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16. Abstract

The objectives of the study were to evaluate the operational, safety, and cost-effectiveness of retroreflective raised pavement markers (RPMs) supplementing the existing painted centerline as an alternative to existing post-mounted delineators (PMDs) at horizontal curves on rural two-lane highways. The safety and operational evaluations were based upon the collection of nighttime speed and lateral placement data at seven study sites. The operational data analysis focused on those measures of effectiveness that previous research has suggested are correlated to accident rates at horizontal curves. The results of the analysis suggest that new RPMs compare favorably to PMDs. A limited evaluation at one site of RPMs that had been in place 11 months and had lost most of their reflectivity suggests that the RPMs continued to provide near delineation but that their far delineation was at least partially degraded. The cost comparisons were sensitive to the service lives of the two delineation treatments. For RPMs with a 1-year service life, the breakeven service life of PMDs ranges from 4 to 8 years, corresponding to curvature increasing from 1 to 8 degrees. For RPMs with a 2-year service life, the breakeven service life of PMDs ranges from 8 to 18 years.

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AN ALTERNATIVE TO POST-MOUNTED DELINEATORS AT HORIZONTAL CURVES ON TWO-LANE HIGHWAYS

by

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Research Report 1145-1F
Research Study Number 2-18-88-1145
An Alternative to Delineators

Sponsored by

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TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
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July 1990

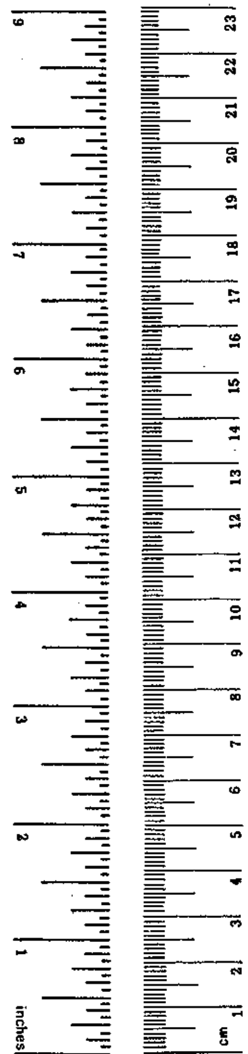
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
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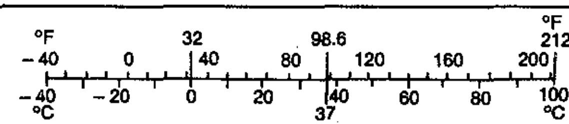
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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* SI is the symbol for the International System of Measurements

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Personnel in Districts 1, 2, 7, 9, 10, 15, 17, 18, and 19 supplied data on the costs of post-mounted delineators and raised pavement markers. Their assistance is also greatly appreciated.

F. Thomas Creasey served as Study Co-Supervisor during the first 17 months of the study. He played a key role in formulating the experimental design and data collection procedures for the field studies. The participation of the following Texas Transportation Institute personnel in one or more field studies is also gratefully acknowledged: Carlton Allen, Bobby Breedlove, Allen Crozier, Keith Davis, Steve Glascock, Tom Hammons, Maurice Hart, Doug Skowronek, Richard Timm, Nada Trout, Diana Wallace, Marc Williams, and Steve Wohlschlaeger.

The authors also gratefully acknowledge Dr. Olga J. Pendleton for her valuable contributions to the statistical analysis methodology and for her review of the final report.

SUMMARY OF FINDINGS

The objective of the study was to evaluate the operational, safety, and cost-effectiveness of using retroreflective raised pavement markers (RPMs) supplementing the existing painted centerline as an alternative to existing post-mounted delineators (PMDs) at horizontal curves on rural two-lane highways.

The safety and operational evaluations were based upon the collection of nighttime speed and lateral placement data at seven study sites. Data were collected in both the inside and outside lane of the curve at the study sites. Both short-term and long-term evaluations were conducted. That is, data were collected both when the RPMs were new (short-term) and after they had been in place and lost some of their reflectivity (long-term). The operational data analysis focused on those measures of effectiveness that previous research has suggested are correlated to accident rates at horizontal curves. The measures studied were the mean and standard deviation of speeds at the midpoint of the curve, mean and standard deviation of the speed change from the beginning to the midpoint of the curve, mean and standard deviation of lateral placement at the midpoint of the curve, and vehicle encroachments into the opposing lane at the midpoint of the curve.

In the short-term evaluation, several differences between the existing PMDs and new RPMs were observed in the outside lane of the curves studied:

- o The mean speeds at the midpoint of the curves were consistently 1-3 mph higher with the new RPMs than with the existing PMDs.
- o The mean lateral placement (measured from the center of the roadway to the front left wheel of the vehicle) was consistently 1-2 ft further from the center of the roadway at the midpoint of the curve with the new RPMs than with the existing PMDs.
- o The variability in lateral placement at the midpoint of the curve was less with the new RPMs than with the existing PMDs.
- o Fewer vehicles crossed the center of the roadway with the new RPMs than with the existing PMDs.

The short-term operational data analysis suggests that operations with the new RPMs compared favorably with the existing PMDs. The results suggest that the new RPMs provided better path delineation (as evidenced by the findings related to lateral placement and encroachments) which may give drivers the confidence to operate at higher speeds through the curves.

The long-term operational data analysis revealed few changes in the operational effectiveness of RPMs as they aged and lost reflectivity. Vehicle operations were observed at only one site at which the RPMs had been in place 11 months and had lost most of their reflectivity. After 11 months at that site, the RPMs compared favorably to the existing PMDs with respect to the mean lateral placement and the number of encroachments. The only concern with the 11-month-old RPMs was a small, but statistically significant, increase in deceleration from the beginning to the midpoint of the curve, which may indicate that the RPMs either did not provide sufficient advance warning of the curve. These results suggest that even after RPMs had lost most of their reflectivity they continued to be effective at providing near delineation, but their effectiveness at providing far delineation was degraded. Unfortunately, there is no objective basis for determining whether the performance level of the 11-mo-old RPMs was adequate. Additional research will be necessary to define minimum performance levels and to determine how long RPMs continue to function acceptably.

The cost-effectiveness evaluation of RPMs and PMDs at isolated horizontal curves on two-lane rural highways was based upon cost data obtained from a survey of SDHPT District personnel. The relative cost-effectiveness of the two treatments depends upon the degree of curvature (which affects the number of PMDs required) and their service lives. Therefore, the cost comparisons were summarized in terms of the service lives for which the costs of the two treatments were equal. For RPMs with a 1-year service life, the breakeven service life of PMDs ranges from 4 to 8 years, corresponding to curvature increasing from 1 to 8 degrees. For RPMs with a 2-year service life, the breakeven service life of PMDs ranges from 8 to 18 years. The results suggest that RPMs, even with a 1-year service life, are likely to be more cost-effective at horizontal curve locations where PMDs are frequently knocked over. However, at curves where PMDs are not susceptible to hits, RPMs would require a service life of 2 or more years to be more cost-effective than PMDs. The SDHPT should consider performing an updated cost comparison after their new maintenance management information system has been in place several years and the service life of RPMs is better defined.

IMPLEMENTATION STATEMENT

The results of the study suggest that from a safety and operational standpoint new retroreflective raised pavement markers (RPMs) supplementing the existing painted centerline are an acceptable alternative to post-mounted delineators at horizontal curves on two-lane rural highways. This conclusion applies only to locations for which there is adequate sight distance to the horizontal curve. The study did not evaluate any curves to which sight distance was restricted by the vertical alignment.

Data collected at one study site suggest that 11-month-old RPMs that had lost much of their reflectivity continued to provide adequate near delineation (i.e., path guidance within the curve) but somewhat degraded far delineation (i.e., advance warning of the curve). However, the results of the study do not give sufficient information to determine how long RPMs continue to function at an acceptable performance level. Additional research is needed to determine how the operational effectiveness of RPMs changes as they age and lose reflectivity and at what time intervals they should be replaced.

The results of the cost-effectiveness evaluation suggest that the relative cost-effectiveness of RPMs and PMDs at isolated horizontal curves on two-lane rural highways depends upon their service lives. The results of this study, which were based solely upon installation and replacement costs, suggest that RPMs may be more cost-effective at horizontal curves where PMDs would be hit frequently, but that PMDs may be more cost-effective at other locations, unless the service life of RPMs is 2 or more years. The total life-cycle costs of the two treatments cannot be estimated accurately based upon the Department's current maintenance cost records. Therefore, the Department should consider performing an updated cost comparison after their new maintenance management information system has been in place several years, and the service life of RPMs is better defined.

DISCLAIMER

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1. INTRODUCTION

Post-mounted delineators (PMDs) are "intended to be a guide to the vehicle operator as to the alignment of the highway" (1). This report focuses on one common application of PMDs: to provide guidance through horizontal curves on two-lane rural highways. Maintenance problems associated with PMDs have proven to be a nuisance. As a result, engineers in the Districts of the Texas State Department of Highways and Public Transportation (SDHPT) have sought an alternative on-pavement delineation treatment to replace PMDs. The research reported herein was performed at the Texas Transportation Institute to evaluate one specific alternative to PMDs, i.e., retroreflective raised pavement markers (RPMs) supplementing the existing painted centerline.

1.1. PROBLEM STATEMENT

Adequate path delineation is particularly important on horizontal curves. In a study on the accident characteristics of horizontal curves on two-lane rural highways, Glennon et al. (2) found that the average accident rate on horizontal curves is three times that of tangent sections, that the average rate of single-vehicle run-off-the-road accidents on horizontal curves is four times the rate on tangent sections, and that single-vehicle run-off-the-road accidents were proportionally greater than other accidents under poor environmental (wet/icy) and light (nighttime) conditions. Glennon (3) also reported that more than two-thirds of the single-vehicle run-off-the-road accidents were on the outside of the curve.

PMDs at the side of the roadway, according to the Texas Manual on Uniform Traffic Control Devices (1), "are effective aids for night driving and are to be considered as guidance devices rather than warning devices." One recommended application is at horizontal curves where changes in the alignment may surprise or confuse some motorists. PMDs are intended to provide supplemental information about the alignment of the roadway that will allow the driver to navigate the roadway more safely.

Widespread use of PMDs has brought about considerable maintenance problems. Vegetation around the posts must either be sprayed with a herbicide or cut back by hand because it is difficult to maneuver heavy mowing equipment around the posts. Furthermore, it is frequently necessary to repair or replace posts knocked over by large vehicles, such as farm equipment, or by vehicles that run off the roadway. As a result, there is a desire to replace PMDs on less potentially hazardous horizontal curves on rural, two-lane roads with an alternative on-pavement delineation treatment that is equally effective and less costly to maintain. Currently, the SDHPT has no guidelines on the removal of PMDs or on what alternative treatments may be used to replace them. The research documented herein provides some of the information necessary to establish such guidelines.

1.2. SCOPE AND OBJECTIVES OF THE STUDY

The objective of the study was to evaluate the safety, operational, and cost-effectiveness of removing existing PMDs at horizontal curves on two-lane rural highways and replacing them with an alternative on-pavement delineation treatment. Early in the study, the TTI researchers and SDHPT technical coordinator agreed to restrict the study to one alternative delineation treatment: retroreflective raised pavement markers (RPMs) supplementing the existing painted centerline. This decision was based upon a review of previous research and a survey of practices throughout the Districts of the SDHPT, which suggested that RPMs supplementing the existing painted centerline were an effective and commonly used alternative to PMDs. Chapter 2 summarizes the findings of the literature review.

Figure 1 illustrates the pattern of RPMs that was studied. RPMs are placed on the centerline at 40-ft intervals within the curve. An additional 4 RPMs are placed at 80-ft intervals on the tangents approaching both ends of the curve.

The basic approach for the safety and operational evaluations was to focus on operational measures of effectiveness (MOEs) that could be observed in the field and that were reasonable surrogate measures for accident experience. This approach was taken for two reasons. First, previous efforts in Texas to determine the effectiveness of raised pavement markers at reducing accidents proved inconclusive because of the difficulty in controlling other factors that affect accident frequencies at the large number of sites needed to provide statistically reliable results. Second, the two-year duration of the study was too short to obtain before and after accident data in sufficient quantity and with sufficient control to be conclusive.

The operational evaluation considered both the short- and long-term operational effectiveness of RPMs. That is, nighttime operational data were collected immediately after the RPMs were installed (i.e., short term) as well as after the RPMs had been in place and lost some of their reflectivity (i.e., long-term). The weather was clear and dry during all data collection. Operational data were collected at 7 horizontal curves where existing PMDs were replaced with new RPMs and at 3 of those curves after the RPMs had been in place up to 11 months. The collection and analysis of the operational data are documented in Chapter 3.

The cost-effectiveness analysis was based upon cost data that were available from various District and Division offices of the SDHPT. The data were compiled, and the analysis is presented in Chapter 4.

A summary of findings and recommendations is presented in Chapter 5.

The report also contains four appendices. Appendix A provides descriptions of the study sites. Appendix B contains graphical summaries of observed vehicle speeds and lateral placements through the horizontal curves. Appendix C contains summary statistics and the results of the statistical analysis of the operational data. Appendix D summarizes the results of the survey of Districts about the costs of PMDs and RPMs.

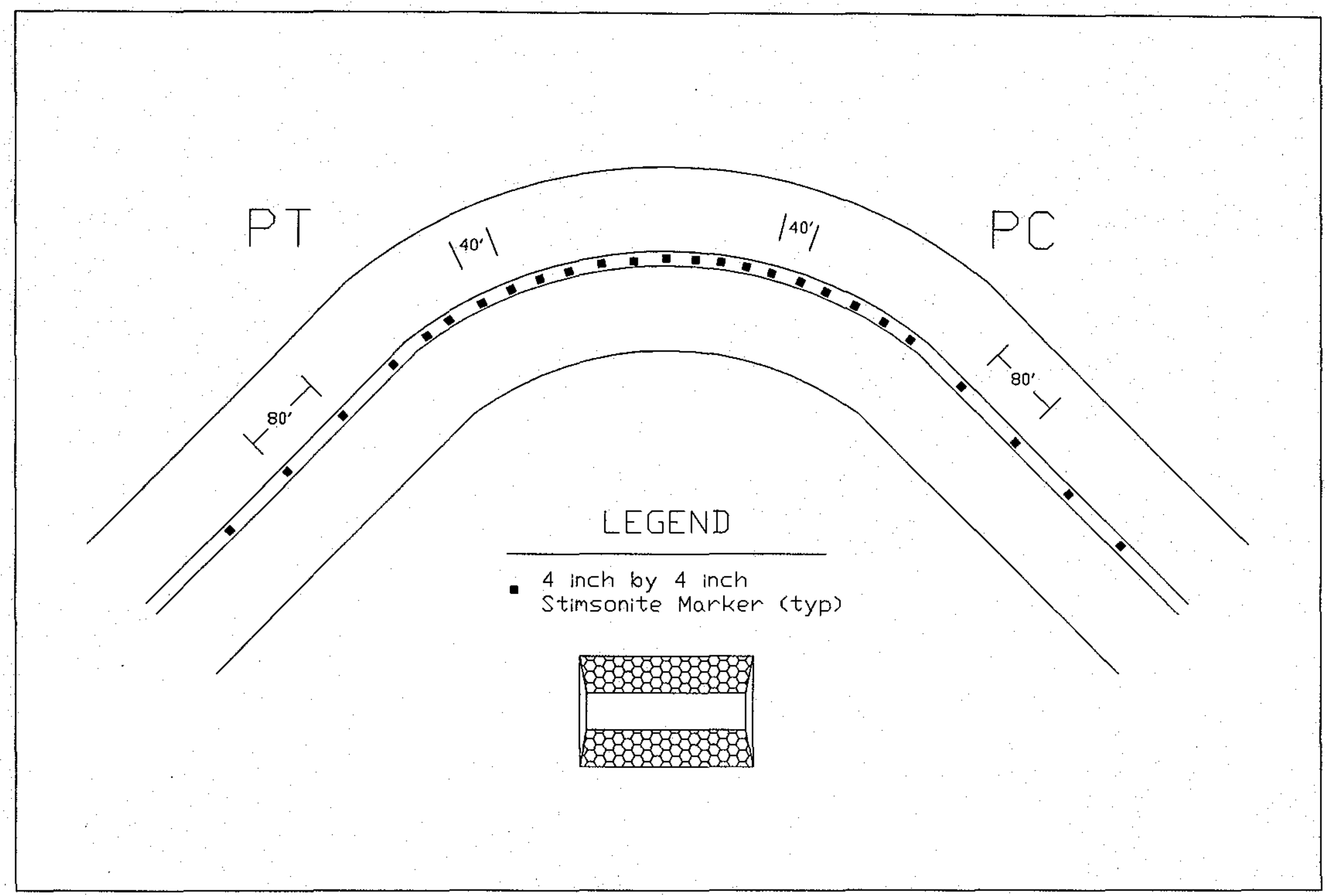

Figure 1. Pattern of RPMs Supplementing the Existing Painted Centerline

2. LITERATURE REVIEW

Several previous research studies have evaluated delineation treatments for horizontal curves on two-lane rural highways. The results of these studies formed the foundation and influenced the conduct of the research documented herein. The literature review is divided between those studies that evaluated PMDs and/or RPMs and those studies that evaluated other delineation treatments.

2.1. Safety and Operational Effectiveness of PMDs and RPMs

Several studies have considered the safety and operational effectiveness of PMDs and RPMs on two-lane rural highways. Two basic approaches have been used. Some studies looked directly at the accident experience on roadway sections with various combinations of centerlines, edgelines, PMDs, and RPMs. The difficulty in directly evaluating the safety effectiveness of alternative delineation treatments prompted other studies to evaluate operational MOEs that are correlated to accident experience and, therefore, could be used as surrogates for accident experience in safety evaluations. Most of the studies suggest that (1) PMDs and RPMs, either individually or in combination, are effective as supplements to painted centerlines, and (2) that RPMs compare favorably to PMDs.

The research by Taylor et al. (4) represented the state of the art in roadway delineation systems through 1972 and was the basis for most subsequent research in the area. The researchers gave considerable attention to the delineation of horizontal curves on two-lane rural highways. They collected operational data at two horizontal curve locations with various combinations of centerlines, edgelines, PMDs, and RPMs. They concluded that RPMs either alone or in conjunction with PMDs as supplements to existing centerlines improve driver performance through horizontal curves, when compared to weathered, painted centerlines.

Taylor et al. (4) evaluated the relationship between operational MOEs and accident rates using accident and operational data for nine horizontal curves on two-lane rural highways. They found that "A fairly strong correlation between accident rates and the variance of lateral placement on the horizontal curve seems to exist. Thus, if delineation treatments can be shown to reduce the variance in lateral placement, accident rates probably will also be reduced." They also concluded that "Although strong evidence does not exist in support of the hypothesis that accident rates are correlated with deceleration rates on horizontal curves, there seems to be some justification in concluding that this correlation may also exist. It would seem that delineation treatments that reduce this statistic are ones that provide advance warning of curves." The analyses by Taylor et al. (4) did not indicate that any other MOE related to speed (the mean, variance, and skewness of speed distributions on horizontal curves) was correlated to accident rates.

Later, in the mid-1970s, the Federal Highway Administration sponsored three major studies to evaluate the safety and cost-effectiveness of delineation treatments. One study (5) focused on driver's visibility requirements for white and yellow pavement striping and, therefore, is not directly related to the problem at hand. The other two studies by

Stimpson et al. (6) and Bali et al. (7) addressed the delineation of two-lane rural highways, including the evaluation of PMDs and RPMs.

Stimpson et al. (6) performed safety and operational evaluations of delineation treatments on two-lane rural highways. One objective of their study was to establish relationships between operational MOEs and accident probability on two-lane rural highways. They collected accident and operational data at 32 study sites on two-lane rural highways. The sites were classified as tangent sections, winding sections, or isolated curves. The researchers were unable to correlate any operational MOEs to the accident rates at the isolated curve sites. They did, however, identify two variables correlated to accident rates at the sites with tangent or winding alignment. One variable measured the extent to which the mean lateral placement of vehicles deviated from the center of the lane. The second variable was the difference in the variance of lateral placement at two critical points (the midpoint of the tangent and the midpoint of the curve for the winding alignments).

