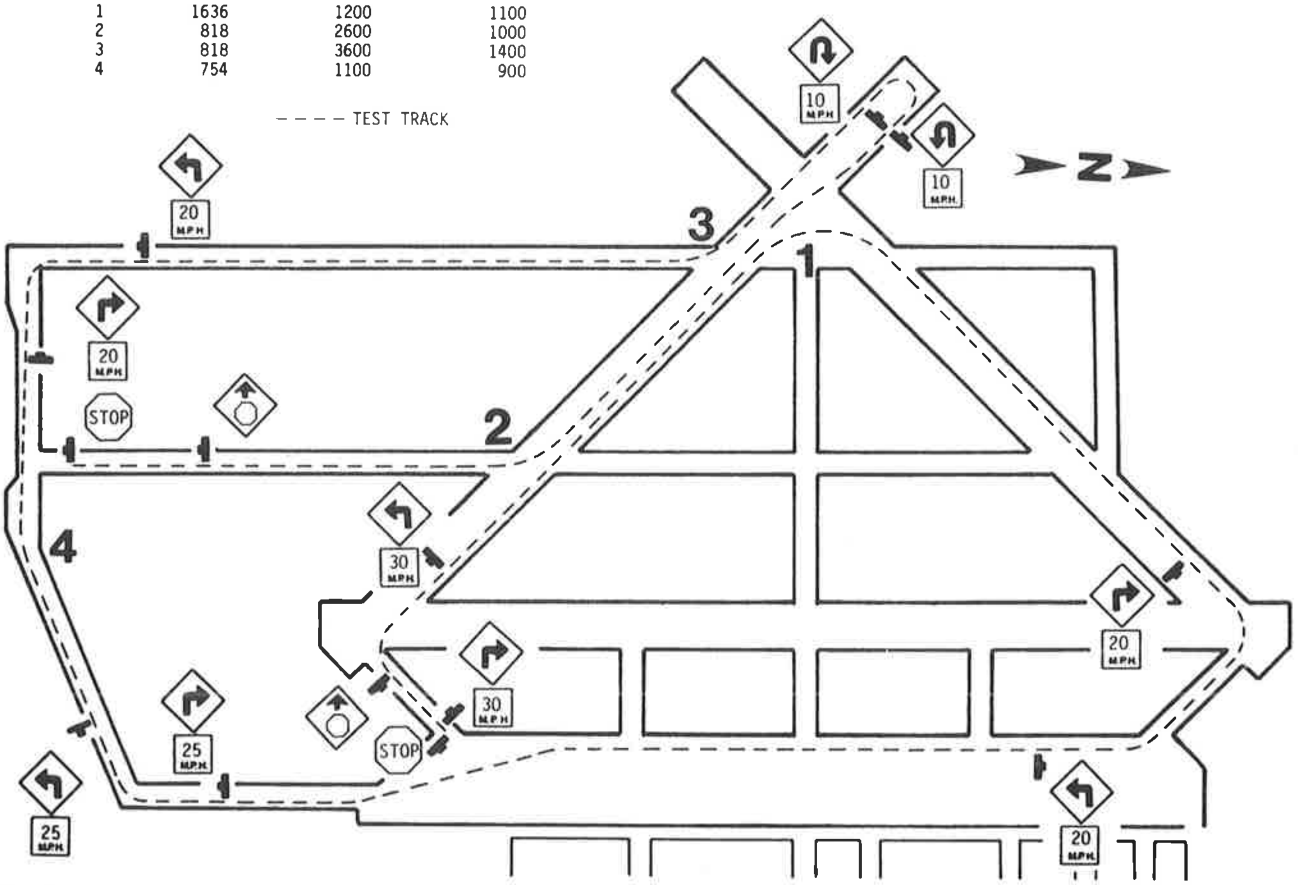

FIGURE 1 Test track at the Texas A&M Research and Extension Center.

Experimental Protocol

Measures of Effectiveness

The measures of effectiveness (MOEs) consisted of (a) seven measures derived from the speed and distance measurements, (b) frequency of erratic maneuvers (deviation from the centerline) and curve misses, and (c) drivers' subjective comments and ratings of treatment effectiveness.

The speed and distance MOEs were as follows: (a) maximum entry speed into the curve, (b) minimum speed while in the curve, (c) magnitude of the speed change (difference in maximum entry speed and minimum speed), (d) distance from the edgeline drop point to the location where the driver reached minimum speed, (e) minimum speed within the first 1,000 ft, (f) speed change within the first 1,000 ft, and (g) distance to the point of minimum speed within the first 1,000 ft.