Stimpson et al. (6) also performed field studies comparing various combinations of centerlines, edgelines, PMDs, and RPMs at eight sites on two-lane rural highways. They recommended the use of 2- to 4-in centerline and edgeline striping for continuous delineation on two-lane rural highways. They concluded that RPMs supplementing painted edgelines for continuous delineation "did not appear to yield a safety gain justifying the very large installation expenses" (6). They recommended the use of RPMs to supplement the centerline where severe visibility problems due to fog or blowing sand are common. For isolated horizontal curves on two-lane rural highways, Stimpson et al. (6) concluded, based upon field studies at two locations, that RPMs "are preferred over" PMDs as supplements to centerlines. They also stated, however, "When RPMs cannot be used because of economic problems, consideration should be given to the installation of post delineators on the outside of the curve. Although not likely to be as beneficial as RPM supplements, PMDs apparently do provide some degree of near as well as far delineation" (6).

Bali et al. (7) developed a cost-benefit methodology for the evaluation of specific delineation treatments and guidelines for cost-effective delineation. The methodology was based upon the safety effectiveness of the various delineation treatments studied. The continuous delineation treatments studied included various combinations of centerlines, edgelines, PMDs, and RPMs. Treatments for isolated horizontal curves included combinations of centerlines, edgelines, and PMDs. Accident data were obtained for more than 500 sites in 10 states. Regression models were developed to predict accident rates based upon roadway, traffic, environmental, and delineation variables. Separate models were developed for the following categories of alignment: tangent, winding, and isolated horizontal curves. The type of delineation did not explain accident rate variance in most of the models. The difficulties in isolating and estimating the effect of delineation on accident rates led the researchers to urge users to exercise extreme caution in applying the models. With these cautions in mind, Bali et al. (7) drew the following conclusions with respect to the effect of delineation treatments on accident rates:

For tangent and/or winding sites:

1. Highways with centerlines have lower accident rates than those with no treatment at all.

2. Highways with raised pavement marker centerlines have lower accident rates than those with painted centerlines.

3. Highways with post delineators have lower accident rates than those without post delineators (in the presence or absence of edgelines).

4. Results of analyses of accident rates with edgelines versus those without edgelines are mixed.

5. In general, reductions in accident rates, where stronger delineation treatments are employed, are more clearly indicated for tangent sections than for winding sections.

For isolated horizontal curves:

1. The results of the analyses are not as definitive as for tangent and/or winding sites.

2. There is some indication that sites with post delineators have lower accident rates than sites without post delineators.

3. Accident rates appear to be somewhat lower at horizontal curves with centerlines than at curves with no delineation treatment.

In the early 1980s, Niessner (8, 9) coordinated separate field evaluations of PMDs and RPMs. He concluded, based upon field evaluations of PMDs by eight states, "It is not possible to state that the installation of post delineators under all conditions will result in a reduction in the number of run-off-the-road-type accidents. The data that was collected indicates a trend toward reducing this type of accident with the installation of post delineators" (8). His finding with respect to RPMs, based upon field evaluations by twelve states, was as follows: "The general consensus was that the raised pavement markers do provide improved nighttime pavement delineation when compared to and used in conjunction with conventional paint stripes. However, they should not be construed as a panacea for reducing the potential hazards at all locations" (9).

Several other studies have also evaluated operational impacts of RPMs and/or PMDs. Nemeth et al. (10) evaluated various combinations of centerlines, edgelines, PMDs, and RPMs with respect to the distance from which a curve could be detected and found that, compared to no delineation, the addition of RPMs to centerline and edgelines gave the largest increase in detection distance. Zador et al. (11) compared the operational effects of chevrons, PMDs, and RPMs at horizontal curves on two-lane highways. They found that vehicles moved toward the centerline when PMDs were added but moved away from the centerline when chevrons and RPMs were added. The variability in speeds and lateral placements were slightly reduced when chevrons and RPMs were used. Zador et al. (11) concluded, "Although drivers did change their behavior in response to the delineation modifications, there was no clear evidence that any one of the devices is superior to the others."

2.2. Safety and Operational Effectiveness of Other Delineation Treatments

Several delineation treatments other than standard applications of PMDs and RPMs have also been evaluated. These treatments include RPMs on the edgelines, wide edgelines, and chevrons.

Stimpson et al. (6) evaluated a delineation treatment that included RPMs on both the painted centerline and edgelines. They estimated that this treatment could reduce accident potential, but concluded that its cost did not justify the benefits and, therefore, that the treatment did not warrant further research.

Both Hall (12) and Cottrell (13) analyzed the safety effects of 8-in wide edgelines on rural two-lane highways. Both researchers concluded that the wide edgelines did not have a significant effect on the frequency of run-off-the-road accidents. Cottrell (13) also concluded that "Lateral placement and speed were not practically affected by a change from a 4-in to an 8-in wide edgeline."

Jennings and Demetsky (14) evaluated operations through horizontal curves on two-lane rural highways with both chevron signs and standard PMDs. They recommended the use of chevrons at curves sharper than 7 degrees, based upon observations of fewer centerline encroachments and lower speeds with chevron signs than with standard PMDs at such curves. Their analysis of operational data for curves less than 7 degrees supported the use of standard PMDs.

2.3. Summary of Literature Review

Previous research suggests that PMDs and RPMs, either individually or combined, are effective supplements to painted centerlines. Most of the studies based their conclusions upon comparisons of operational MOEs (speed and lateral placement). There has been little success at isolating the effect of these delineation treatments on accident frequencies in horizontal curves. Little attention has been paid to the short-term effects of changing from one delineation treatment to another or to the long-term operational effectiveness of the treatments.

3. OPERATIONAL DATA ANALYSIS

This section documents the collection and analysis of operational data for PMDs and RPMs at horizontal curves on two-lane roadways. First, the basic study approach, operational MOEs, data collection procedure, and statistical analysis methodology are described. Then, the results of the short-term and long-term analyses are presented.

3.1. STUDY APPROACH

The principal research question was whether RPMs supplementing the existing painted centerline were a suitable alternative delineation treatment to PMDs at horizontal curves on two-lane rural highways. The scope of the study was restricted to two-lane rural highways whose existing delineation included PMDs on the outside shoulder.

The basic study approach was to monitor vehicle operations (speeds and lateral placement) at selected horizontal curves. Data were collected only at night and under clear, dry weather conditions. At each site, operational data were collected on successive nights (Monday through Thursday only) with the existing PMDs and then with the new RPMs. At three sites, data were also collected with new PMDs and after the RPMs had been in place for some time. Therefore, the only factor that might affect vehicle operations, other than the change in delineation treatments, was the population of drivers traveling through the sites on different nights. Data were collected only during Monday through Thursday evenings, so that the characteristics of the driving population should be similar.

Seven horizontal curves on two-lane rural highways were selected as field study sites. Every attempt was made to control factors related to the geometry and roadside environment so that the operational effects of the delineation treatments could be isolated. Site selection criteria included the following:

- The existing delineation treatment consisted of centerlines and PMDs,
- The curve was an isolated, simple circular curve,
- The speed limit on the roadway was 45 mph or higher,
- Shoulders, if present, were no wider than 4 ft,
- Roadside development was minimal, and, therefore, the nighttime ambient light level was low,
- There were few, if any, intersecting driveways in the vicinity of the site,
- The AADT was at least 2000 vehicles per day, and
- The roadway was not scheduled to be seal coated or overlayed during the next one to two years.

Table 1 summarizes the characteristics of the curves that were studied. The degree of curvature at the sites ranged from 3 to 5 degrees, the length of curve ranged from 850 to 1670 ft, and pavement widths (measured at the midpoint of the curve) ranged from 19 to 28 ft. All of the sites had weathered centerlines and PMDs on the outside of the curve. Two of the sites had partial or full edgelines. The FM 120 site had edgelines on both sides of the roadway throughout the curve studied. The SH 94 site had edgelines on the inside of the curve, but the edgelines on the outside of the roadway through most of the curve had been covered by pavement patching. The five other sites had no edgelines. More detailed descriptions and schematics of the study sites are presented in Appendix A. The accident history at the sites is also summarized in Appendix A.

TABLE 1. GEOMETRICS OF THE STUDY SITES

Site	AADT	Degree of Curvature	Length of Curve (ft)	Pavement Width (ft)
FM 1753	2700	5	1020	20
FM 730	1650	3	1670	19
FM 2280	3700	3	1110	22
FM 219	1350	5	850	28
FM 933	1350	4	890	25
SH 94	2300	3	990	21
FM 120	5400	5	1050	23

Table 2 summarizes the delineation treatments studied at each site. Treatments were installed in essentially the same sequence at all sites. During the first evening of the study, data were collected with the existing PMDs in place. During the next day, the PMDs were removed and new RPMs were installed in the pattern illustrated in Figure 1. During the second evening, data were collected with new RPMs in place. At two sites (FM 219 and FM 933), new delineators were placed on the posts and data were collected with the new PMDs during the second evening. At these two sites, the new PMDs were removed during the third day and new RPMs were installed. Then data were collected with the new RPMs during the third evening.

TABLE 2. DELINEATION TREATMENTS TESTED

Site	Existing PMDs	New PMDs	New RPMs	6-Week-Old RPMs	10-11-Week-Old RPMs	11-Month-Old RPMs
FM 1753	X		X			X
FM 730	X		X			
FM 2280	X		X			
FM 219	X	X	X	X	X	
FM 933	X	X	X	X	X	
SH 94	X		X			
FM 120	X		X			

The long-term effectiveness of RPMs, i.e., after they had been in place for some time, was monitored at 3 sites. At the FM 1753 site, data were collected after the RPMs had been in place approximately 11 months. At the FM 219 and FM 933 sites, data were collected 6 weeks after the RPMs were installed, and again 10-11 weeks after installation.

3.2. OPERATIONAL MEASURES OF EFFECTIVENESS

The results of previous research, which were summarized in Chapter 2, were used as the basis for selecting the MOEs to be analyzed. The focus was on those operational MOEs that have been found to be correlated with accident rates on horizontal curves. The delineation treatments were compared with respect to their effect on the following MOEs:

- Speed at the midpoint of the curve,
- Speed change from the beginning to the midpoint of the curve,
- Lateral placement at the midpoint of the curve, and
- Number of vehicle encroachments into the opposing lane at the midpoint of the curve.

Several researchers have argued that run-off-the-road accidents result from vehicles traveling too fast and, therefore, that it is desirable for delineation treatments to reduce mean speeds (15, 16). Taylor et al. (4), however, did not find a statistically significant correlation between accident rates and speed measures including the mean, variance, and skewness of the speed distribution. In spite of Taylor's finding, the mean and standard deviation of speeds at the midpoint of the curves were studied because they are such fundamental measures of traffic operations.

The speed change between the beginning and midpoint of a curve is a measure of the deceleration within the curve. Taylor et al. (4) suggested that a decrease in the deceleration between the beginning and midpoint of a curve is an indication that a delineation treatment is providing more effective advance warning of the curve. Thompson and Perkins (17) also identified the speed differential between the approach and midpoint of the curve as a good surrogate measure for the accident rate in the outside lane of isolated horizontal curves.

For the purposes of this study, lateral placement is measured from the center of the roadway to the outside edge of the left front wheel of the vehicle. Stimpson et al. (6) have suggested that the ideal vehicle path is parallel to the centerline and centered on the lane and have reported a positive correlation between the variance of lateral placement and accident frequency. Taylor et al. (4) found that a delineation treatment that produces a smaller variance in lateral placement would generally have a lower accident rate.

The number of vehicle encroachments is related to the variance of the lateral placements. In this study, an encroachment is said to occur if the left front wheel crosses the center of the roadway. Thompson and Perkins (17) have reported positive correlations between the total encroachment rate (i.e., "number of edgeline plus centerline touches per 100 vehicles entering curve") and accident experience at horizontal curves. A smaller number of encroachments would be indicative of a more effective delineation treatment.

3.3. DATA COLLECTION

3.3.1. Types of Data

Data were collected on the spot speeds and lateral placements of vehicles at the beginning, midpoint, and end of the horizontal curve as well as at points on the tangents at each end of the curve. Data were collected in both lanes at each location.

3.3.2. Data Collection Equipment

An automated data collection system was used to collect the vehicle operations data. Electronic impulses generated by each axle passing over tapeswitches placed on the roadway were transmitted to a Golden River Environmental Computer, which converted the data to real-time information and stored it on an IBM-compatible microcomputer for later processing.

Tapeswitches are a long thin pair of metal contacts that are separated along their edges by insulating material and encased in a protective, waterproof sheathing. They function as a normally open momentary contact switch. The tapeswitches were placed on the roadway surface and covered with a nylon mesh protective mat material with a bitumen backing. The mat material is a flat gray in color and blends well with the color of the roadway surface. The tapeswitches are approximately 1/4 inch high when placed on the roadway. When covered with the protective mat material, a barely audible rumble is heard within vehicles passing over the tapeswitches. Observation of drivers passing over the tapeswitches in a previous study showed no noticeable effect on driver behavior (18).

The typical tapeswitch configuration is shown in Figure 2. The tapeswitches are arranged in a double Z-trap configuration (see Figure 2 inset) that allows data to be collected in both directions at each location. Three double Z-traps were placed in the curve: at the midpoint and at both ends. One double Z-trap was placed on each tangent, 300-800 ft from the end of the curve.

The data collected using this system are believed to be quite accurate. The principal source of error would be the improper placement of the tapeswitches. A 0.1-ft error in the placement of the parallel tapeswitches would result in a 1-mph error in speed. A 1-degree error in the placement of the diagonal tapeswitch would result in a 0.1-ft error in the lateral placement. Because the same template for outlining the Z-trap configuration was used at each site and the same tapeswitch setup was used to collect data with the existing PMDs and new RPMs on successive nights, errors of such magnitude are unlikely.

3.4. STATISTICAL ANALYSIS METHODOLOGY

3.4.1. Objective

The basic objective of the statistical analysis was to determine whether any undesirable changes in the operational MOEs occurred at the study sites after the PMDs were removed and replaced with new RPMs supplementing the existing centerline, or after the RPMs had aged and lost some of their reflectivity.

3.4.2. Data Screening Process

The raw data from the study sites were screened so that the data base to be analyzed included only those vehicles that could be tracked through the entire study site and whose operations were unaffected by other vehicles. The objective of the data screening process was to isolate the effect of delineation on how drivers operate their vehicles through horizontal curves. Vehicles were considered to be unaffected by other vehicles if they were neither closely following another vehicle in their lane nor within the study section at the same time as a vehicle in the other lane.

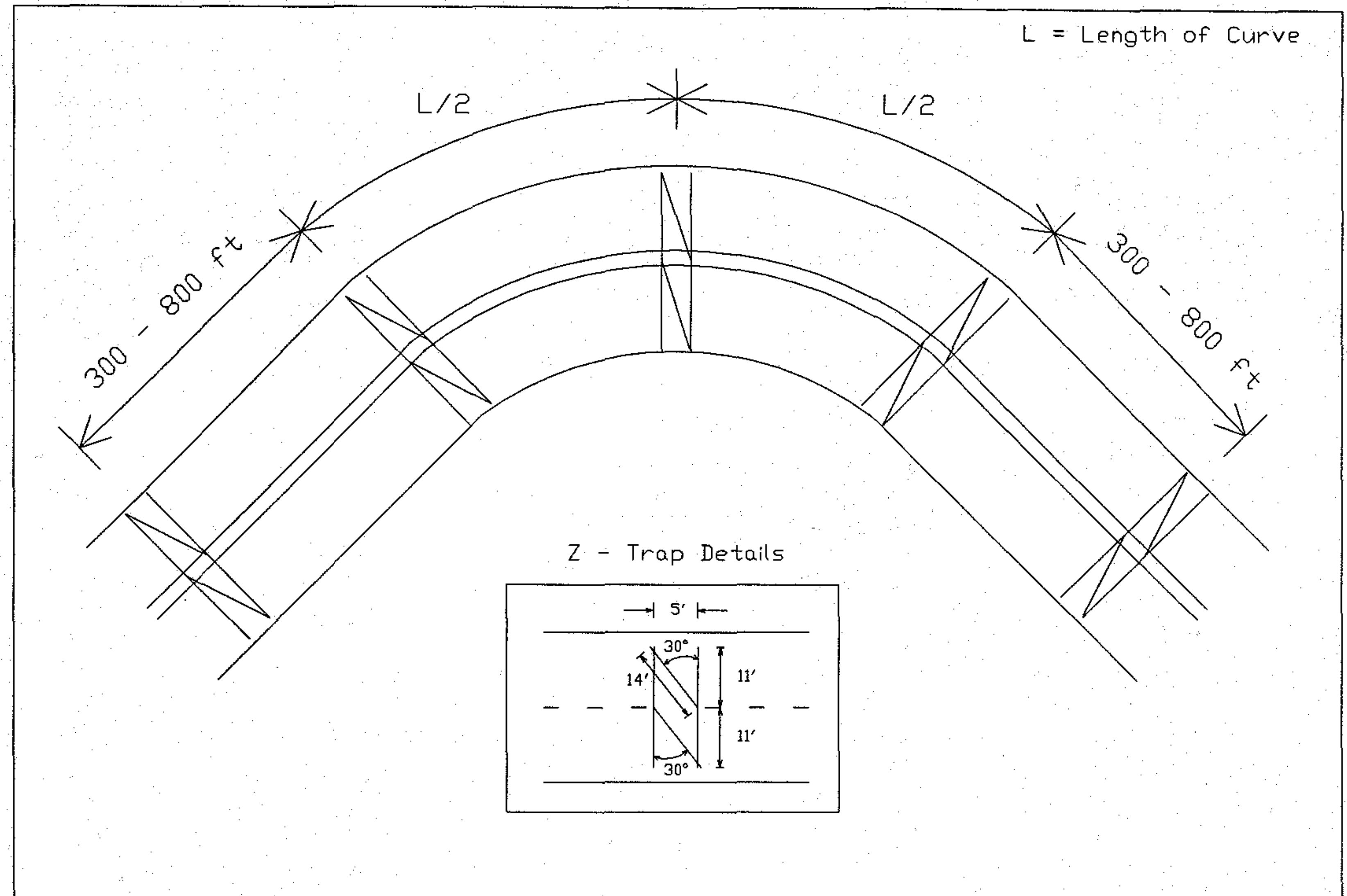

Figure 2. Schematic of Typical Data Collection Equipment Setup.

The data collection system allows individual vehicles to be tracked through the curve. Only vehicles that could be tracked through each data collection location at a study site were included in the data base. Including only tracked vehicles helps isolate the effect of the different delineation treatments on vehicle operations by controlling the driver-related factors that may also affect vehicle operations through horizontal curves. Vehicles that could not be tracked included vehicles that were in the curve when the data collection began and ended, and vehicles that left the roadway at driveways within the study section.

Vehicles were removed from the data base if they were closely following another vehicle in their lane through the study site. Drivers closely following another vehicle have visual cues from the leading vehicle as well as from the roadway delineation to guide them through a curve. A headway of 4 sec was the criteria used to screen vehicles that were following closely. Headways were checked at each data collection station in the curve, and vehicles were removed from the data base if their headway was 4 sec or less at any one data collection location.

Vehicles were also removed from the data base if they were within the study site during the same time as a vehicle in the other lane. Illumination from the headlights of oncoming vehicles affects driver behavior through curves. In cases where vehicles in opposing directions were within the study section at the same time, both vehicles were removed from the data set.

In summary, the data base that was analyzed included only vehicles that traveled through the entire study section, were not closely following another vehicle in their lane, and were not within the study site at the same time as a vehicle in the other lane. The data screening process reduced the size of the data base, but increased its quality.

3.4.3. Sample Size

Prior to data collection, it was estimated that a sample size of approximately 50 vehicles would be required with each treatment at each site in order to be reasonably confident of being able to detect a 2-mph difference in mean speeds and a 0.5-ft difference in mean lateral placements between the treatments. Budgetary and logistical considerations limited the data collection to one night per treatment at each site. Therefore, one of the study site selection criteria was an AADT of at least 2000 vehicles per day.

Table 3 summarizes the number of vehicles in the data base for each treatment and site. The total number of vehicles was 1355. For all sites except FM 730, at least 25 vehicles in the outside lane were included in the data base. Two sites (FM 1753 and FM 2280) had less than 25 vehicles in the inside lane.

TABLE 3. SAMPLE SIZE

Site	Delineation Treatment	Sample Size: Outside Lane	Sample Size: Inside Lane	Sample Size: Total
FM 1753	Existing PMD	52	28	80
	New RPM	33	13	46
	11-Mo-Old RPM	27	12	39
FM 730	Existing PMD	8	27	35
	New RPM	24	45	69
FM 2280	Existing PMD	62	11	73
	New RPM	34	22	56
FM 219	Existing PMD	28	39	67
	New PMD	28	28	56
	New RPM	31	27	58
	6-Wk-Old RPM	28	27	55
	11-Wk-Old RPM	35	30	65
FM 933	Existing PMD	47	27	74
	New PMD	50	27	77
	New RPM	56	28	84
	6-Wk-Old RPM	46	28	74
	10-Wk-Old RPM	35	24	59
SH 94	Existing PMD	27	37	64
	New RPM	29	33	62
FM 120	Existing PMD	37	47	84
	New RPM	33	45	78
	TOTAL	750	605	1355

3.4.4. Control Data

The design of the data collection setup included an observation point that was intended to serve as a control point at which speed and lateral placement would be unaffected by changes in the delineation treatment on the horizontal curve. The reason for including a control point in the design of the data collection setup was to minimize the effect of the variability among drivers by basing the analysis upon the differences in each vehicles' speed and lateral placement at the midpoint and the control point. That is, instead of looking directly at the mean speeds and lateral placements at the midpoint, the intent was to analyze the difference in speed between the midpoint and the control and the difference in lateral placement between the midpoint and the control for each vehicle traced through the curve.

The control points were located as far from the curve as the data collection equipment allowed (500-800 ft). At most of the study sites, the curve was visible from the control point. Studies by Glennon et al. (2) on vehicle speeds through horizontal curves suggested that, during the day, "Drivers tend to begin adjusting their speeds only as the curve becomes imminent." Glennon et al. found little if any reduction in speed further than 200 ft upstream of curves milder than 5 degrees. Therefore, 500-800 ft was believed to be far enough away from the curve that drivers' speeds and lateral placements at these points would not be affected by the change in delineation treatments on the curve.

Two-sample t-tests were performed to evaluate whether statistically significant differences existed between the mean speeds and lateral placements at the control point with the existing PMD and new RPM delineation treatments. The results of the t-tests are summarized in Table C-1[1] and Table C-2 for mean speeds and lateral placements, respectively. The mean speeds in the outside lane at the control point were higher with the new RPMs than with the existing PMDs at all sites. In the outside lane at three sites, the differences were less than 1 mph, but at the other four sites the differences were 2-4 mph. The differences in speeds in the outside lane were statistically significant (at a 0.05 significance level) at three sites[2]. There were no significant or consistent differences in mean speeds in the inside lane. The differences in mean lateral placements at the control point for the two delineation treatments were as large as 1.2 ft. The differences between the two delineation treatments were statistically significant at three sites for the outside lane and at two sites for the inside lane.

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[1]All tables documenting the statistical analyses discussed in Chapter 3 have been placed in Appendix C.

[2]A 0.05 significance level is used for all statistical tests. All of the statistical analyses involve testing whether or not the delineation treatments differ. The significance level is the probability that the differences observed are due to the natural variability among the vehicles observed and are not the result of real differences between the delineation treatments. If the probability is greater than 0.05, then the data do not provide sufficient evidence to conclude that there are real differences between the delineation treatments.

It is not clear whether the differences in speed and lateral placement at the control points were due to the change in delineation treatments or to random fluctuations that occur from night to night. At several sites, the differences observed were generally small enough that use of the data for control purposes would be legitimate. However, the fact that mean speeds at the control point were consistently higher with the new RPMs than with the existing PMDs suggests that speeds approaching the curves may have been affected by the change in delineation treatments as far as 500-800 ft upstream of the curve. If the differences observed truly were a result of the change in delineation treatments, then the conclusions drawn assuming otherwise could be erroneous. Therefore, to minimize the potential for drawing incorrect conclusions, the decision was made not to use the data from the "control" point for control purposes. Vehicle operations at the midpoint of the curves are assessed using the actual mean speeds and mean lateral placements at the midpoint.

3.4.5. Short-Term and Long-Term Effects of RPMs

Separate analyses were performed to evaluate the short-term and long-term effects of RPMs on each of the operational MOEs. Short-term refers to the evening after the existing PMDs were removed and the new RPMs were installed. Long-term includes the observations approximately 6 weeks, 10-11 weeks, and 11 months after the RPMs were installed. The statistical analyses for each MOE were performed separately for each study site.

The short-term operational data analysis of existing PMDs versus new RPMs included comparisons of the means of the speed at the midpoint, speed change from the beginning to the midpoint, and lateral placement at the midpoint using t-tests. The variability in these MOEs, measured using the standard deviation, was analyzed using F-tests. The number of encroachments into the opposing lane is a discrete variable and, therefore, was analyzed using a chi-squared test at each site.

The methodology for the statistical analysis of the long-term operational data was similar to the methodology for the short-term data. The same MOEs were analyzed. Separate analyses were performed for each site. Since there were more than two delineation treatments at each site, a single-factor analysis of variance (ANOVA) was performed to compare the speed and lateral placement MOEs with the various treatments (existing PMDs, new PMDs, new RPMs, and 6-week/10-week/11-week/11-month-old RPMs) at each site. ANOVA indicates whether or not any pair of treatments has significantly different means. If the ANOVA results suggested that differences existed, then a pairwise (least-significant-difference) t-test was performed to determine which pairs of treatments differed significantly.

Most of the previous research reviewed in Chapter 2 compared new PMDs with new RPMs. Little is known about the short-term effects of changing delineation treatments or about the long-term effectiveness of RPMs as their reflectivity diminishes. The results reported herein provide some insights into these issues.

3.4.6. Inside and Outside Lanes

Separate analyses were performed for the inside and outside lanes of the curve. Previous research suggests that the run-of-the-road accident problem and the delineation requirements are greater for the outside lane than for the inside lane of a horizontal curve on a two-lane rural highway. The painted centerline is better illuminated by vehicles traveling in the inside lane and therefore, can be expected to satisfy most of the guidance requirements of vehicles on the inside lane of the curve. Therefore, one would expect vehicle operations in the inside lane to be less affected by replacing existing PMDs with RPMs than in the outside lane of a curve. Indeed, as will be reported in subsequent sections, few changes were observed in any of the operational MOEs for vehicles in the inside lane.

3.4.7. Curves with Edgelines versus Curves without Edgelines

The data from each study site were analyzed separately. Five of the curves had no edgelines, one curve had edgelines on both sides, and one curve had edgelines on the inside only. Some differences were noted in the effects of the PMDs and RPMs that might be attributed to the presence of edgelines. These differences are reported, but must be viewed cautiously since the number of curves with edgelines was so small.

3.5. SHORT-TERM OPERATIONAL DATA ANALYSIS

3.5.1. Data Plots

A series of data plots are presented in Figures B-1 through B-14 of Appendix B. The mean speeds and mean lateral placements through each study site are presented in separate figures. Figures B-1 through B-7 illustrate the mean speed profiles through each of the seven study sites. Figures B-8 through B-14 illustrate the mean lateral placement through the seven study sites.

Each figure has two parts. The top part is for the outside lane of the curve and the bottom part is for the inside lane. Mean speeds or lateral placements are plotted for the approach tangent; beginning, midpoint, and end of the horizontal curve; and departure tangent in each lane. The direction of traffic is from left to right for each lane.

Readers are urged to scan Figures B-1 through B-14 before proceeding with Chapter 3. These figures provide an excellent representation of the differences in vehicle operations between delineation treatments and among the study sites. Several interesting patterns may be observed in the data plots:

- The mean speeds in the outside lane are consistently higher with RPMs than with PMDs.
- The differences between the mean speeds with RPMs and PMDs in the inside lane are smaller and less consistent than in the outside lane.

- o The mean vehicle paths in the outside lane through the curves more closely parallel the centerline and are further from the centerline with RPMs than with PMDs.

- o There is little difference between the mean lateral placement with RPMs and PMDs in the inside lane.

The following sections summarize the statistical analyses performed to determine the significance of the differences between the operational MOEs with existing PMDs and new RPMs. The results for each MOE are discussed in turn. For each MOE, results are presented first for the outside lane and then for the inside lane. Histograms of the various MOEs are included in the chapter to illustrate the similarities and differences between the delineation treatments and among the sites. The histograms should provide sufficient information for most readers. For readers wishing to study the data in more detail, tables presenting the actual numerical values and summarizing the results of the statistical tests are included in Appendix C.

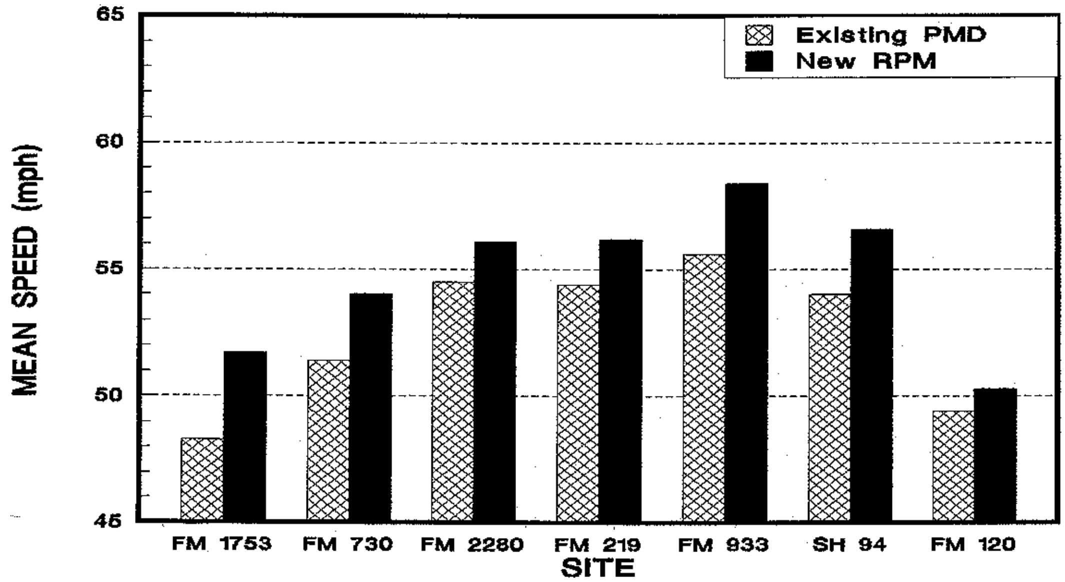
3.5.2. Speed at the Midpoint of the Curves

3.5.2.1. Outside Lane

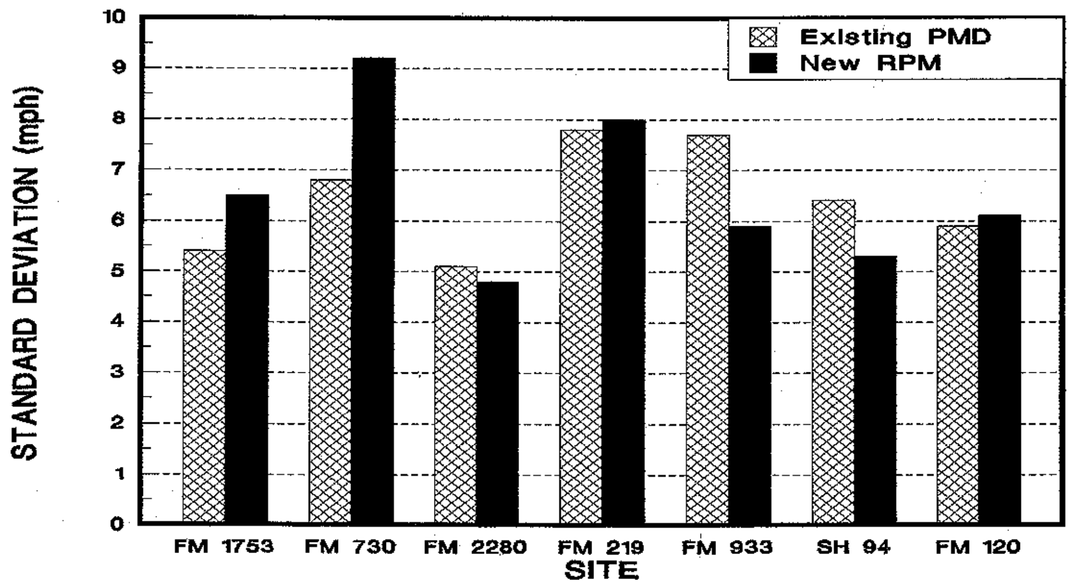
Figure 3 illustrates the mean and standard deviation of speeds in the outside lane at the midpoints of each curve with both existing PMDs and new RPMs. The mean speeds with the new RPMs are consistently 1-3 mph higher than with the existing PMDs. Table C-3 summarizes the statistical analysis. The results of the t-tests indicate that the differences between the mean speeds with the two delineation treatments are statistically significant at the FM 1753 and FM 933 sites.

It is not clear whether the higher speeds with the new RPMs is good or bad. The answer may be site specific. Higher speeds may indicate that the new RPMs provided better delineation than the existing PMDs. Drivers may have had more confidence traveling through curves and, therefore, operated at higher speeds. Some engineers and researchers argue that high speeds are a factor in run-off-the-road accidents and therefore, that it is desirable to reduce speeds at curves (15, 16). This argument may well be valid at curves with high accident rates. However, previous research has not demonstrated that a correlation exists between higher speeds and higher accident rates with different delineation treatments (4).

The standard deviation of the speeds at the midpoint of the curve in the outside lane were compared with the new RPMs and with the existing PMDs using F-tests. The results of the F-tests, which are summarized in Table C-3, indicate that the standard deviation in speeds at the midpoint do not differ significantly at any of the sites.



(a) Mean Speeds



(b) Standard Deviation of Speeds

Figure 3. Speeds at the Midpoint of the Curve: Outside Lane.

3.5.2.2. Inside Lane

Figure 4 illustrates the mean speeds in the inside lane at the midpoint of each curve. As would be expected, speeds in the inside lane appear to be less affected by the change in delineation treatments than speeds in the outside lane. At four curves, speeds were slightly higher with the new RPMs than with the existing PMDs; but at the other three curves, speeds were lower with the new RPMs. The differences in the mean speeds with the two delineation treatments were generally less than 2 mph. The results of the t-tests, which are summarized in Table C-4, indicate that the difference is statistically significant only at the FM 120 site.

Figure 4 also illustrates the standard deviation in speeds on the inside lane. Table C-4 summarizes the results of the F-tests, which indicate that the standard deviations do not differ significantly at any of the sites.

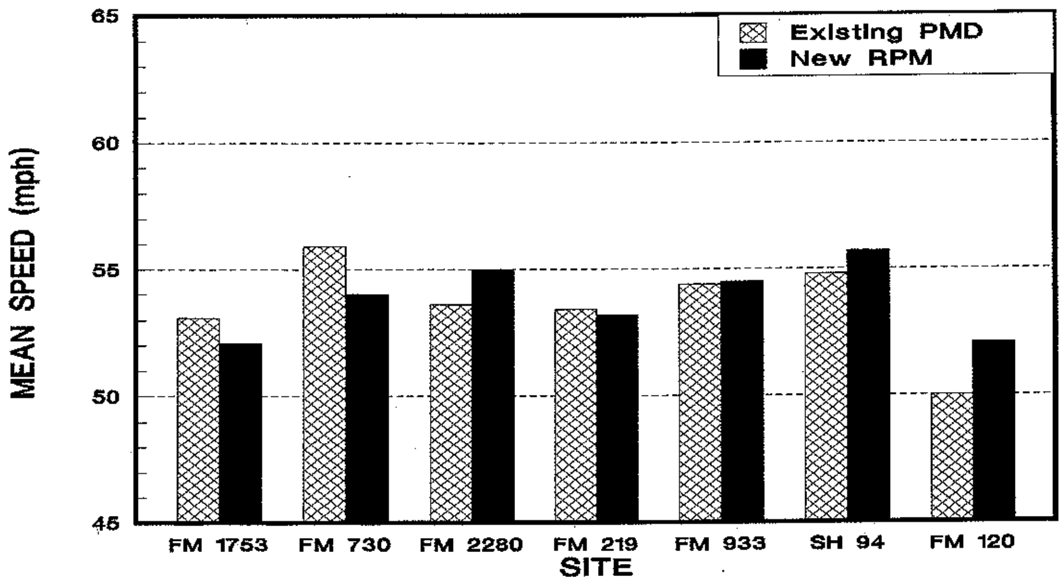
3.5.3. Speed Change from the Beginning to the Midpoint of the Curve

The speed change from the beginning to the midpoint of the curve is used as a measure of a vehicle's deceleration within the curve, which several researchers have found to be correlated to accident rates on horizontal curves--the accident rate increases as the mean deceleration rate increases. The speed change for each vehicle was computed as the vehicle's speed at the midpoint of the curve minus the speed at the beginning of the curve. Therefore, a negative speed change indicates that the vehicle decelerated from the beginning to the midpoint of the curve, and a positive speed change indicates that the vehicle accelerated.

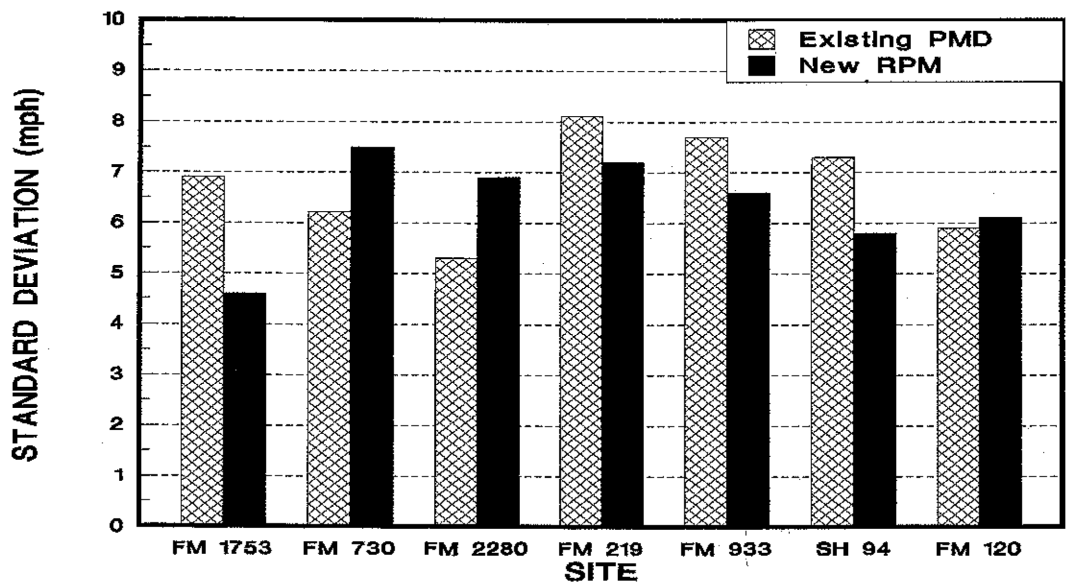
3.5.3.1. Outside Lane

Figure 5 summarizes the mean and standard deviation of the speed changes from the beginning to the midpoint of the curve at each study site. Table C-5 summarizes the statistical analyses comparing the two delineation treatments at each site. The results of the t-tests suggest that the mean speed changes with the two treatments do not differ significantly at any of the sites. This finding is illustrated in Figures B-1 through B-7 by the fact that the mean speed profiles for the two treatments are almost parallel. The fact that there were no significant differences in the mean speed change after entering the curve suggests that drivers were able to maintain the higher speeds observed through the curves with the new RPMs.

The standard deviation of the speed change between the beginning and midpoint of the curves with new RPMs and with existing PMDs was compared at each site using F-tests. The results indicate that the standard deviation in speed change differs significantly only at the FM 120 site, where there was significantly more variability in the speed change between the beginning and midpoint of the curve with the new RPMs than with the existing PMDs.