In addition to speed and distance measures, frequencies of erratic maneuvers were obtained from videotape recordings of the left front wheel and the roadway ahead. The MOEs included total frequencies of erratic maneuvers, frequencies of lateral deviations of 11 to 16 ft to the right, frequencies of deviations of greater than 16 ft to the right, and frequencies of misses or driving past the curve completely, which necessitated a vehicle turnaround. Lateral deviations were measured from the left front wheel of the vehicle to the centerline. Erratic maneuvers were defined as lateral deviations equalling or exceeding 5 ft, or the left front wheel crossing the centerline.

At the end of the test run, drivers drove the course again and commented on what they liked or disliked about each treatment. They were then asked to select the treatments that were the best and least effective in terms of guiding a driver through the curves.

Data Recording Methods

The speed and distance data were recorded using a time-speed-delay and distance measuring device installed in the test vehicle. The printer was set to record data every 100 ft.

A video camera counted on the outside of the left rear door of the test vehicle (Figure 2) provided a permanent visual record of the path of the left front wheel with respect to the centerline on the test track. Therefore, erratic maneuvers could be evaluated by viewing the video recording on a large video monitor.

Instructions to the subjects, post-test interviews, and subject comments were recorded on audio cassette and videotapes. Detailed descriptions of the data collection and equipment calibration procedures are available elsewhere *(1)*.

Procedure

In the main study it was necessary to control for possible order effects that might bias the results. For example, if Curve 1 was always the first curve encountered and Curve 4 the last in succession, there might be uncontrolled effects that could influence the

FIGURE 2 Test vehicle recording equipment.

interpretation of treatment effects. Therefore, a series of eight coded routes (AX, AY, BX, BY, CX, CY, DX, DY) was developed (Table 2). Pairs of routes had one of four entry points: A, B, C, and D. The entry points varied in terms of which curve was encountered first.

Subjects were then assigned to the entry point in systematic fashion so that 4 of the 16 subjects started at each entry point. Two subjects drove the test track in the outbound direction and two subjects started in the inbound direction at each starting point. Each subject then retraced the course in the opposite direction. Therefore, each curve was negotiated as both a left and right curve (a total of eight treated curves observed by each subject).

The test began with the test administrator sitting in the passenger seat. Standardized instructions *(1)* were read to the drivers. Once on the test track, drivers were instructed to drive as fast as comfortable at a maximum speed of 50 mph, paying attention to safety in vehicle-control and traffic-control devices.

After driving the course (outbound and inbound), subjects were given a debriefing *(1)* during which they again drove the test course and evaluated the treatments.

THE PILOT TESTS

Strategy Study

A pilot study was conducted to determine which of two entry speed strategies would be likely to result in the most useful test data. Specifically, a decision was needed on whether to control for initial speed on entry of the curves by having drivers accelerate and press a cruise control button set for 50 mph (cruise-control mode), or whether to simply instruct drivers to accelerate to 50 mph but permit variation as they deemed acceptable (noncruise-control mode). A study with five subjects was administered with both sets of instructions. The same treatment (Treatment 1) was applied to all curves.

TABLE 2 TEST TRACK ENTRY POINTS AND ROUTES

Entry Point	Route	Curve Order 1	2	3	4
A	AX	1L	2L	3R	4L
	AY	4R	3L	2R	1R
B	BX	2L	3R	4L	1L
	BY	1R	4R	3L	2R
C	CX	3R	4L	1L	2L
	CY	2R	1R	4R	3L
D	DX	4L	1L	2L	3R
	DY	3L	2R	1R	4R

Note: L = left-turn curve (turn to the driver's left), and R = right-turn curve (turn to the driver's right).

Although the project staff interpreted the results *(1)* as suggesting a need for speed control in the main study, it was decided by FHWA that it would be more realistic not to use the cruise control, thereby permitting drivers to assume whatever comfortable speed they wished on entering the curves. Therefore, in both the base and main studies, the noncruise control mode was used. It was also decided by the project staff that in the main study a reduction of speed of less than 4 mph would not be of practical significance, and that a sample size of 16 per set would be retained according to the originally proposed experimental design.

Base Study

The base study was conducted initially to determine if there were differences among the curve means and variances and possible direction of travel effects, that is, whether the curve broke to the driver's left or right. If the variances on the MOEs were approximately the same, then the treatments could be applied randomly to any curve. Tests on equality of means are permissible only when the associated variances are homogeneous. This is a basic assumption of the statistical testing procedure.