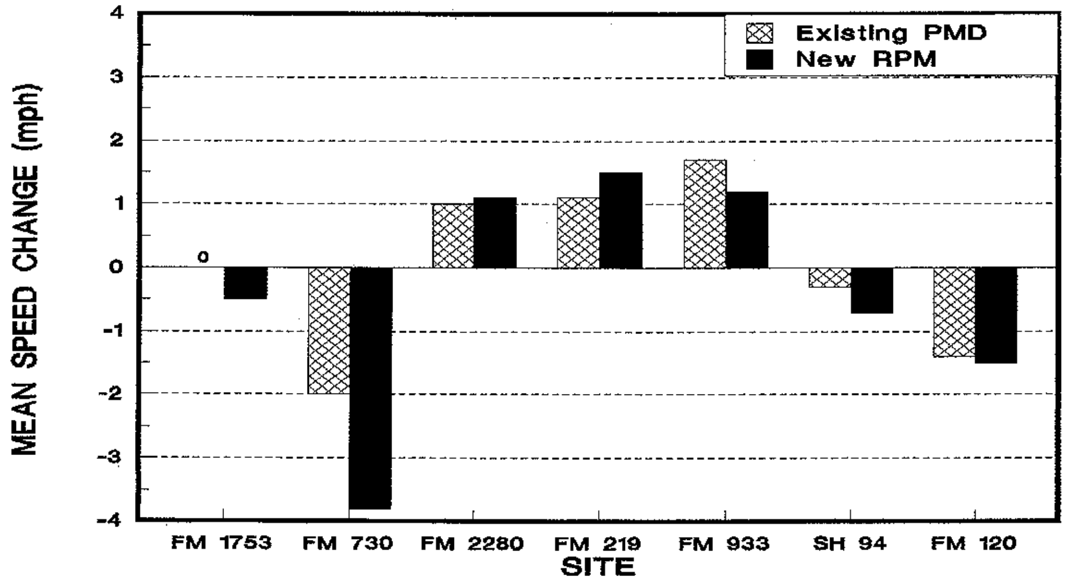


(a) Mean Speeds

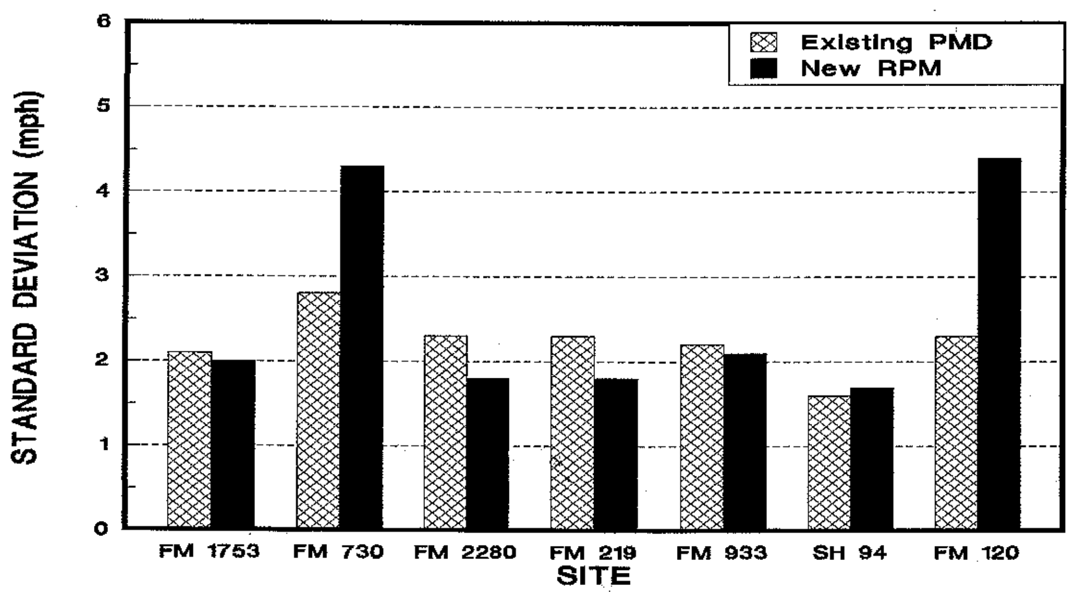


(b) Standard Deviation of Speeds

Figure 4. Speeds at the Midpoint of the Curve: Inside Lane.



(a) Mean Speed Changes



(b) Standard Deviation of Speed Changes

Figure 5. Speed Changes from the Beginning to the Midpoint of the Curve: Outside Lane.

3.5.3.2. Inside Lane

Figure 6 illustrates the mean and standard deviation of the speed changes from the beginning to the midpoint of the curve. Table C-6 summarizes the results of the t-tests and F-tests.

The results of the t-tests do not indicate any significant differences in the mean speed changes in the inside lane. The results of the F-tests indicate significant differences in standard deviation at three sites. The standard deviation of speed change was significantly lower with the new RPMs than with the existing PMDs at the FM 730 site. However, at the two sites with edgelines on the inside lane (FM 120 and SH 94) the standard deviation was significantly higher with the new RPMs than with the existing PMDs. Generally, increases in standard deviation are undesirable. A review of the data for the individual vehicles observed at the FM 120 and SH 94 sites did not reveal any serious problems. At the FM 120 site, for example, the larger standard deviation with the new RPMs appears to result from one vehicle that entered the study site at a very low speed and accelerated rapidly throughout the site.

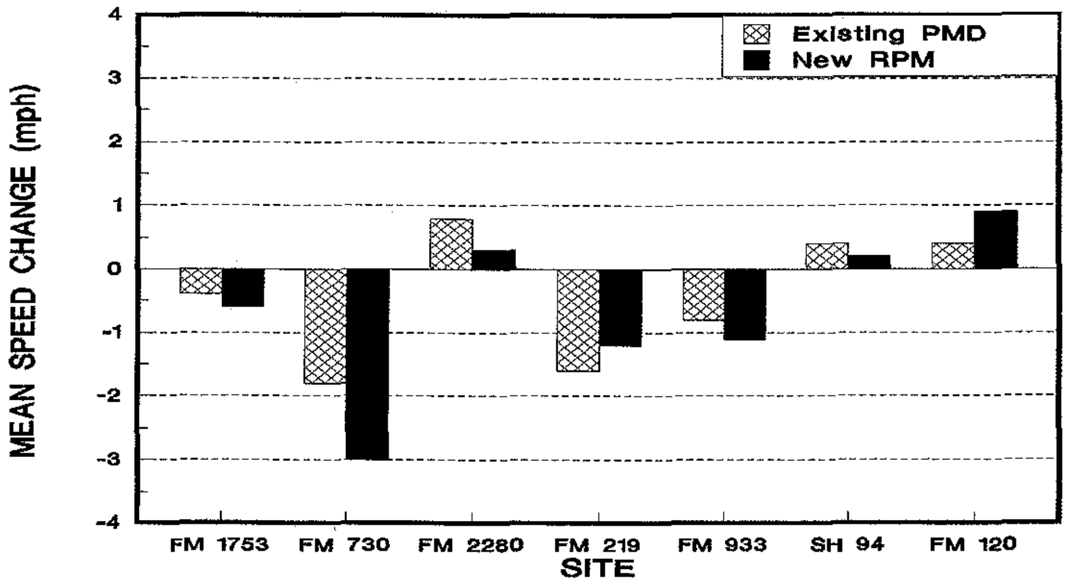
3.5.4. Lateral Placement at the Midpoint of the Curve

Previous research has suggested that the more uniform and centered the mean path of the vehicle as it traverses a horizontal curve (and particularly at the midpoint of the curve), the lower the accident rate on the curve is likely to be. The lateral placement was measured from the center of the roadway to the front left wheel of the vehicle.

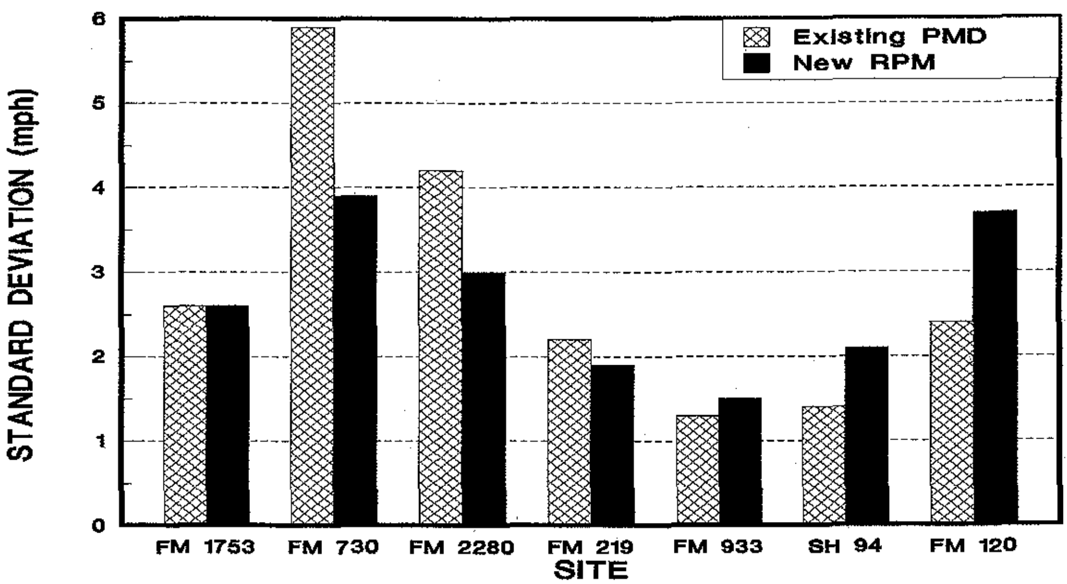
3.5.4.1. Outside Lane

Figures B-8 through B-14 trace the mean lateral placement of vehicles through the seven study sites. Two patterns are observed in the outside lane: (1) the mean path through the curves with the new RPMs more closely parallels the centerline than with the existing PMDs, and (2) the mean path with the new RPMs is further from the center of the roadway than with the existing PMDs.

Figure 7 illustrates the mean and standard deviation of the lateral placements at the midpoint of the curves. The mean lateral placement at the midpoint with the new RPMs was 1 ft or more further from the center of the roadway than with the existing PMDs at most of the study sites without edgelines. The t-test results in Table C-7 indicate that the mean lateral placement is significantly greater with the new RPMs than with the existing PMDs at all of the sites without edgelines except the FM 730 site. These results demonstrate that motorists are much less inclined to flatten their path through horizontal curves with RPMs than with PMDs. Previous research has suggested that the ideal vehicle path is centered in the lane. Therefore, these results suggest that the new RPMs compare favorably to the existing PMDs.

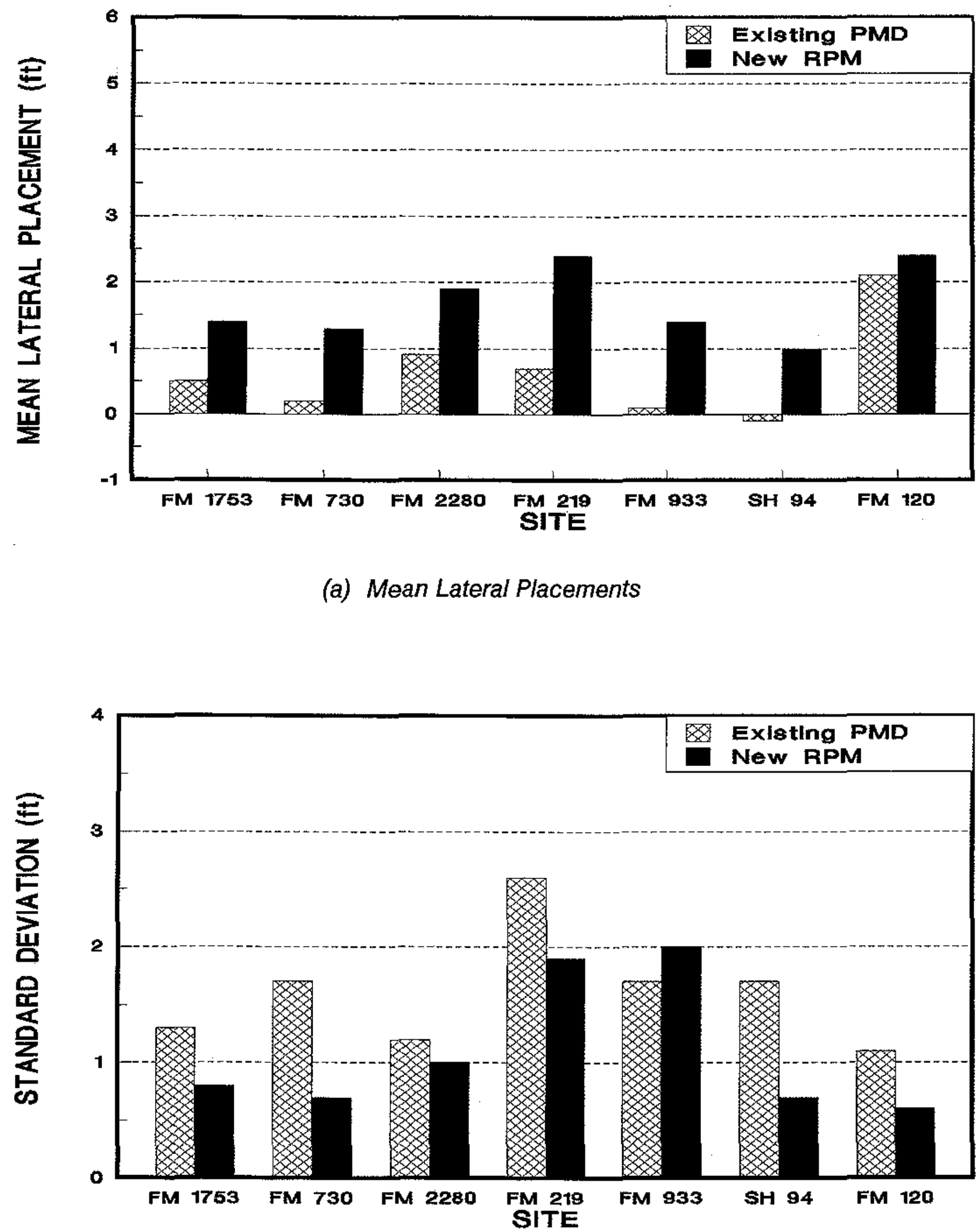


(a) Mean Speed Changes



(b) Standard Deviation of Speed Changes

Figure 6. Speed Changes from the Beginning to the Midpoint of the Curve: Inside Lane.



(a) Mean Lateral Placements

(b) Standard Deviation of Lateral Placements

Figure 7. Lateral Placements at the Midpoint of the Curve: Outside Lane.

The data from FM 120 suggest that edgelines affect the lateral placement of vehicles through horizontal curves. The mean vehicle position with the existing PMDs is much more centered at FM 120 than at the sites without edgelines, and the effect of replacing the existing PMDs with new RPMs at FM 120 is minimal.

The standard deviation of lateral placement was smaller with the new RPMs than with the existing PMDs at all but one site. The F-test results indicate that the standard deviation of lateral placement was significantly smaller at three of the sites without edgelines as well as the FM 120 site with edgelines. Previous research suggests that the variance in lateral placement is correlated with accident rates on horizontal curves. Lower variances tend to be associated with lower accident rates. Therefore, the new RPMs compare quite favorably to the existing PMDs with respect to this MOE.

3.5.4.2. Inside Lane

There is less difference between the two delineation treatments on the inside lane. Figure 8 summarizes the mean lateral placement on the inside lane at the midpoint of the curve. Table C-8 summarizes the results of the t-tests comparing the mean lateral placements with the two treatments. The two treatments differ by no more than 0.5 ft at any of the sites. Only at the site on FM 730 is the difference between the two treatments statistically significant.

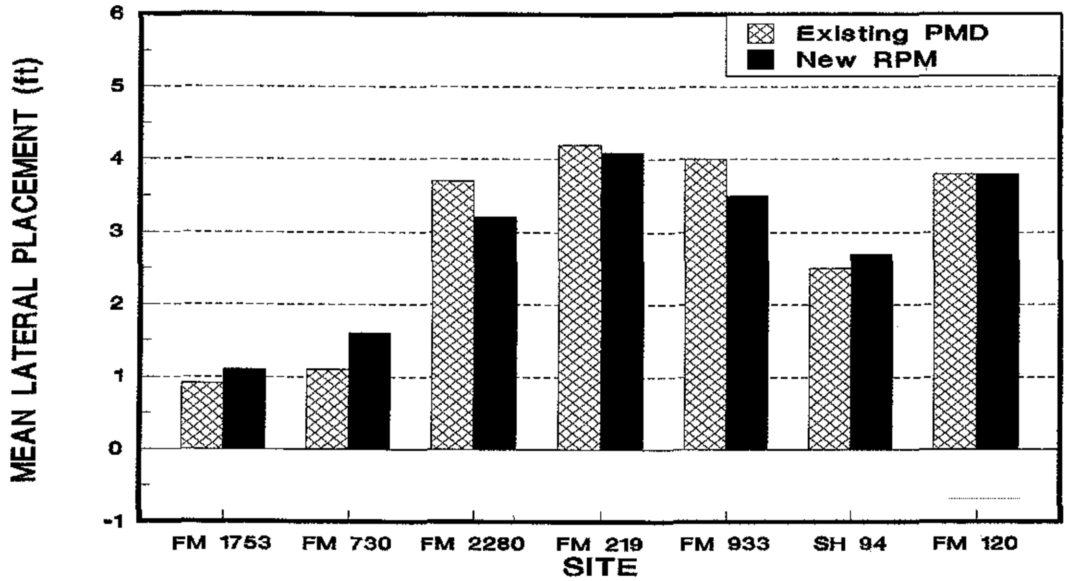
Table C-8 also summarizes the F-tests comparing the standard deviation of lateral placement at the midpoint. The results suggest that replacing the existing PMDs with new RPMs has little effect on the standard deviation of lateral placement at the midpoint of the curve.

3.5.5. Encroachments at the Midpoint of the Curve

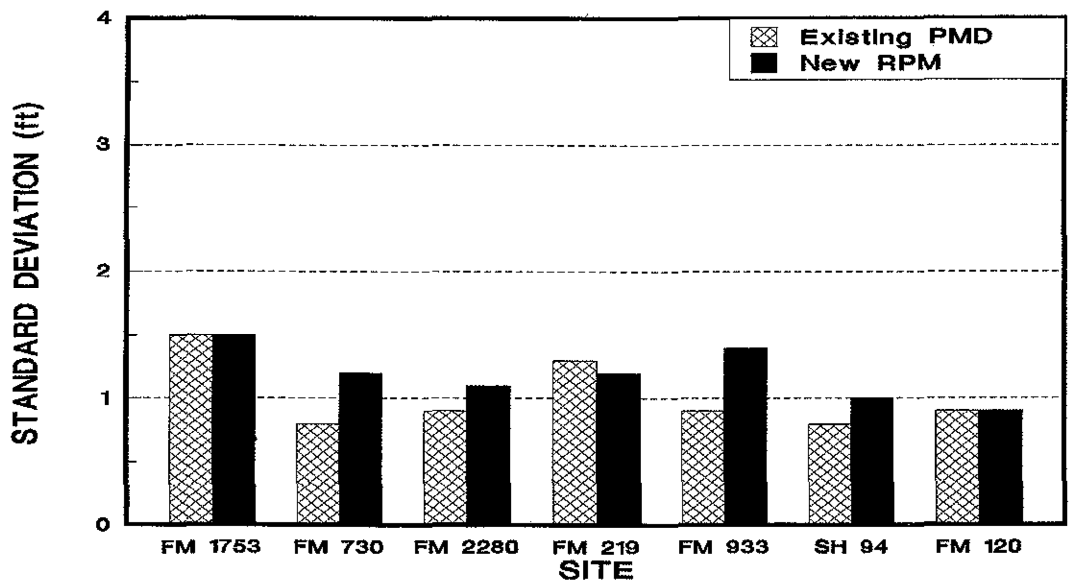
3.5.5.1. Outside Lane

The number of encroachments into the opposing lane at the midpoint of the curve with the existing PMDs and the new RPMs were compared using chi-squared tests. Figure 9 summarizes the percentage of vehicles in the outside lane that crossed the center of the roadway at the midpoint of the curve. Table C-9 summarizes the number of encroachments for each delineation treatment and reports the chi-square test results. There were fewer encroachments with the new RPMs than with the existing PMDs at all sites. The results of the chi-squared test indicate the differences in encroachments were statistically significant at four of the six study sites without edgelines.

The results from the FM 120 site suggest that edgelines may affect the number of encroachments. No encroachments were observed with either existing PMDs or new RPMs at the FM 120 site.

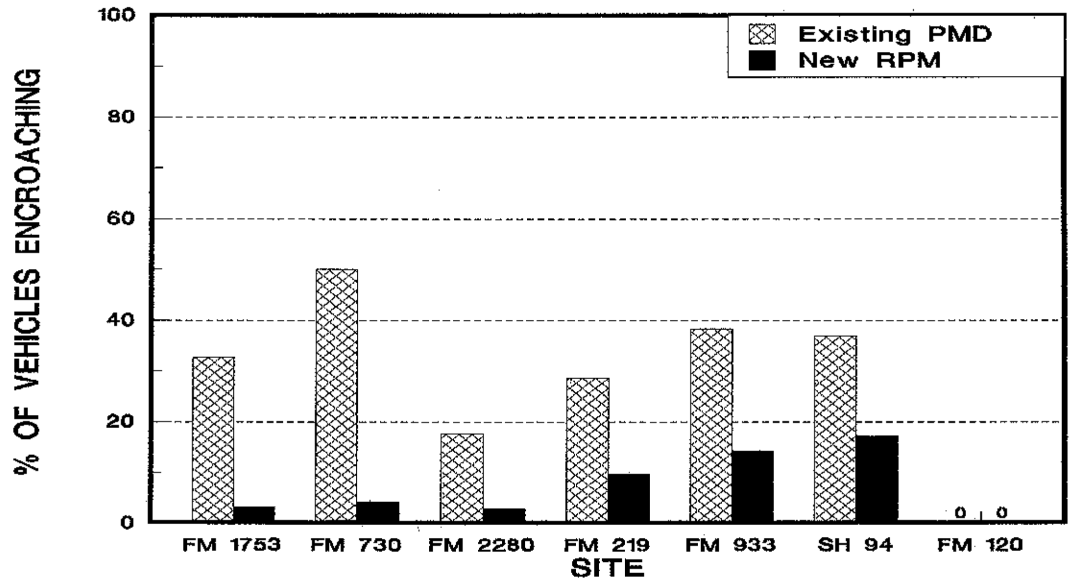


(a) Mean Lateral Placements

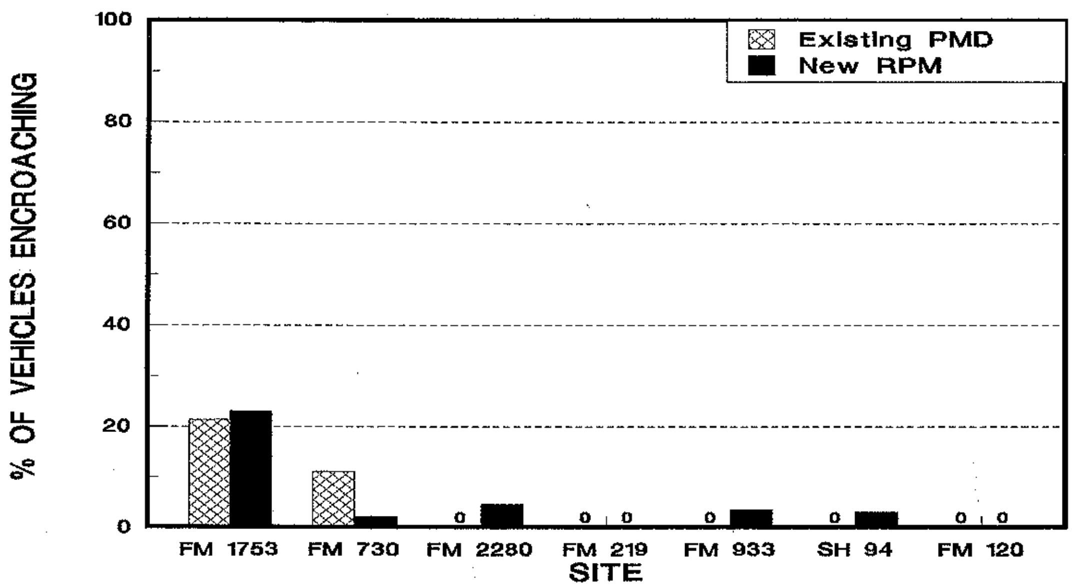


(b) Standard Deviation of Lateral Placements

Figure 8. Lateral Placements at the Midpoint of the Curve: Inside Lane.



(a) Outside Lane



(b) Inside Lane

Figure 9. Percentage of Vehicles Encroaching into the Opposing Lane at the Midpoint of the Curve.

3.5.5.2. Inside Lane

Figure 9 also summarizes the percentage of vehicles in the inside lane that crossed the center of the roadway at the midpoint of the curve. Table C-10 summarizes the results of the chi-squared tests. As one would expect, very few vehicles in the inside lane crossed the center of the roadway. The results of the chi-squared tests indicate that there are no differences between the two delineation treatments at any of the sites.

3.5.6. Summary of Findings of Short-Term Operational Data Analysis

The short-term operational data suggest that drivers operated differently in the outside lane of horizontal curves when the existing PMDs were replaced with RPMs supplementing the centerline. Whereas, little difference in vehicle operations was observed in the inside lane.

The following differences between existing PMDs and new RPMs were observed in the outside lane of the curves studied:

- The mean speeds at the midpoint of the curves were consistently 1-3 mph higher with the new RPMs than with the existing PMDs.
- The mean lateral placement was consistently 1-2 ft further from the center of the roadway at the midpoint of the curve with the new RPMs than with the existing PMDs.
- There was less variability in lateral placement at the midpoint of the curve with the new RPMs than with the existing PMDS.
- Fewer vehicles crossed the center of the roadway with the new RPMs than with the existing PMDs.

The focus of the study was on curves without edgelines. However, one site (FM 120) with edgelines on the outside lane was studied. The differences in vehicle operations at the FM 120 site were similar in nature but smaller in magnitude than at the curves without edgelines. In comparison with the curves with edgelines, the FM 120 site had the smallest differences in mean speed and mean lateral placement at the midpoint of the curve, and in speed change between the beginning and midpoint of the curve. In addition no encroachments were observed at the FM 120 site with either the existing PMDs or new RPMs. The FM 120 site compares favorably to the sites with edgelines with respect to all of the MOEs. However, since only one site with edgelines was studied, it could not be determined whether the differences at the FM 120 site were due to the presence of edgelines or to other characteristics of the site. Additional research would be required to determine how edgelines influence the effectiveness of RPMs and PMDs and what supplemental delineation would be appropriate at curves with edgelines.

Overall, operations with the new RPMs compare favorably with the existing PMDs. The results suggest that the new RPMs provide better path delineation (as evidenced by the findings related to lateral placement and encroachments) which may give drivers the confidence to operate at higher speeds through the curves.

3.6. LONG-TERM OPERATIONAL DATA ANALYSIS

Follow-up field studies were conducted at three sites to monitor changes in vehicle operations through the curves as the RPMs aged and lost some of their reflectivity. At the site on FM 1753, operational data were collected approximately 11 months after the new RPMs were installed. At the sites on FM 219 and FM 933, data were collected 6 weeks after the new RPMs were installed. Data were collected again 10 weeks after the RPMs were installed at the FM 933 site and 11 weeks after installation at the FM 219 site. At the FM 219 and FM 933 sites, data were collected with the existing PMDs as well as with new PMDs (i.e., with new delineators installed on the existing posts).

3.6.1. Reflectivity Measurements

Samples of RPMs were removed from all of the study sites at approximate 6-month intervals for reflectivity measurements. Measurements were made by the SDHPT lab in Austin. Figure 10 is a scatter plot of the reflectivity measurements (for a 20-degree incidence angle) from all study sites. Each box plotted represents the mean specific intensity of the sample of unwashed RPMs taken from one study site a specified number of months after they were installed. Only one new RPM was tested at each of six sites. Most of the other boxes represent the mean reflectivity measurement for a sample of 5 RPMs taken from a site. The plot indicates that the RPMs lost much of their reflectivity within 6 months after installation. These results are consistent with previous research findings (19).

Table 4 summarizes the reflectivity measurements that correspond to the long-term operational data collected at three sites. The mean specific intensity at the FM 1753 site had dropped to 0.1 candlepower per foot-candle (CP/FT-C) when the follow-up field study was conducted 11 months after the new RPMs were installed. At the FM 219 site, the mean specific intensity during both follow-up field studies still exceeded the 2.0 CP/FT-C specification for new RPMs at a 20-degree incidence angle. At the FM 933 site, the mean specific intensity dropped from 2.3 CP/FT-C at 6 weeks to 1.0 CP/FT-C at 10 weeks.

TABLE 4. MEAN SPECIFIC INTENSITY OF RPMs DURING LONG-TERM FIELD STUDIES (CP/FT-C)*

Site	New RPM	6-Week-Old RPM	10-11-Week-Old RPM	11-Month-Old RPM
FM 1753	2.8	--	--	.1
FM 219	--	2.4	2.1	--
FM 933	--	2.3	1.0	--

* 20-degree incident angle

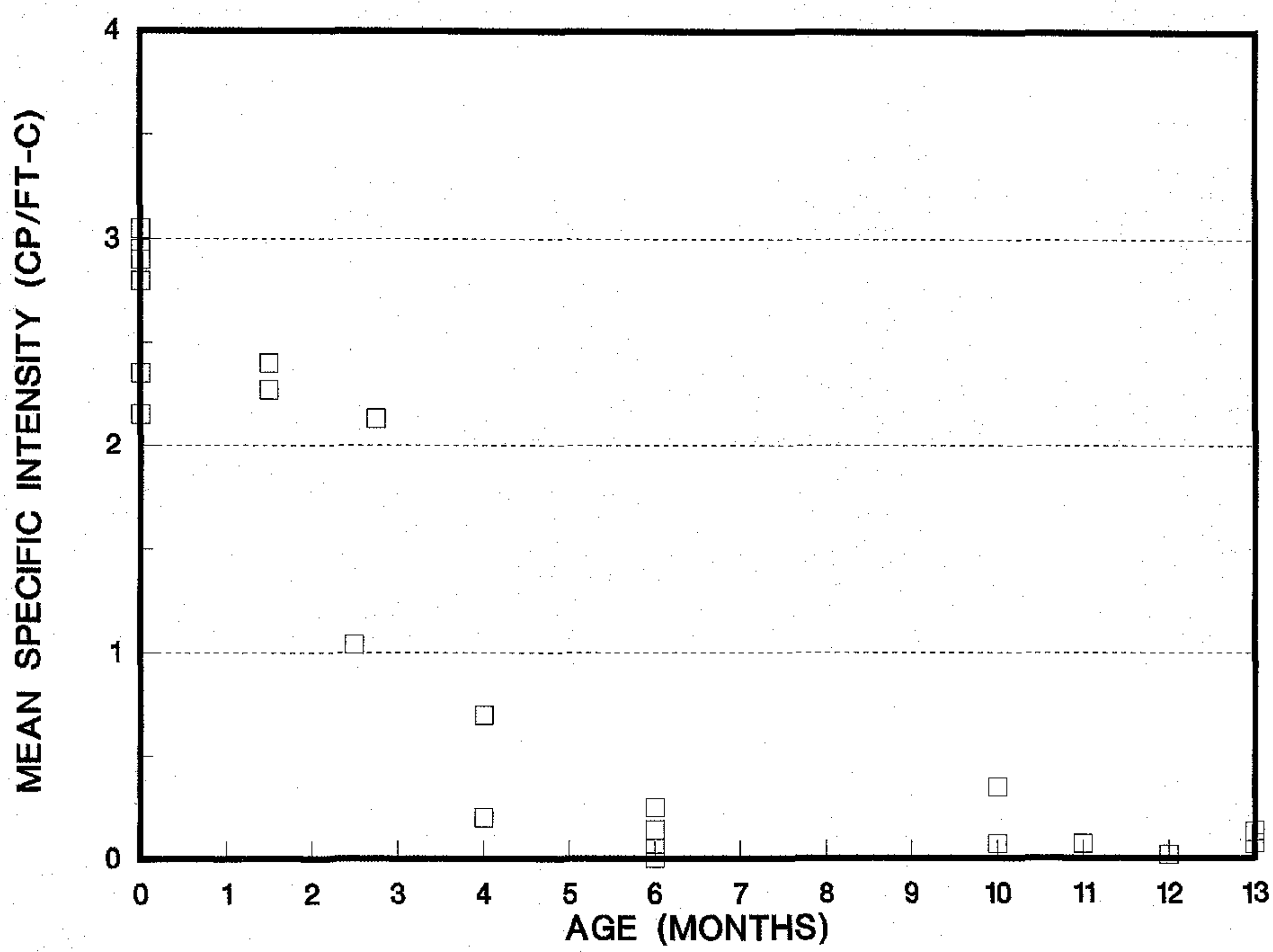


Figure 10. Scatter Plot of Mean Specific Intensity versus the Age of RPMs.

3.6.2. Speeds at the Midpoint of the Curve

3.6.2.1. Outside Lane

The mean and standard deviation of the speeds observed in the outside lane for all delineation treatments at the FM 1753, FM 219, and FM 933 sites are summarized in Figure 11. A single-factor ANOVA was performed separately for each site. For sites which the ANOVA indicated that differences among the delineation treatments existed, a pairwise (least-significant-difference) t-test was performed to identify the pairs of treatments whose mean speeds differed significantly.

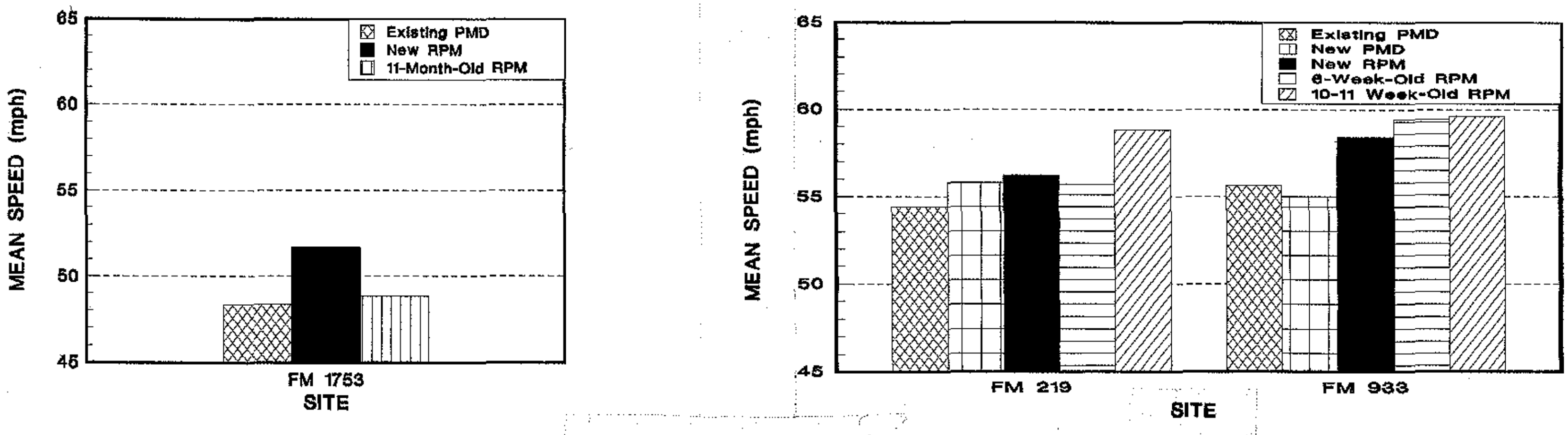
The delineation treatments at the FM 1753 site were the existing PMDs, new RPMs, and 11-month-old RPMs. Table C-11 documents the mean and standard deviations of the mean speeds with each treatment and summarizes the results of the statistical analyses. Treatments are listed in order from lowest to highest mean speed. The results indicate that the mean speed with the new RPMs was significantly higher than with either the existing PMDs or the 11-month-old RPMs. The existing PMDs and 11-month-old RPMs did not have significantly different mean speeds.

Five delineation treatments were observed at the FM 219 site: existing PMDs, new PMDs, new RPMs, 6-week-old RPMs, and 11-week-old RPMs. The reflectivity measurements for both the 6-week-old and 11-week-old RPMs exceeded the 2.0 CP/FT-C initial-brightness specification for new RPMs. Therefore, one would expect to observe similar operations with all three RPM treatments. Indeed, the results of the single-factor ANOVA for the FM 219 site, presented in Table C-11, indicate that none of the treatments differ significantly.

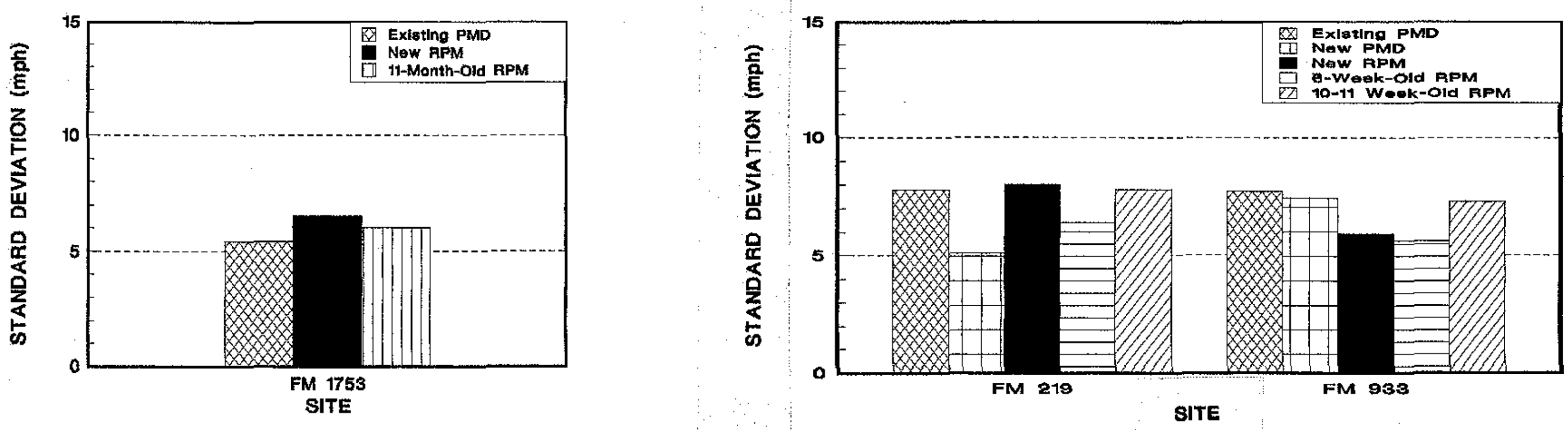
Five delineation treatments were observed at the FM 933 site: existing PMDs, new PMDs, new RPMs, 6-week-old RPMs, and 10-week-old RPMs. The reflectivity measurements for the 6-week-old RPMs exceeded the 2.0 CP/FT-C specification for new RPMs. However, the reflectivity for the 10-week-old RPMs dropped to 1.0 CP/FT-C. The results of the single-factor ANOVA and pairwise t-test, presented in Table C-11, indicate that (1) the speeds with the three RPM treatments were the same, (2) the mean speeds with the two PMD treatments were not significantly different, but (3) the mean speeds with the RPM treatments were higher than the mean speeds with the PMD treatments.

3.6.2.2. Inside Lane

The mean and standard deviation of the speeds on the inside lane are presented in Figure 12. The results of the statistical analysis for the FM 1753, FM 219, and FM 933 sites are summarized in Table C-12. The results for all three sites indicate that none of the treatments have significantly different mean speeds.