Tests of the equality of variances of the curve data revealed only random differences in curves and direction, and it was concluded that they were sufficiently homogeneous to permit the testing of the equality of means. A three-factor ANOVA model with curve, direction and subjects as main effects, and curve by direction interaction was used.

The new Duncan Multiple Range Test was also applied to the data. It was concluded that there were curve differences (notably Curve 4). Therefore, for the main study, it was recommended that the control condition (Treatment 1) always be applied to Curve 4. The other curves were sufficiently similar for different treatments to be applied with the assurance that differences in MOEs were due to the treatments rather than to the curves.

DATA SUMMARY OF SPEED AND DISTANCE MEASURES FOR DAYTIME STUDIES

Results for Speed and Distance Measures

The data collected included speed and lane position throughout the test track. Table 3 gives the means and variances across conditions for one of the MOEs (speed change within curve). Space limitations do not permit including tabulated results for all seven MOEs. Detailed results are available elsewhere *(1)*.

No differences among variances for the treatments in study Set A were found ($\alpha = 0.01$). For Sets B and C, the homogeneity of variance assumption was questionable for speed change, speed change in the first 1,000 ft, distance to minimum speed in the curve (Set B), and distance to minimum speed within the first 1,000 ft of the curve in the right direction of travel (Set C).

Statistical analyses of means revealed some individual differences in curves regardless of treatments. A point-by-point dis-

TABLE 3 SPEED CHANGE WITHIN CURVE: MEANS AND VARIANCES FOR DAYTIME STUDIES

Curve No.	Direction	Speed (mph) by Set Base	A	B	C
Means					
1	L	12.6	9.9	10.9	10.2
2	L	9.4	6.6	8.6	8.0
3	L	9.3	7.6	7.6	8.3
4	L	3.4	3.7	4.3	4.0
1	R	14.5	13.7	13.1	14.2
2	R	12.7[a]	9.5	8.3[a]	9.2[a]
3	R	9.2	6.7	9.9	8.5
4	R	8.3	8.2	7.9	8.6
Variances					
1	L	22.0	11.5	27.8[b]	23.1[b]
2	L	12.3	7.3	25.5	14.1
3	L	7.2	9.7	5.8	3.9
4	L	5.2	3.7	5.8	3.9
1	R	30.9	35.6	27.7	58.4[b]
2	R	30.5	18.3,	15.4	8.6
3	R	22.7	11.0	13.1	14.8
4	R	11.3	13.7	23.3	12.7

[a] Significantly different from base (0.01 level).
[b] Variances unequal. Means above cannot be compared.

cussion is not merited, but the consistency of the results did suggest the four subject groups responded to certain curves in similar fashion regardless of the treatment applied. This would be a disturbing finding (curve differences above and beyond treatment differences), however, the combined differences were very small. In other words, both curve and treatment effects were not sufficiently dramatic to reflect differences of a practical nature in the MOE. A practical difference in speed was defined as a change greater than 4 mph.

Although there are less powerful statistical tests (such as analysis of response change) that could be applied to the statistical data, the small differences in the MOEs would not seem to merit further statistical analysis.

Discussion of Speed and Distance Data

The ANOVA and Duncan's tests revealed a few significant differences in means. However, inspection of the data suggested the differences among treatment sets were too small to be of practical significance. No clear trends in any of the treatments were observed from the MOEs. In short, the speed and distance data did not provide a basis for selecting one or more treatments either better or worse, in a practical sense, than the base treatment.

SUMMARY OF ERRATIC MANEUVER DATA FOR DAYTIME STUDIES

Erratic maneuver data for the daytime studies were analyzed by a categorical (log linear regression) test to determine if there were differences across curves and treatment sets. The frequencies of erratic maneuvers are given in Table 4. The categorical data analysis revealed no significant curve or set differences. Drivers were equally likely to have an erratic maneuver regardless of curve; however, Curve 1 had slightly more erratic maneuvers.

Three additional MOEs on lane placement were: (a) frequency of driving more than 11 but less than 16 ft to the right of centerline, (b) frequency of driving greater than 16 ft to the right but essentially parallel to the centerline, and (c) frequency of missing curves completely (requiring redirection back to the course). A deviation of 11 ft would place the vehicle outside the marked lane. Sixteen feet or more would place the vehicle off the normal roadway crown. Data are given in Table 5. Assuming the maneuvers were random and discrete, the Poisson distribution assumption applies, with mean and variance essentially equal. Values that differ significantly are noted. Treatments 7 and 8 were found to have the greatest number of misses, course deviations, or both. Treatment 7 was the 2-ft stripe with 48-ft gap. The lengthy gaps on a curve may contribute to losing track of the centerline. Treatment 8 had 2-ft stripes with 38-ft gaps and widely separated (80-ft) RPMs.