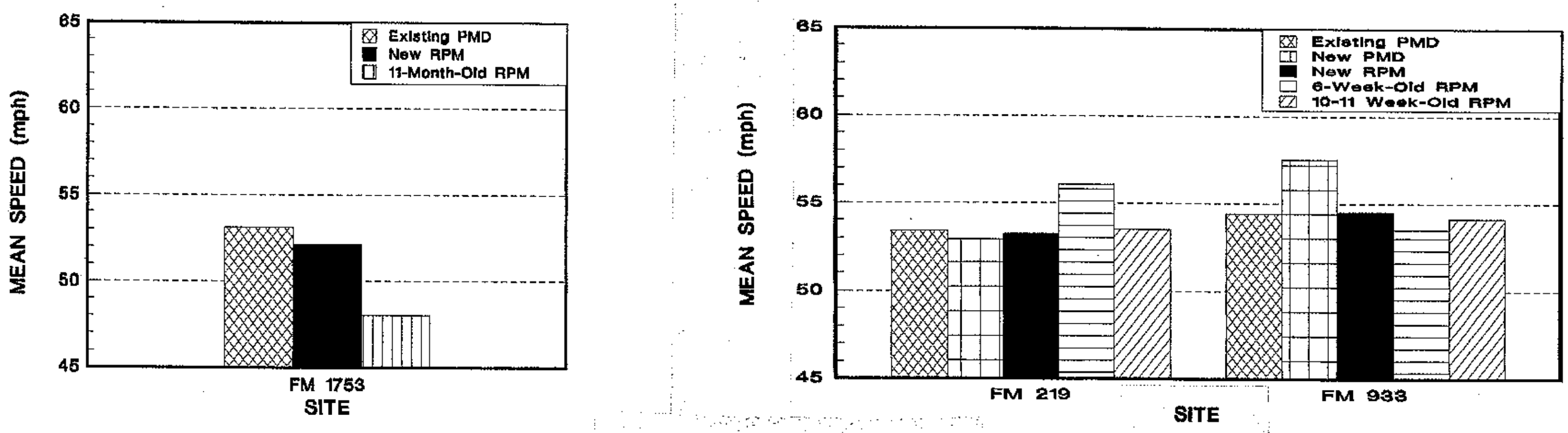


(a) Mean Speeds

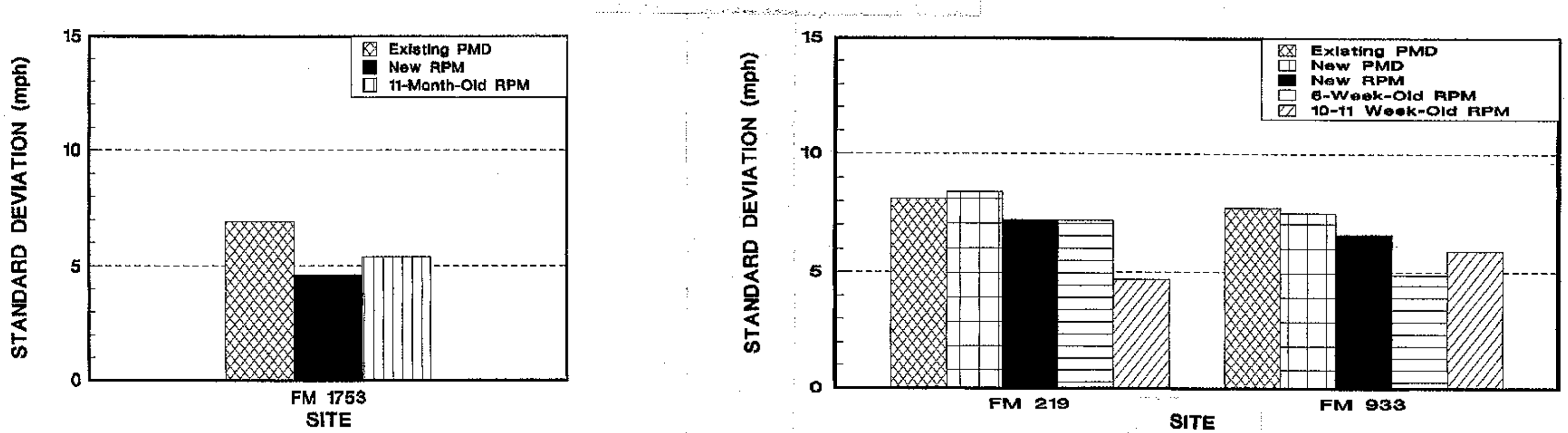


(b) Standard Deviation of Speeds

Figure 11. Speeds at the Midpoint of the Curve at the Long-Term Study Sites: Outside Lane.



(a) Mean Speeds



(b) Standard Deviation of Speeds

Figure 12. Speeds at the Midpoint of the Curve at the Long-Term Study Sites: Inside Lane.

3.6.3. Speed Change from the Beginning to the Midpoint of the Curve

3.6.3.1. Outside Lane

The mean and standard deviation of the speed changes from the beginning to the midpoint of the curve on the outside lane of the FM 1753, FM 219, and FM 933 sites are presented in Figure 13. The results of the single-factor ANOVA and pairwise t-test for the FM 1753 site presented in Table C-13 indicate that the mean speed reduction with the 11-month-old RPMs was significantly greater than with either the existing PMDs or new RPMs. This result suggests that the 11-month-old RPMs may not have had enough reflectivity to provide motorists sufficient advance delineation to allow them to adjust their speed before entering the curve. Previous research has suggested that large speed reductions are undesirable, although there was not a statistically significant correlation between greater deceleration and increased accident rates (4).

Speeds increased from the beginning to the midpoint of the curve in the outside lane of the FM 219 site for all delineation treatments. The results of the single-factor ANOVA and pairwise t-test, summarized in Table C-13, indicate that the mean speed increase with the 11-week-old RPMs was significantly greater than with either the existing or the new PMDs. No other statistically significant differences were identified among any of the other treatments.

As with the FM 219 site, speeds increased, on average, from the beginning to the midpoint of the curve at the FM 933 site. The results of the single-factor ANOVA in Table C-13 do not indicate any significant differences among the treatments at this site.

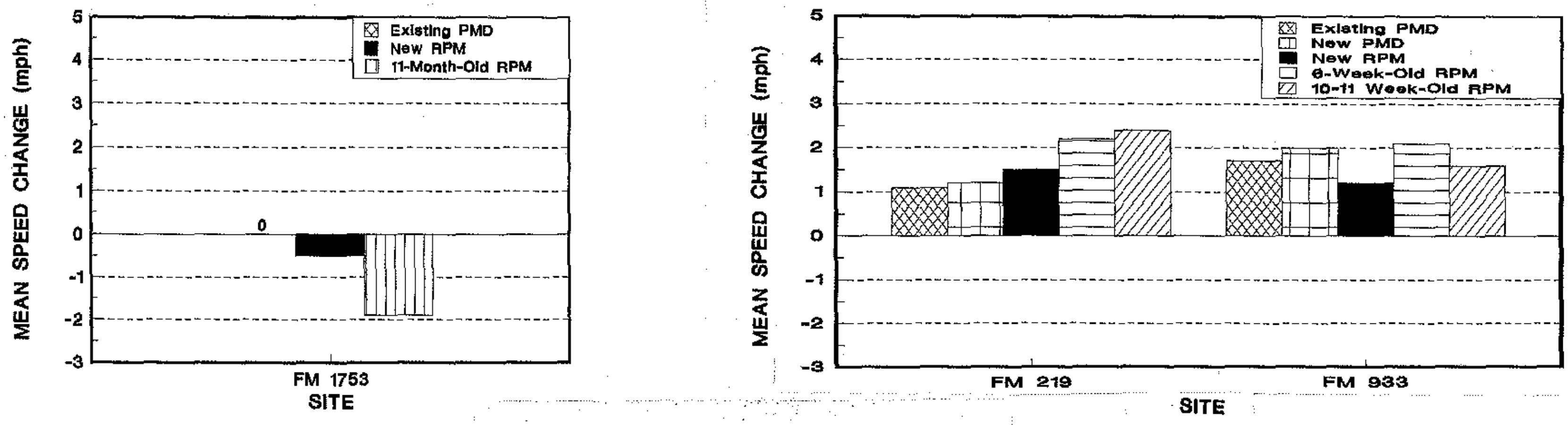
3.6.3.2. Inside Lane

Summary statistics on the speed change from the beginning to the midpoint of the curve in the inside lane of the FM 1753, FM 219, and FM 933 sites are presented in Figure 14. The results of the single-factor ANOVA, summarized in Table C-14, do not indicate any significant differences among the treatments at any of the three sites.

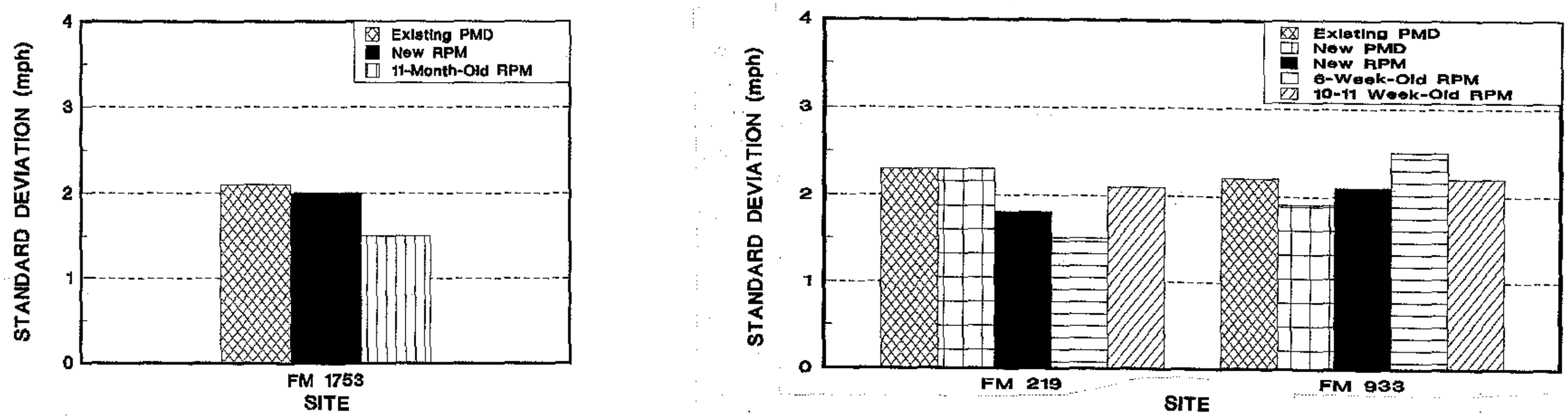
3.6.4. Lateral Placement at the Midpoint of the Curve

3.6.4.1. Outside Lane

Summary statistics for the lateral placement in the outside lane at the midpoint of the curve are presented in Figure 15 for the FM 1753, FM 219, and FM 933 sites. The results of the single-factor ANOVA and pairwise t-tests in Table C-15 indicate that the mean lateral placements with all of the RPM treatments are greater than with any of the PMD treatments at all three sites.

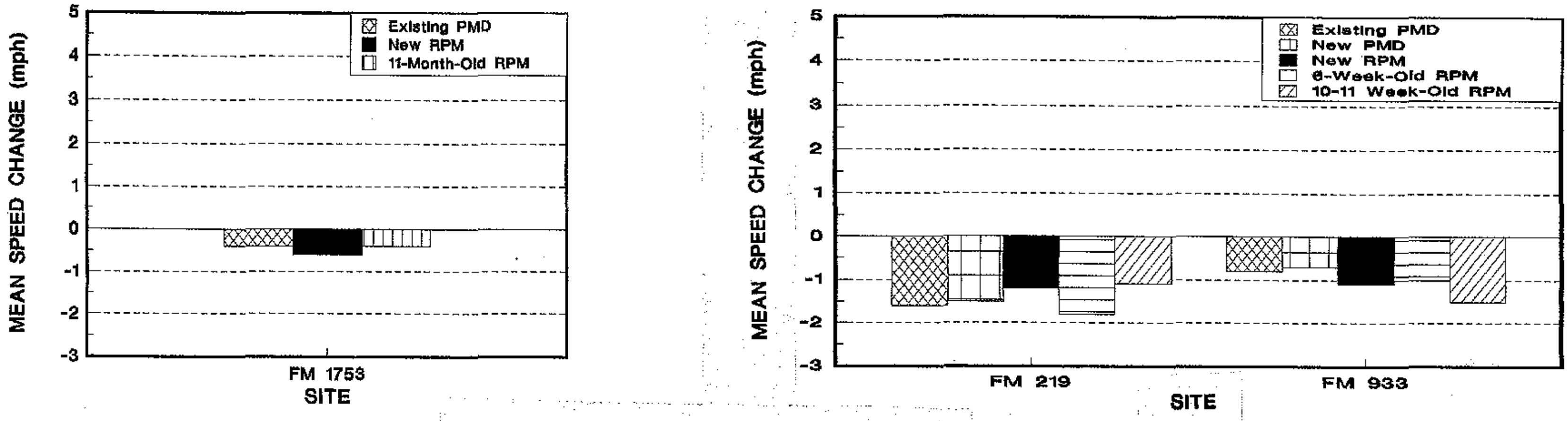


(a) Mean Speed Changes

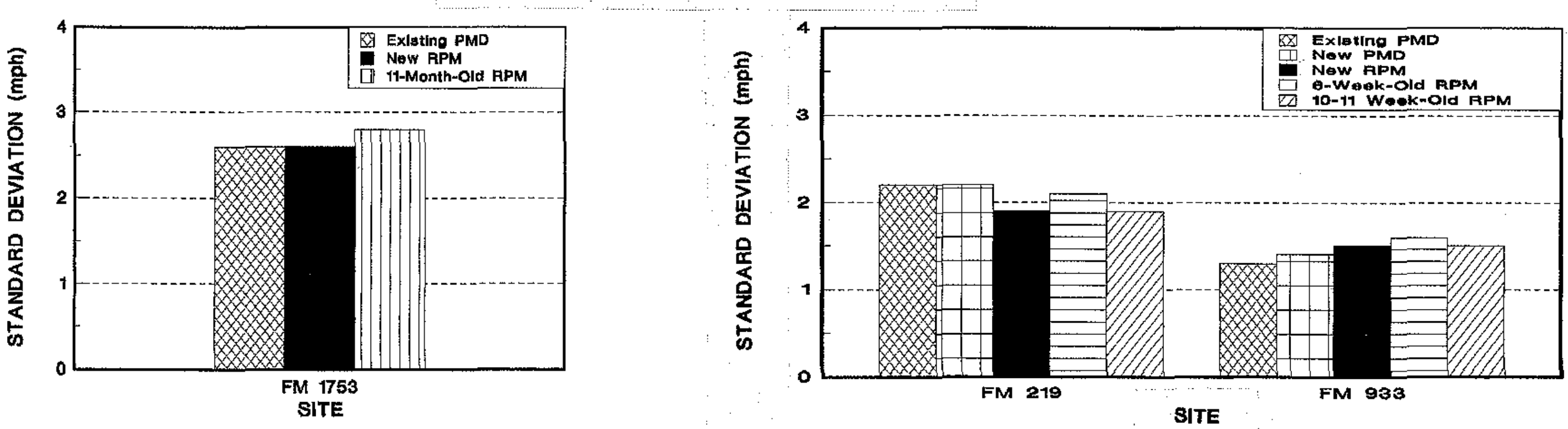


(b) Standard Deviation of Speed Changes

Figure 13. Speed Changes from the Beginning to the Midpoint of the Curve at the Long-Term Study Sites: Outside Lane.

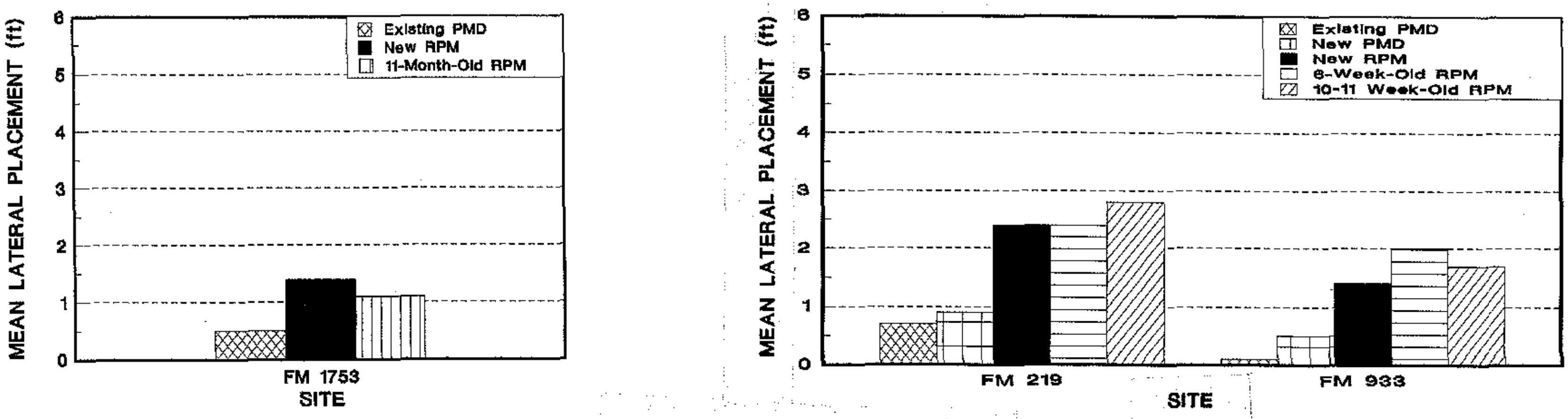


(a) Mean Speed Changes

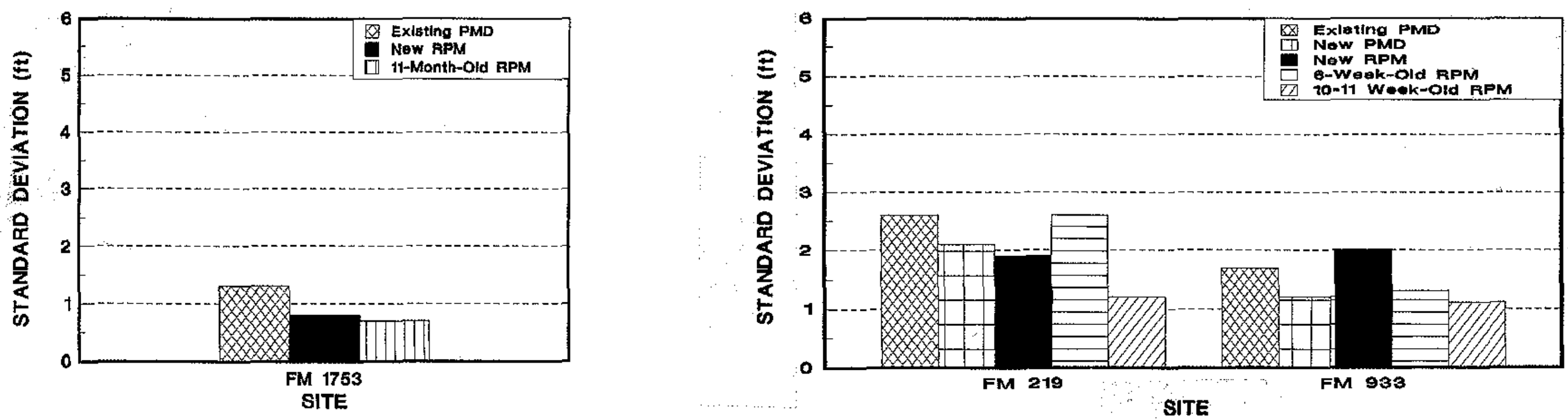


(b) Standard Deviation of Speed Changes

Figure 14. Speed Changes from the Beginning to the Midpoint of the Curve at the Long-Term Study Sites: Inside Lane.



(a) Mean Lateral Placements



(b) Standard Deviation of Lateral Placements

Figure 15. Lateral Placements at the Midpoint of the Curve at the Long-Term Study Sites: Outside Lane.

3.6.4.2. Inside Lane

Statistics on lateral placements in the inside lane are summarized in Figure 16. The results of the single-factor ANOVA in Table C-16 do not indicate any significant differences among the treatments in the inside lane at any of the sites.

3.6.5. Encroachment at the Midpoint of the Curve

3.6.5.1. Outside Lane

Figure 17 summarizes the percentage of vehicles encroaching into the opposing lane at the midpoint of the curve for each treatment at the FM 1753, FM 219, and FM 933 sites. The results of the chi-squared tests in Table C-17 indicate statistically significant differences in the proportion of vehicles encroaching at all three sites. The proportion of vehicles encroaching is less for the RPM treatments than for the PMD treatments.

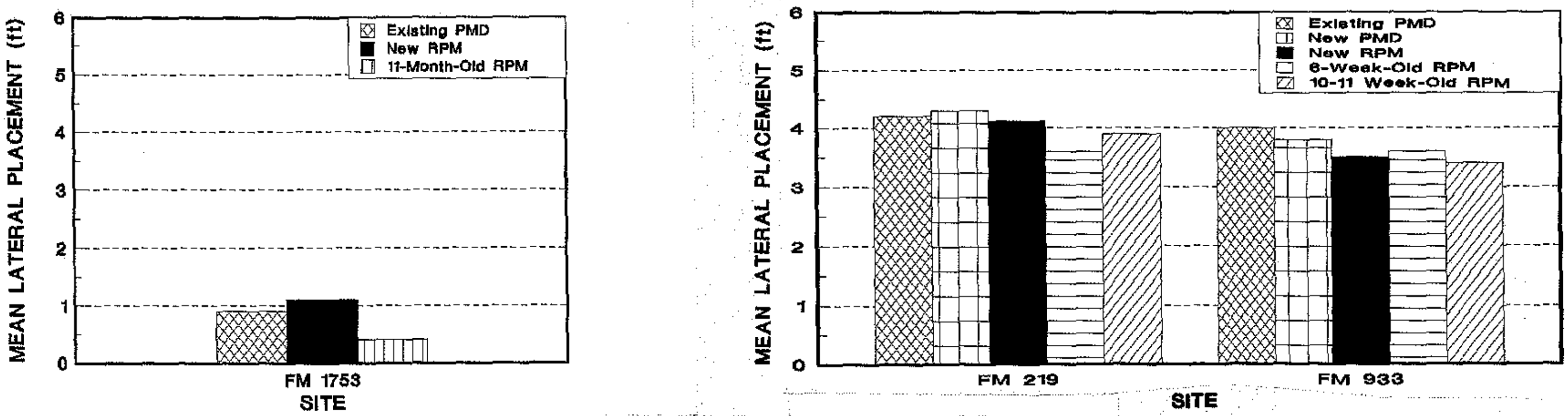
3.6.5.2. Inside Lane

Figure 17 summarizes the encroachments by vehicles in the inside lane. The results of the chi-squared tests in Table C-18 did not indicate significant differences among any of the treatments at any of the sites.

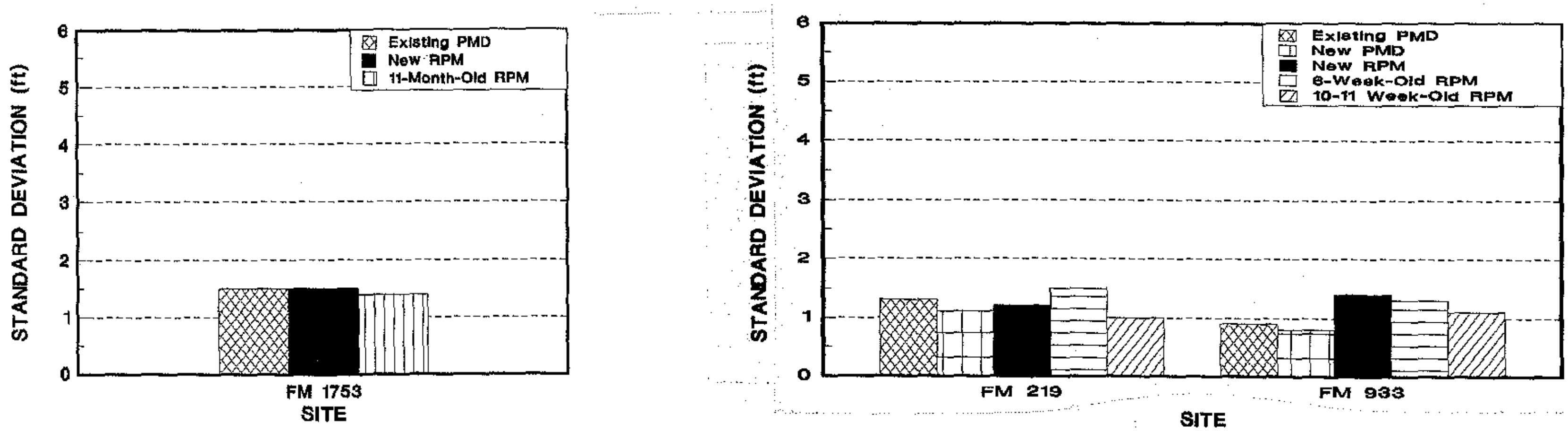
3.6.6. Summary of Findings of Long-Term Operational Data Analysis

Few changes in the operational effectiveness of RPMs were observed as the RPMs aged and lost some of their reflectivity. At the FM 219 and FM 933 sites, little reduction in reflectivity was observed, and vehicle operations changed very little up to 11 weeks after the new RPMs were installed. Therefore, the results at the FM 219 and FM 933 sites reinforce the findings of the short-term analysis.

At the FM 1753, vehicle operations were observed after the RPMs had been in place 11 months and had lost much of their reflectivity. Even after 11 months, the RPMs compared favorably to the existing PMDs with respect to the mean lateral placement and the number of encroachments. These results suggest that the RPMs, in spite of their lack of reflectivity, influenced drivers' paths within the curve. The mean speed at the midpoint of the curve with the 11-month-old RPMs was the same as with the existing PMDs but significantly lower than with the new RPMs. The mean speeds provide some indication of the relative confidence levels of drivers. The only MOE that caused concern with the 11-month-old RPMs was a small but statistically significant increase in deceleration from the beginning to the midpoint of the curve. This increase in deceleration may indicate that motorists did not have sufficient advance warning to adjust their speeds before reaching the curve.

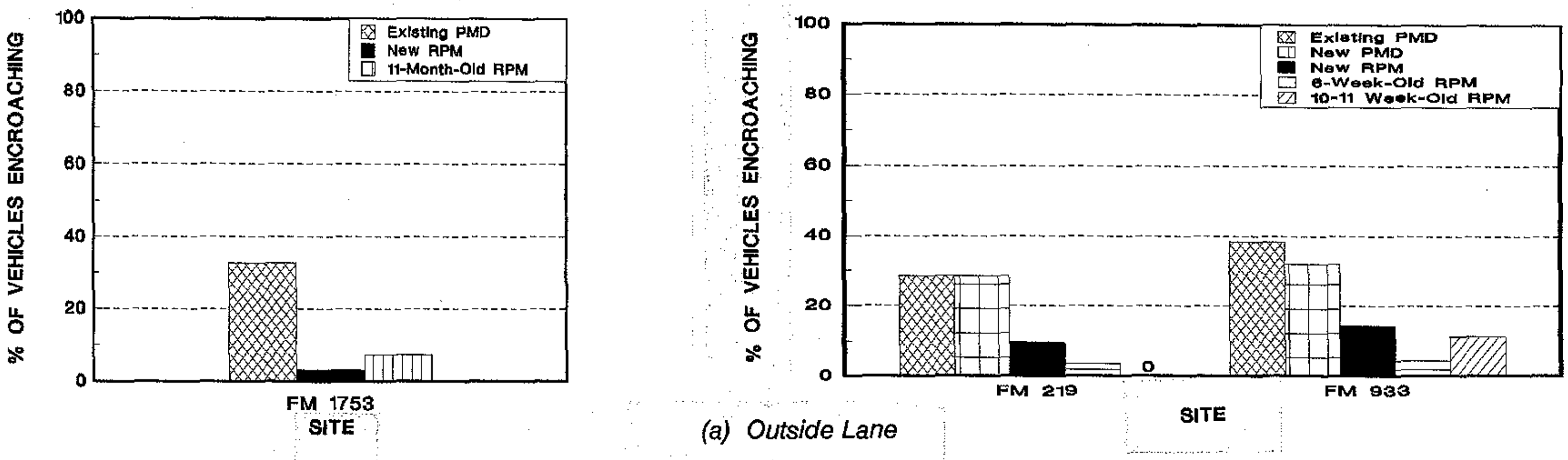


(a) Mean Lateral Placements

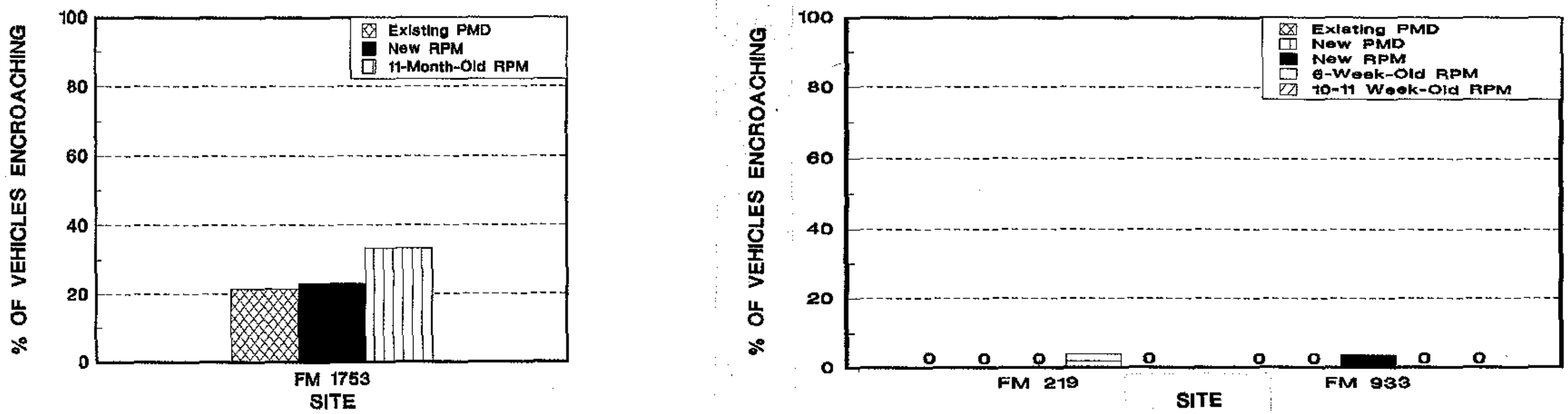


(b) Standard Deviation of Lateral Placements

Figure 16. Lateral Placements at the Midpoint of the Curve at the Long-Term Study Sites: Inside Lane.



(a) Outside Lane



(b) Inside Lane

Figure 17. Percentage of Vehicles Encroaching into the Opposing Lane at the Midpoint of the Curve at the Long-Term Study Sites.

It appears that the 11-month-old RPMs at the FM 1753 site continued to provide near delineation, but that their effectiveness at providing far delineation was at least partially degraded. There is no objective basis for determining whether or not the performance of the 11-month-old RPMs was acceptable.

The results from the FM 1753 site suggest that the operational effectiveness of RPMs is due in part to their reflectivity, and in part to their profile above the pavement surface. Even with low reflectivity, it appears that the RPMs continue to serve at least part of their intended function due to their profile and rumble effect. Since previous research has not addressed the long-term effectiveness of RPMs and since the findings of this study are based upon data at only one site, additional research would be necessary to determine how long RPMs continue to function adequately (i.e., what is the service life of RPMs?). The determination of the service life of RPMs should be based upon both reflectivity measurements and operational data, since it appears that both their reflectivity and profile contribute to their effectiveness.

4. COST OF ALTERNATIVE DELINEATION TREATMENTS

4.1. INTRODUCTION

This chapter provides a comparison of the cost of using PMDs and RPMs at horizontal curves on two-lane highways. The focus was on the treatment of isolated horizontal curves. Cost estimates were based upon the placement of PMDs as specified in the MUTCD (1) and the pattern of RPMs illustrated in Figure 1. Cost data were obtained during telephone surveys of personnel in SDHPT Districts 1, 2, 7, 9, 10, 15, 17, 18, and 19. Differences exist between the various Districts in the delineation of curves on two-lane roadways. Some of these differences affect the costs of the two delineation treatments evaluated. Appendix D documents the information supplied by District personnel during the survey.

4.2. PROCEDURE

At the outset, factors that were thought to influence the costs of each delineation treatment were material costs, labor costs for installation, inventory costs, and periodic maintenance costs. Costs were also expected to depend upon whether devices were installed by state forces or by contractor.

Several difficulties in obtaining cost data became apparent as the survey got underway. As a general rule, all Districts treated entire stretches of roadway by placing all new devices or by replacing damaged or missing devices. None of the District offices were easily able to quantify costs accurately for the treatment of curves only.

Another problem encountered was that individuals at the district level who were familiar with cost information were not necessarily knowledgable with the manner in which the devices were used. Similarly, District maintenance sections were familiar with their own work with state forces, but they were not generally familiar with larger projects of the same type that were let to private contract.

Material costs were difficult to determine accurately. No overhead costs for storage, shipment, and handling were readily available. The SDHPT purchases delineators and posts to be stored in regional warehouses for use by individual districts. Differing bid quantities caused differentials in cost. The type of RPMs and type of post and delineator were other variables creating cost differences. Posts, for example, come in different unit weights and lengths which affect their cost.

The service life of each device was highly variable. Districts have different policies determining when RPMs are replaced. The service life of PMDs is either the effective life of the delineator or the length of time before an errant vehicle or mower damages the post. Even with flexible posts (another variable), maintenance is required to straighten the devices because they tend to lean even if they return to a relatively upright position. The frequency and extent of this maintenance are highly variable. In some districts in East Texas, movement of oversize farm equipment increases the need for maintenance.

4.3. RESULTS

Table 5 provides a summary of findings of the cost survey. Table 5 suggests that contractor costs for both RPMs and PMDs are less variable than the costs for installing devices by state forces. Two reasons are apparent. One is that with contractors entering competitive bidding, there is a natural tendency toward a mean value (i.e., a value which a contractor thinks can win the contract and still make a profit). The second reason has to do with the quality of the maintenance cost records maintained by the Districts for work by state forces. For the installation of devices by state forces, the allocation of both labor and equipment was significantly variable both within and between districts.

Caution should be exercised in comparing costs by state force and by contractor. Table 5 suggests that the cost of devices installed by state forces is consistently lower than by contractor. However, the costs for installation by state forces do not include either overhead or inventory costs.

TABLE 5. SUMMARY OF COSTS FOR INSTALLED RPMs AND PMDs

	Contractor		State Forces	
District	RPM	PMD	RPM	PMD
1	$2.25-3.50	$19.81	$1.52	$20.52[1]
2	$2.56	--	$1.45	--
9	$2.25	$17.61	--	--
10	$2.47[2]	--	--	N/A
15	$2.40	$18.72	$1.38	--
17	$2.25	$15.00	--	--
18	$2.50	$18.83	--	$13.19
19	$2.22	--	--	--

[1] Includes equipment usage cost ($0.43/mi * 30 miles), no maintenance.

[2] Includes $1.47 for marker, $1.00 for labor and equipment.

(--) Denotes that the District did not provide this information.

4.4 COST COMPARISON FOR A TYPICAL HORIZONTAL CURVE

The cost data summarized in Table 5 suggest that a typical unit cost for RPMs is $2.50, and a typical unit cost for PMDs is $18.00 (using contractor forces). Using these values, one can compare the two delineation treatments on a life-cycle basis using an appropriate interest rate (to account for the time value of money). This comparison is somewhat simplified in that no maintenance costs for either device are included. Only the costs associated with installation and replacement are included. In addition to the unit cost of the devices, two key factors are the service life of the devices and the number of devices used in a typical installation.

The service life of the devices is a critical factor in comparing costs. The SDHPT does not have guidelines on when to replace RPMs. Several Districts report replacement cycles of 2-3 years on low-volume roads, which reflects the needs for both tangent sections and curves, as well as budget considerations and the availability of materials and manpower. PMDs can remain effective as long as 10 years, unless they are hit (20). The average life of a PMD depends on the roadway and the type of traffic. One District reported the need to replace PMDs every year on some roadways with significant movements of oversized farm equipment. Since the service life of both RPMs and PMDs is variable, the analysis was performed to determine the service lives for which the present value of the life-cycle costs of the two delineation treatments would be equal.

The number of devices required depends upon the length and sharpness of curve. A 1000-ft long curve is assumed for comparison purposes. The MUTCD (1) specifies the spacing of PMDs as a function of the radius of curvature. The MUTCD (1) also specifies the placement of 3 additional PMDs on each tangent. As summarized in Table 6, MUTCD requirements for the number of PMDs that would be required at a 1000-ft long horizontal curve range from 11 PMDs for a 1-degree curve to 19 PMDs for an 8-degree curve.

TABLE 6. MUTCD REQUIREMENTS FOR THE NUMBER OF PMDs IN A 1000-FT LONG HORIZONTAL CURVE

Degree of Curvature	Number of PMDs
1	11
2	13
3	14
4	15
5	16
6	17
7	18
8	19

The use of RPMs supplementing the existing painted centerline would require 25 RPMs in the curve at 40-ft spacings and 4 additional RPMs on each approach tangent at 80-ft spacings. Therefore, a total of 33 RPMs would be required to delineate a 1000-ft long horizontal curve, regardless of the degree of curvature.

Table 7 summarizes the present value for the unit cost of installing RPMs and PMDs based upon the average costs summarized in Table 5. A 10-percent interest rate is used. This table could be used to make cost comparisons using site-specific assumptions about the number and service lives of RPMs and PMDs.

TABLE 7. PRESENT VALUE OF UNIT COSTS FOR INSTALLED RPMs AND PMDs

Number of Years in Future	Unit Cost ($)	
	RPM	PMD
0	2.50	18.00
1	2.27	16.36
2	2.07	14.88
3	1.88	13.52
4	1.71	12.29
5	1.55	11.18
6	1.41	10.16
7	1.28	9.24
8	1.17	8.40
9	1.06	7.63
10	.96	6.94
11	.88	6.31
12	.80	5.74
13	.72	5.21
14	.66	4.74
15	.60	4.31
16	.54	3.92
17	.49	3.56
18	.45	3.24
19	.41	2.94
20	.37	2.68

Note: 10-percent interest rate is assumed.

Table 8 summarizes the cost comparison for a 1000-ft long horizontal curve. The table indicates, for various degrees of curvature, the service lives of RPMs and PMDs for which the cost of the two treatments would be equal. The breakeven service lives in Table 8 are based upon the unit installation costs in Table 7 and the number of PMDs specified in Table 6.

Consider, for example, an 8-degree curve. If RPMs had a 1-year service life, then PMDs would have to last 8 years for the present value of the life-cycle installation cost of the two treatments to be equal. Similarly, if the service life of RPMs were 2 years, then the breakeven service life of PMDs would be 18 years. These comparisons assume that devices are installed now and then replaced at the intervals specified and that no intermediate maintenance costs are incurred. If, at a particular 8-degree curve, PMDs had a 10-year service life and RPMs had a 1-year service life, then PMDs would have a lower life-cycle installation cost (because the actual 10-year service life is greater than the breakeven, 8-year service life). If, instead, RPMs had a 2-year service life, then the RPMs would have a lower cost (because the actual 10-year service life of PMDs is less than the breakeven, 8-year service life).

TABLE 8. BREAKEVEN SERVICE LIVES OF RPMs and PMDs FOR A 1000-FT LONG HORIZONTAL CURVE

Service Life of RPMs (Years)	Breakeven Service Life of PMDs (in Years) for Various Degrees of Curvature							
	1°	2°	3°	4°	5°	6°	7°	8°
1	4	5	6	6	7	7	8	8
2	8	10	12	14	14	16	18	18
3	15	18	--	--	--	--	--	--
4	20	--	--	--	--	--	--	--

(--) Denotes a service life greater than 20 years.

4.5. SUMMARY OF COST COMPARISON OF RPMs AND PMDs

It is difficult to estimate the total costs of RPMs and PMDs at isolated horizontal curves on two-lane highways from the maintenance cost records kept by the SDHPT. Labor, equipment, and overhead costs are particularly difficult to allocate to a specific maintenance activity. Site-specific factors significantly influence the service life and, therefore, the cost-effectiveness of RPMs and PMDs. For this reason, the cost comparisons were based upon the service lives for which the costs of RPMs and PMDs would be equal. At horizontal curves where the average service life for PMDs is 10 years, as reported by Niessner (20), RPMs would be more cost-effective only if their service life were 2 years or more. At curves where PMDs are frequently knocked over and their service life is considerably less than 8 years, RPMs are likely to be more cost effective even with a 1-year service life. It is recommended that the Department update these cost comparisons after their new maintenance management information system has been implemented, and the service lives of RPMs and PMDs are better defined.

5. SUMMARY AND RECOMMENDATIONS

5.1. SUMMARY OF FINDINGS

The safety, operational, and cost-effectiveness of RPMs as an alternative to PMDs at horizontal curves on two-lane rural highways was evaluated. RPMs were used to supplement the existing painted centerline at horizontal curves at which the existing PMDs had been removed. The RPMs were spaced at 40-ft intervals in a single row on the centerline in the curve, with an additional four RPMs spaced at 80-ft intervals on both tangents approaching the curve.

The safety and operational evaluations were based upon the collection of nighttime speed and lateral placement data at seven study sites. The operational data analysis focused on those MOEs that previous research has suggested are correlated to accident rates at horizontal curves.