TABLE 4 NUMBER OF DRIVERS COMMITTING AN ERRATIC MANEUVER FOR DAYTIME STUDIES

Curve No.	Direction	No. of Subjects	No. of Drivers by Set Base	A	B	C	Total
1	L	16	9	13	14	10	46
2	L	16	4	11	7	4	26
3	L	16	9	11	7	6	33
4	L	16	7	10	8	6	31
1	R	16	13	12	14	12	51
2	R	16	10	10	10	8	38
3	R	16	11	13	11	10	45
4	R	16	12	8	9	10	39

TABLE 5 FREQUENCIES OF DRIVING OUTSIDE NORMAL TRAFFIC LANE AS MEASURED FROM LEFT FRONT TIRE TO CENTERLINE FOR DAYTIME STUDIES

Treatment	Deviations to Right 11-16 ft[a]	Deviations to Right 16+ ft[b]	Misses[c]	Cumulative Misses and Deviations[d]	Passes
1	11 (1.5)	7 (1.0)	4 (0.5)	22 (3.0)	224 (32)
2	0	0	1	1	32
3	1	0	1	2	32
4	2	0	0	2	32
5	0	0	0	0	32
6	2	2	0	4	32
7	1	2	6[e]	9[e]	32
8	0	4	3	7[e]	32
9	1	1	2	4	32
10	0	0	0	0	32
Total	18 (8.5)	16 (10.0)	17 (13.5)	51 (32.0)	512 (320)
Average	0.9	1.0	1.4	3.2	

Note: Numbers in parentheses are normalized to 32 observations.
[a] Frequencies of maximum lateral displacement between 11 and 16 ft.
[b] Frequencies of maximum lateral displacement over 16 ft but not including misses.
[c] Frequency of missed curves only.
[d] Total of Columns 2, 3, and 4.
[e] Significantly different at the 0.05 level using the Poisson assumption.

SUMMARY OF SUBJECTIVE DATA FOR DAYTIME STUDIES

Results of Driver Evaluation of Treatments

At the end of the driving run each driver subject retracted the course and was asked to comment on the treatment on each curve and to select the treatments that were the most and least effective. Subjects were allowed to select two treatments as being equal; therefore, the number of observations in each set are not equal. A given subject saw only four treatments: the control condition (Treatment 1) and three other candidate treatments. All subjects saw the control condition (Treatment 1).

Table 6 summarizes the frequency of subjects judging treatments as most and least effective. Treatments 5, 6, and 9 were

TABLE 6 PERCENT OF VOTES FOR MOST AND LEAST EFFECTIVE TREATMENTS FOR DAYTIME STUDIES

	Set A Treatments				Set B Treatments				Set C Treatments			
Effectiveness	1	2	3	5	1	4	6	7	1	8	9	10
Most	0	0	38	62	31	13	56	0	28	13	59	0
Least	12	88	0	0	17	17	5	61	6	19	6	69

judged to be the most effective by the subjects. These treatments, judged best in each set, are all RPMs. Treatment 5 is four nonreflective RPMs at 3.33-ft intervals with 30-ft gaps and one reflective marker centered in alternate gaps at 80-ft intervals. Treatment 6 is three nonreflective RPMs and one reflective RPM at 3.33-ft intervals with 30-ft gaps. Treatment 9 is two nonreflective RPMs at 4-ft intervals with 36-ft gaps.

Treatments 2, 7, and 10 were judged least effective overall. No driver rated any of these treatments as most effective in comparison with the other three treatments in their set. Treatments 2 and 7 both have 2-ft stripes. Treatment 2 has 38-ft gaps and Treatment 7 has 48-ft gaps. Treatment 10 has 1-ft stripes and 19-ft gaps.

Although the best treatment appeared each time on Curve 2 there is no evidence that the subjects were rating the curve rather than the treatment. In the baseline study, best and worst ratings were distributed in equal proportion (3 to 5) on each curve.

Clearly, the drivers strongly preferred the RPMs. Of the striping systems without RPMs, Treatment 3 (8-ft stripes with 32-ft gaps) was preferred over Treatment 2 (2-ft stripes with 38-ft gaps).

Results of Driver Comments

The subjective ratings were largely supported by the drivers' verbal comments *(1)*. Positive ratings were supplemented by favorable comments and negative ratings by unfavorable comments.

The reasons given by drivers were that the RPMs clearly identified curves, were highly visible at a great distance, and provided noise and vibration when vehicles crossed them (a fact that drivers knew from previous experience). Comments on Treatments 5, 6, and 9 were almost equivalent. The markers stand out more than tape.

The comments on disliked markings (Treatments 2, 7, 10) were as follows:

1. In comparison with the RPMs and 4-ft stripes, the 1-ft stripes (Treatment 10) were judged to be short and required drivers to search for them even with the 19-ft gap; drivers could not see very far ahead to predict curves and plan actions.
2. The 48-ft gaps (Treatment 7) were deemed too far apart making the 2-ft stripes hard to follow and easy to lose sight of.
3. Two-foot stripes with 38-ft gaps (Treatment 2), called dots, were not long enough in comparison with the RPM pattern (Treatment 5), the 4-ft stripes and 36-ft gaps (Treatment 1), or the 8-ft stripes and 32-ft gaps (Treatment 3).
4. Two-foot stripes with 48-ft gaps (Treatment 7) were similarly judged in comparison with 2-ft stripes with 18-ft gaps (Treatment 4), 4-ft stripes with 36-ft gaps (Treatment 1), and RPMs (Treatment 6).

Treatments 3 (8-ft stripes) and 1 (4-ft stripes) received generally satisfactory comments on line length.

Comparison of Erratic Maneuvers and Driver Evaluation

Treatment 7, one of the three judged least effective, also had the most erratic maneuvers. Treatment 8, another with many misses and deviations, was judged least effective by 19 percent of the drivers.

Treatments 9 and 6, although highly rated, had four erratic maneuvers each, which was more than the average across all treatments. However, Treatment 5 with high ratings had no erratic maneuvers and was one of the most effective treatments. Treatment 1 (normalized for the number of observations) had an average number of erratic maneuvers and received favorable ratings.

Based on the erratic maneuvers, ratings, and comments collectively, RPM Treatment 5 was the best single treatment, but all RPM treatments were highly preferred. Of the striping systems, the 8-ft stripe pattern was preferred and the 1- and 2-ft stripe patterns were least acceptable. A maximum gap less than 38 ft was suggested by the results.

APPROACH FOR NIGHTTIME STUDIES

Objective and Scope

The objective of the nighttime studies was to investigate the base treatment and six other candidate temporary pavement markings for use at night in work zones. The six markings selected were based on the results of the daytime studies. It was decided that three striping patterns and three RPM configurations would be investigated further under nighttime conditions using an analogous test procedure.

Experimental Plan

The six treatments and the base or control condition (Treatment 1) were the same as those investigated under daytime conditions except for the deletion of three treatments (7, 8, and 10).

The experimental plan involved dividing the six marking treatments into two sets (A and B). Each set consisted of three randomly assigned treatments and the control condition: Set A was the base condition (Treatment 1) and three stripe conditions (Treatments 2, 3, 4); Set B was the base condition and three RPM conditions (Treatments 5, 6, 9).

DATA SUMMARY OF SPEED AND DISTANCE MEASURES FOR NIGHTTIME STUDIES

In order for valid statistical comparisons to be made to treatments across sets (1, 2, 6; 1, 4, 9; and 1, 3, 5), it was necessary first to establish that drivers responded identically on Curve 4, which always had the same treatment (base condition). It was concluded that this was true and that, therefore, each curve could be analyzed across sets. However, a two-way ANOVA revealed no significant differences on any MOE except distance of minimum speed within the first 1,000 ft on Curves 1 and 2. There were no treatment differences in the major MOEs (maximum and minimum speeds or speed changes). Therefore, it was concluded that for these comparisons, all of the candidate treatments tested were as effective as Treatment 1 (4-ft stripes with 36-ft gaps).

Another part of the analysis involved treatment comparisons within each set (2, 4, 3 and 6, 9, 5). The pattern noted in the daytime studies—the fact that all but two of the MOEs had the smallest mean value on Curve 4 from the left—was also evident in the nighttime studies. The new Duncan Multiple Range Test was applied to the data. If the base condition applied to each curve had resulted in no differences in MOE performance, then it could be assumed there were no curve effects except as related to the treatments and the above comparisons were valid. Unfortunately, curve differences for the base condition were found on all MOEs except two (minimum speed and distance in both directions, both absolute and at 1,000 ft). Therefore, only these MOEs were valid for making comparisons within sets. For Set A minimum speed and distance, it was found that Treatment 2 (2-ft stripes with 32-ft gaps) had a lower minimum speed than Treatment 4 (2-ft stripes with 18-ft gaps). This finding was plausible because the longer gaps should encourage maintaining a lower minimum speed. However, minimum speed was not less than the base condition. No other differences were found except for those confounded with curve differences.

In summary, the performance data offered no startling differences that would permit ranking one condition above the others. Of the limited comparisons that could be made statistically, no major findings can be reported.

SUMMARY OF ERRATIC MANEUVER DATA FOR NIGHTTIME STUDIES

Table 7 summarizes the frequencies of erratic maneuvers by treatment. Deviation frequencies were 0 to 2 per cell except for Treatment 9, an unexplained higher frequency of 5. Three of the nine misses were on Treatment 5. No particular significance can be attached to these higher frequencies and the overall distribution could be attributed to chance. Of the 13 misses with Treatment 1, four were on Curve 1, three on Curve 2, two on Curve 3, and four on Curve 4, again at essentially random expectation. The highest frequencies occurred on the base treatment on the first two curves (4 and 3 respectively) and Treatment 5 (three on Curve 3).

TABLE 7 FREQUENCIES OF DRIVING OUTSIDE NORMAL TRAFFIC LANE AS MEASURED FROM LEFT FRONT TIRE TO CENTERLINE FOR NIGHTTIME STUDIES

Treatment	Deviations to Right 11-16 ft[a]	Deviations to Right 16+ ft[b]	Misses[c]	Cumulative Misses and Deviations[d]	Passes
1	10 (1.7)	2 (0.3)	13 (2.2)	25 (4.2)	192 (32)
2	1	0	2	3	32
3	2	0	1	3	32
4	1	0	0	1	32
5	2	0	3	5	32
6	2	1	0	3	32
9	5	2	1	8	32
Total	23 (14.7)	5 (3.3)	20 (9.2)	48 (27.2)	384 (224)
Average	2.1	0.5	1.3	3.9	

Note: Numbers in parentheses are normalized to 32 observations.

[a] Frequencies of maximum lateral displacement between 11 and 16 ft.

[b] Frequencies of maximum lateral displacement over 16 ft but not including misses.

[c] Frequency of missed curves only.

[d] Total of Columns 2, 3, and 4.

Table 8 summarizes total erratic maneuvers by curve, direction, and set. No curve or set differences are evident except those related to direction. Over twice as many erratic maneuvers occurred for right curves as for left curves (122 versus 56).

In short, the deviation and miss data revealed no significant trends relative to treatments. The only significant result was the unusually high frequency of erratic maneuvers for right turns compared to left turns.

TABLE 8 NUMBER OF DRIVERS COMMITTING AN ERRATIC MANEUVER FOR NIGHTTIME STUDIES

Curve No.	Direction	No. of Subjects	No. of Drivers by Set			Total
			Base	A	B	
1	L	16	5	5	2	12
2	L	16	3	3	6	12
3	L	16	7	6	4	17
4	L	16	7	6	2	15
1	R	16	10	10	10	30
2	R	16	12	11	11	34
3	R	16	12	9	13	34
4	R	16	10	8	6	24

SUMMARY OF SUBJECTIVE DATA FOR NIGHTTIME STUDIES

Results of Driver Evaluation of Treatments

Table 9 summarizes the results of the driver preference study. Set A drivers compared only striping treatments (Treatments 2, 3, and 4 with the baseline Treatment 1). The Set A findings regarding most effective treatment clearly support Treatment 3 (8-ft stripes with 32-ft gaps) in preference to the other striping conditions with 2-ft and 4-ft stripes. The least effective treatment was judged to be Treatment 2, which had the 38-ft gaps in combination with 2-ft stripes. These findings essentially confirmed the daytime study results.

TABLE 9 PERCENT OF VOTES FOR MOST AND LEAST EFFECTIVE TREATMENTS FOR NIGHTTIME STUDIES

	Set A Treatments				Set B Treatments			
Effectiveness	1	2	3	4	1	5	6	9
Most	6	6	75	13	13	31	37	25
Least	13	68	6	13	68	13	13	6

Set B drivers compared the three RPM treatments with the baseline. Although there was no single RPM treatment that was judged most effective, all RPM treatments were judged superior to the baseline treatment. This finding was further clarified in the drivers' judgments of least effective treatments, in that over two-thirds felt the baseline treatment (4-ft stripes with 36-ft gaps) was poorest in comparison to the RPM treatments.

Results of Driver Comments

The driver comments confirmed the ratings of the treatments. Regarding most effective, 12 of the 16 subjects (75 percent) in Set A had positive comments regarding Treatment 3. All stated that longer stripes were easier to follow in curves. Only two (13 percent) commented positively on Treatment 4, and one positive comment each (6 percent) was given on the other treatments.

Eleven (68 percent) of the Set A drivers commented negatively on Treatment 2 (2-ft stripes with 38-ft gaps). All stated that the short stripes with long gaps were more difficult to see at a distance. Two (13 percent) drivers had negative comments on Treatments 1 and 4, and one (6 percent) negative comment was given on Treatment 3.

In Set B, the positive comments were fairly evenly divided among the three RPM treatments with six for Treatment 6, five for Treatment 5, and four for Treatment 9. Comments were similar in each group, that is, closer reflectors made it easier to see ahead around the curve. Only two (13 percent) subjects commented positively on the baseline Treatment 1.

Eleven (68 percent) of the Set B drivers had negative comments on the baseline Treatment 1. Comments varied, but in essence the lack of buttons made it more difficult to see ahead. Only two (13 percent) subjects commented negatively on Treatments 6 and 5, and one (6 percent) commented negatively on Treatment 9.

Summary

The drivers' comments, unlike the speed data, provided very definite indications of a common hierarchy of preferences within sets. Of the striping systems, Treatment 3 (8-ft stripes with 32-ft gaps) was judged best, and Treatment 2 (2-ft stripes with 38-ft gaps) was judged poorest. All RPM systems were substantially preferable to Treatment 1 (4-ft stripes with 36-ft gaps), but no single RPM treatment was deemed best.

Unfortunately, the two sets of drivers did not see the treatments in the other set, therefore, an overall hierarchy could not be established; that is, Treatment 3 could not be compared with the RPM treatments. However, Treatment 2, in particular, and Treatments 1 and 4 were judged less desirable than the others. These data show that the 4-ft stripes with 36-ft gaps are judged to be inferior to the 8-ft stripes with 32-ft gaps and the three RPM treatments.

SUMMARY OF FINDINGS

Findings of the daytime studies are summarized by the following significant points:

1. The small differences observed in the speed and distance MOEs were judged not to be of practical significance as a basis for discriminating among the treatments investigated.
2. Drivers rated the 1- and 2-ft stripes with gaps of 38 ft or more as the least effective among the striping patterns tested within their respective groups.
3. Treatments 7 and 8 were found to have the greatest number of erratic maneuvers of any other treatments. These treatments each had 2-ft long stripes. Treatment 7 had 48-ft gaps and Treatment 8 had 38-ft gaps supplemented with RPMs at 80-ft intervals.
4. Treatments 5 and 10 had no observed erratic maneuvers. Treatment 5 consisted of four nonreflective RPM pavement markers at 3.33-ft centers and reflective RPMs at 80-ft centers. Treatment 10 was the 1-ft stripe with 19-ft gaps. However, drivers complained about the short stripe and rated this treatment very ineffective in comparison with Treatments 1, 8, and 9.
5. Treatments 2, 3, and 4 also had only one or two erratic maneuvers. Treatment 3 had 8-ft long stripes with 32-ft gaps and was very high in drivers' rankings of effectiveness. Treatments 2 and 4 each had 2-ft stripes. Treatment 4 had 18-ft gaps and Treatment 2 had 38-ft gaps. Treatment 2 was judged the least effective in comparison with Treatments 1, 3, and 5. Treatment 4 was of only average effectiveness in comparison with Treatments 1, 6, and 7.
6. In general, the subjective data suggested a strong preference for RPMs. Of the nonRPM treatments, Treatment 3 (8-ft stripes with 32-ft gaps) was the most preferred.
7. Drivers were largely indifferent to the 4-ft stripes with 36-ft gaps, rating them average in both most and least effective. However, the erratic maneuver data suggested it would lead to relatively few misses (four in 224 passes), but relative high frequency of deviations (5 ft or more) from centerline (18 in 224 passes).

The following points are significant for the nighttime studies:

1. The performance data, relative to speed and distance measures, yielded only small and insignificant differences across treatments. Therefore, no hierarchy of treatments is possible based on speed and distance data alone.
2. The erratic maneuver data also revealed no significant differences with respect to treatments. Only a high proportion of right-direction erratic maneuvers, as compared with those in the left-direction, was found.
3. The drivers' ratings of effectiveness during the nighttime studies revealed some definite biases in Set A (e.g., Treatment 3's 8-ft stripes with 32-ft gaps was best and Treatment 2's 2-ft stripes with 38-ft gaps was poorest). However, Treatments 5, 6, and 9 (RPM treatments), all of which were most preferred in the daytime studies when appearing in different sets, were approximately equal when compared against one another in Set B. This is taken to mean that they were all equally good, based on their previous daytime ratings.
4. In general, the nighttime studies support the findings of the daytime studies which also found Treatment 3 (8-ft stripes with 32-ft gaps) to be best (in terms of driver preference) of the nonRPM treatments, and the three RPM treatments to be highly effective as well.
5. Drivers did not like the use of Treatment 1 (4-ft stripes with 36-ft gaps) as much as some of the other treatments, but the performance data did not provide evidence that either speeds or erratic maneuvers were any different than with the more preferred treatments.

ACKNOWLEDGMENTS

This paper was prepared from data collected as part of a research project sponsored by FHWA entitled, "Improvements and New Concepts for Traffic Control in Work Zones." Justin True served as the Contracting Officer's Technical Representative for FHWA.

The authors gratefully acknowledge the assistance of Olga Pendleton for the statistical analysis, and Carlton Allen and Nada Huddleston who served as test administrators.

REFERENCE

1. R. D. Hutchingson, C. L. Dudek, and D. L. Woods. *Improvements and New Concepts for Traffic Control in Work Zones, Vol. 4—Abbreviated Marking Patterns in Work Zones.* Texas Transportation Institute, Texas A&M University, College Station, Sept. 1984.

Publication of this paper sponsored by Committee on User Information Systems.

Some Effects of Traffic Control on Four-Lane Divided Highways

CONRAD L. DUDEK, STEPHEN H. RICHARDS, AND JESSE L. BUFFINGTON

Nine field studies were conducted on four-lane divided highways in Texas and Oklahoma to evaluate two alternative traffic control approaches: single-lane closure in one direction versus a crossover with two-lane, two-way traffic operations (TLTWO). The variables studied were: worker productivity, job duration, construction costs, traffic control device costs, highway-user costs, accidents, conflicts, and capacity. Worker productivity was measured indirectly from job duration and construction costs. Because of limited data, it was not possible to identify the conditions under which one traffic control alternative offers costs savings over the other. Highway-user costs for each study site were calculated using a modified version of a work-zone queue and user-costs evaluation model. Graphs and tables show the relationships between hourly traffic volumes and road-user costs for the sites studied.

There is a growing concern among highway agencies and construction contractors about the effects of traffic control management requirements on construction work productivity, safety, and cost. For example, less restrictive traffic control management approaches are generally easier and cheaper to install. However, these approaches may adversely affect worker productivity and therefore increase the duration of work, with accompanying increases in overall cost. Safety may also be adversely affected. On the other hand, highly restrictive traffic control management approaches may improve work productivity, but may result in traffic congestion and delays and therefore increase road-user costs.

This concern is evident at work zones on four-lane divided highways where there are two basic work-zone traffic control practices available:

1. One lane in one direction is closed resulting in little or no disruption of traffic in the opposite direction (e.g., single-lane closure); and
2. One roadway is closed and the traffic that normally uses that roadway is crossed over the median, and two-lane, two-way traffic operation (TLTWO) is maintained on the other roadway.

Single-lane closures are generally less restrictive because they only affect traffic in one direction; however they may tend to increase the duration of construction, and consequently the construction cost. Conversely, a TLTWO traffic control plan may reduce the construction duration and cost, but it may also result in traffic congestion, and consequently it may increase road-user costs. There is a need to select the approach that balances work-zone productivity and safety with costs (e.g., construction, traffic control, and road-user costs). There may be levels of traffic volumes when one traffic control approach (single-lane closure versus TLTWO) becomes the better alternative. The need for highway agencies to objectively evaluate the single-lane closure and the TLTWO traffic control approaches to select the best of the two alternatives prompted FHWA to fund research to begin collecting the necessary data and developing cost relationships.

BACKGROUND

Objectives and Scope

The objectives of the research in this paper were to

1. Conduct field studies to evaluate the current traffic control requirements for work sites on four-lane divided highways to determine their effects in time, cost, and safety to perform the work; and

---

C. L. Dudek and J. L. Buffington, Texas Transportation Institute, Texas A&M University System, College Station, Tex. 77843-3135. S. H. Richards, Transportation Center, University of Tennessee, Knoxville, Tenn. 37996.