The statistical analysis of the short-term operational data suggested that vehicle operations in the inside lane of the curves were not significantly affected by the removal of the PMDs and installation of new RPMs. However, several significant differences were observed in the outside lane of the curves. The mean speeds at the midpoint of the curves were consistently 1-3 mph higher with the new RPMs than with the existing PMDs. The mean lateral placement was consistently 1-2 ft further from the center of the roadway at the midpoint of the curves with the new RPMs than with the existing PMDs. The variability in lateral placement at the midpoint of the curve was less with the new RPMs than with the existing PMDs. Fewer vehicles crossed the center of the roadway with the new RPMs than with the existing PMDs. The short-term evaluation suggests that new RPMs provide better path delineation (as evidenced by the findings related to lateral placement and encroachments) which may give drivers the confidence to operate at higher speeds through the curves.

Long-term operational data were collected at three sites. At two sites, data were collected after the RPMs had been in place 6 weeks and again after 10-11 weeks. The RPMs retained much of their reflectivity at these sites, and the results of the data analysis reinforce the findings of the short-term evaluation.

At one site, data were collected after the RPMs had been in place 11 months and had lost much of their reflectivity. (Their mean specific intensity was 0.1 CP/FT-C.) The mean lateral placement and number of encroachments with the 11-month-old RPMs were not significantly different than with the new RPMs and compared favorably with the PMDs. The only MOE that caused concern with the 11-month-old RPMs was the small, but statistically significant, increase in deceleration from the beginning to the midpoint of the curve, which may indicate that motorists did not receive sufficient advance warning of the curve. These results suggest that after 11 months the RPMs continued to provide near delineation but that their far delineation was at least partially degraded. Unfortunately, there is no objective basis for determining whether the observed deceleration is an indication that the performance of the RPMs is unacceptable.

The cost-effectiveness evaluation of RPMs and PMDs was based upon cost data obtained from a survey of SDHPT District personnel. It proved difficult to accurately estimate the total life-cycle cost of RPMs and PMDs at isolated horizontal curves due to limitations in existing maintenance cost records. The service life of RPMs and PMDs is a critical factor in comparing the costs of the devices, but service lives vary considerably depending upon site-specific roadway and traffic conditions. Therefore, the cost data were analyzed to determine the relative service lives for which the costs of installing and replacing the two delineation treatments are equal. The breakeven service lives depend upon the sharpness of curvature, since the MUTCD (1) requirements for PMD spacing is a function of the curvature. For RPMs with a 1-year service life, the breakeven service life of PMDs ranges from 4 to 8 years, corresponding to curvature increasing from 1 to 8 degrees. For RPMs with a 2-year service life, the breakeven service life of PMDs ranges from 8 to 18 years. Niessner (20) has estimated that PMDs remain effective for as long as 10 years, unless they are hit. At horizontal curves where PMDs are not susceptible to hits, RPMs would require a service life of 2 or more years to be more cost-effective than PMDs. However, at horizontal curve locations where PMDs are frequently knocked over, RPMs are likely to be more cost-effective even with a 1-year service life.

5.2. RECOMMENDATIONS

The results of the study suggest that from a safety and operational standpont new RPMs compare favorably with existing PMDs at horizontal curves on two-lane highways. However, this conclusion is restricted to curves to which adequate sight distance is available. No curves to which sight distance was restricted by vertical alignment were studied. No conclusion may be stated about the appropriate delineation treatment for such curves based upon the results of this study. Curves with restricted sight distance should be studied individually to select the most appropriate delineation treatment.

The data from one study site suggest that 11-month-old RPMs with a mean specific intensity of 0.1 CP/FT-C retained their operational effectiveness with respect to near delineation, but that their effectiveness at providing far delineation was somewhat degraded. However, the results from this study do not provide sufficient information to determine the effective service life of RPMs. In order to determine how long RPMs remain effective and when they should be replaced, additional research should be conducted to document the relationship between the operational effectiveness of RPMs and their reflectivity and to define the minimum acceptable performance level.

Existing maintenance cost records make it difficult to accurately estimate the costs of RPMs and PMDs. Furthermore, the service lives of RPMs and PMDs are not well defined. Therefore, the Department should consider performing an updated cost comparison after their new maintenance management information system has been implemented, and better information is available on the service lives of RPMs and PMDs.

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APPENDIX A.

STUDY SITE DESCRIPTIONS

This appendix contains descriptions of the seven sites at which operational data were collected. The description includes a schematic illustrating the site. A brief summary of the accident experience at the sites is also provided.

A.1. FM 1753 SITE

The FM 1753 site was located in Grayson County (SDHPT District 1), 2 mi east of Denison and 0.5 mi south of FM 120. Figure A-1 illustrates the data collection setup. This site was a 1020-ft long, 5-degree curve. The approach tangent on the outside lane was 800 ft long. The approach tangent on the inside lane was 1200 ft long. The pavement at this location was 20 ft wide. The existing delineation consisted of painted centerlines and PMDs on the outside of the curve. The PMDs had delineators facing both directions of traffic. There were no painted edgelines. The surrounding land use was rural residential with seven driveways within the study section. A county road intersected the curve toward the southern end of the site. A moderate percentage of the southbound traffic turned onto this county road during the study. Operational data were collected with existing PMDs on June 22, 1988, and with new RPMs installed June 23, 1988. Long-term data were collected on May 15, 1989, 11 months after the RPMs were installed.

A.2. FM 730 SITE

The FM 730 site was located in Parker County (District 2), 4.6 mi north of US 80/180 and 3 mi east of Weatherford. Figure A-2 illustrates the data collection setup. The 3-degree curve was 1670 ft long. The approach tangent on the outside lane was 1400 ft long, and the approach tangent on the inside lane was 900 ft long. The pavement width through the curve was 19 ft. The existing delineation consisted of painted centerlines and bidirectional PMDs on the outside of the curve. The surrounding land use was rural with one residence and one county road within the limits of the study site. A large number of vehicles turned onto and off of the county road during data collection. Data were collected with the existing PMDs on the evening of August 15, 1988, and with new RPMs installed on August 16, 1988.

A.3. FM 2280 SITE

The FM 2280 was located in Johnson County (District 2), 3.6 mi north of US 67 and 7 mi northeast of Cleburne. Figure A-3 illustrates the data collection setup. This 3-degree curve was 1110 ft long. The pavement width through the curve was 22 ft. The approach tangent on the outside lane of the curve was 2800 ft long, and the approach tangent on the inside lane was 1100 ft long. The existing delineation consisted of painted centerlines and PMDs on the outside lane. Delineators faced traffic approaching in the outside lane only. Within the limits of the study section, there were two driveways and an entrance to a mobile home park. A convenience store and a county road were located just beyond the southern end of the study section. The store was closed during data collection and, therefore, had little effect on traffic. During the two nights of data collection, the mobile home park road was used only five times. Data were collected with the existing PMDs on the evening of August 17, 1988, and with new RPMs on August 18, 1988.

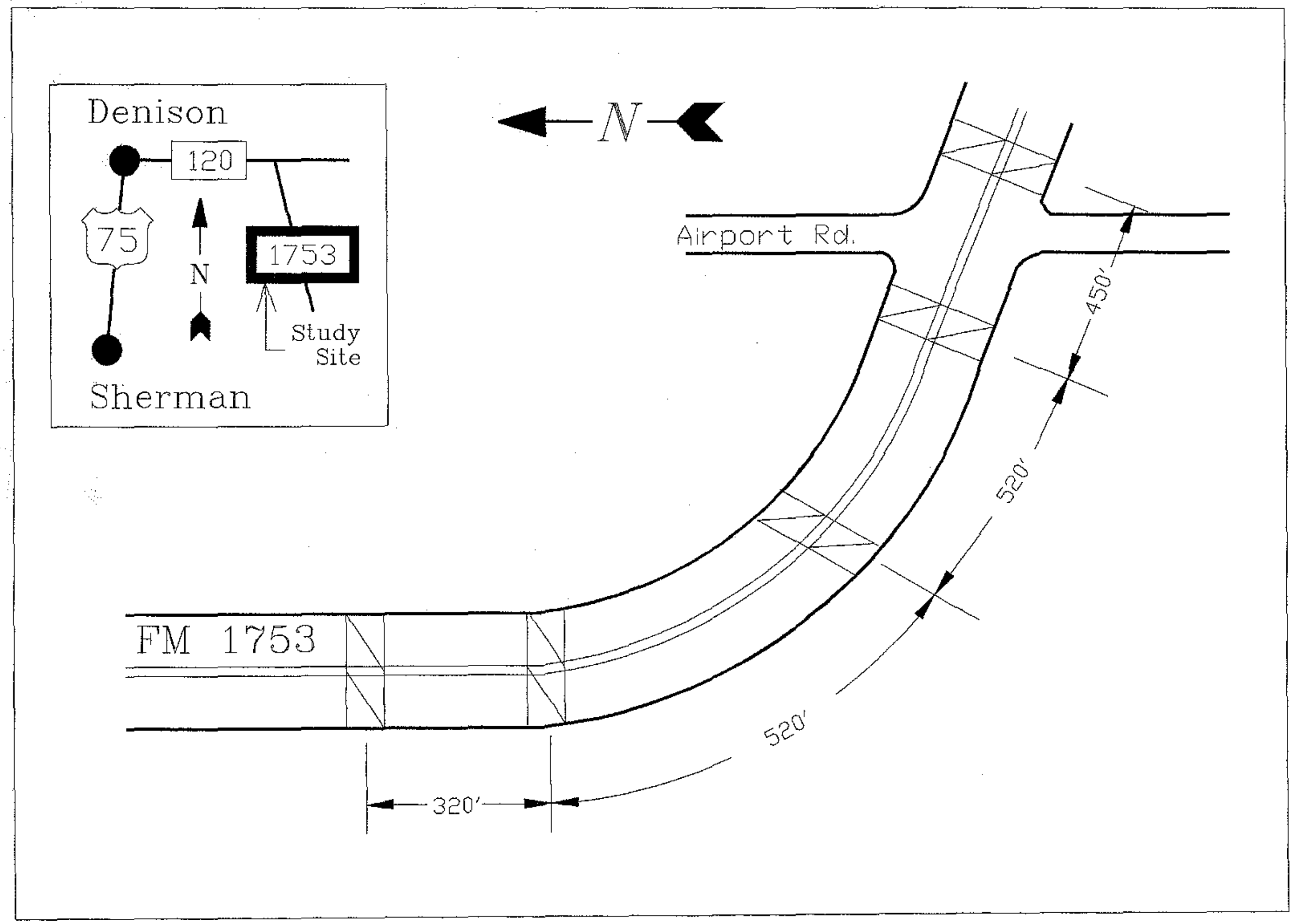


Figure A-1. Schematic of the FM 1753 Study Site.

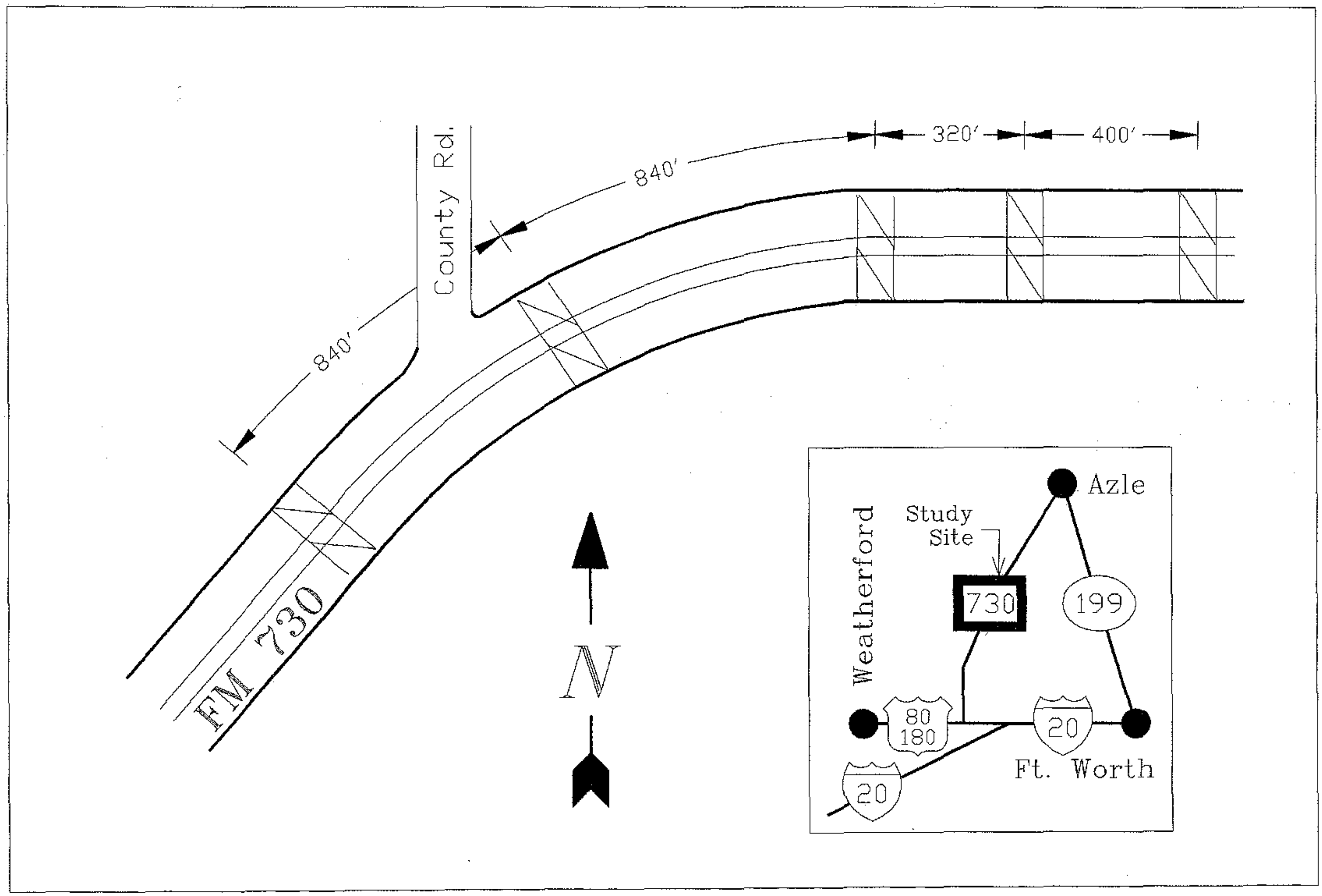


Figure A-2. Schematic of the FM 730 Study Site.

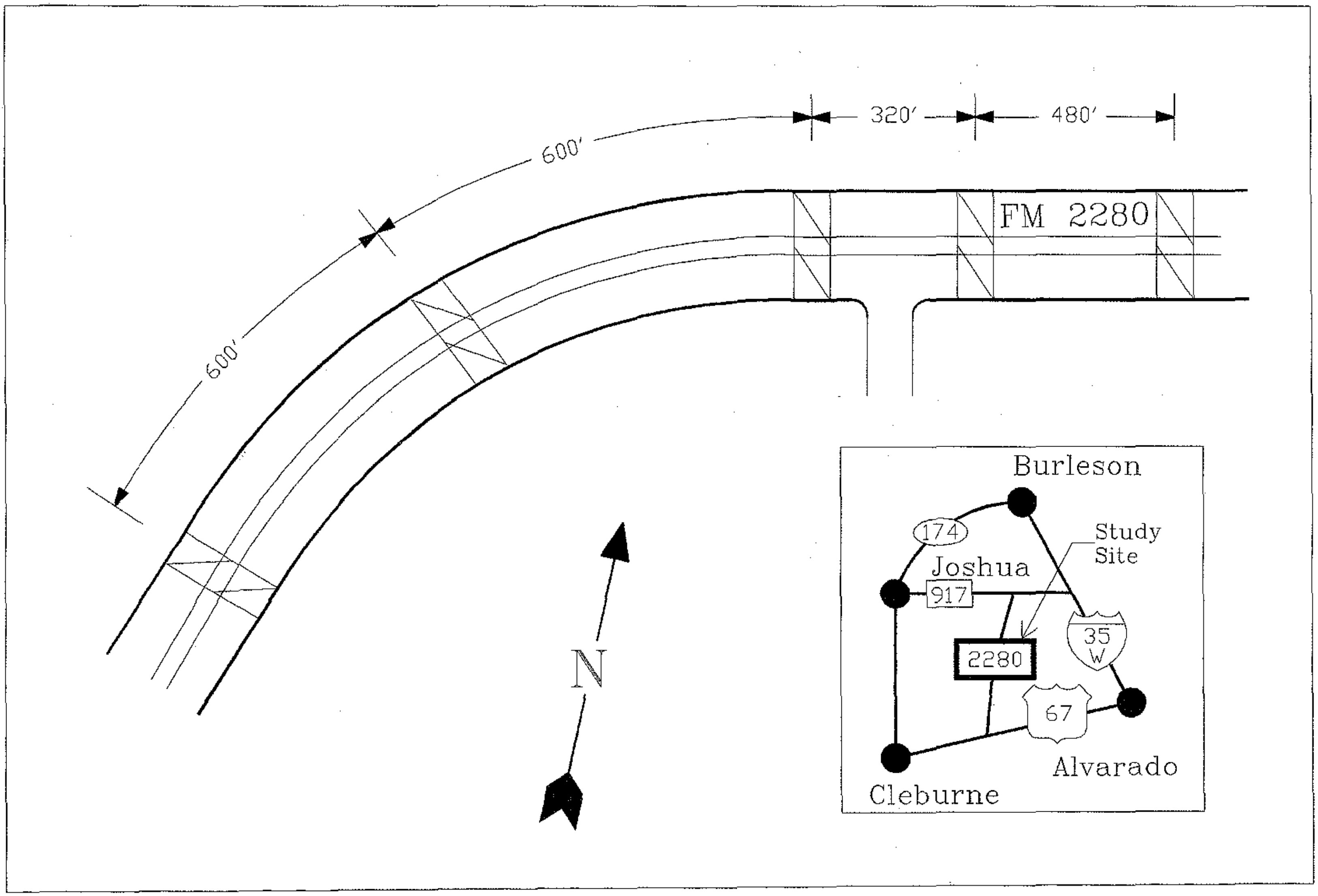


Figure A-3. Schematic of the FM 2280 Study Site.

A.4. FM 219 SITE

The FM 219 site was located in Bosque County (District 9), 2.5 mi south of SH 22. Figure A-4 illustrates the data collection setup. The site was a 5-degree curve, 850 ft in length. The approach tangent on the outside lane was 2200 ft long, and the approach tangent on the inside lane was 400 ft long. The pavement at the midpoint of the curve was 28 ft. The existing delineation consisted of painted centerlines and bidirectional PMDs on the outside of the curve. The surrounding land use was rural. An unpaved county road intersected FM 219 near the midpoint of the curve. Data were collected with the existing PMDs on the evening of May 22, 1989. New reflectors were installed on the posts, and data were collected on May 23, 1989. Data were collected with new RPMs on May 24, 1989. Long-term data were collected on July 5, 1989, and August 8, 1989.

A.5. FM 933 SITE

The FM 933 site was located on FM 933 in Hill County (District 9), 7 mi north of Whitney. Figure A-5 illustrates the data collection setup. The site was an 890-ft long, 4-degree curve. The approach tangent on the outside lane was almost 2400 ft long, and the approach tangent on the inside lane was 1700 ft long. The pavement width in the curve was 25 ft. The existing delineation consisted of painted centerlines and bidirectional PMDs. The surrounding land use was rural with one access point within the study site limits. This access was an unpaved county road forming tangent to the curve. Data were collected with the existing PMDs on May 30, 1989. New reflectors were installed and data were collected May 31, 1989. Data were collected with new RPMs installed on June 1, 1989. Long-term data were collected on July 10, 1989, and August 9, 1989.

A.6. SH 94 SITE

The SH 94 site was located in Trinity County (District 11), 6 mi east of Groveton. Figure A-6 illustrates the data collection setup. The site was a 3-degree curve, 990 ft in length. The approach tangent on the outside lane was 1800 ft long, and the approach tangent on the inside lane was almost 3 mi long. The width of the pavement in the curve was 21 ft. The existing delineation consisted of painted centerlines and bidirectional PMDs. SH 94 has painted edgelines. However, the edgelines on the outside of the curve were mostly obscured by spot pavement patching. Therefore, only the inside edge of the curve had edgelines. SH 94 cuts through the Davy Crockett National Forest, so the surrounding area was heavily wooded. Data were collected with the existing PMDs on May 16, 1988, and with new RPMs installed on May 17, 1988.

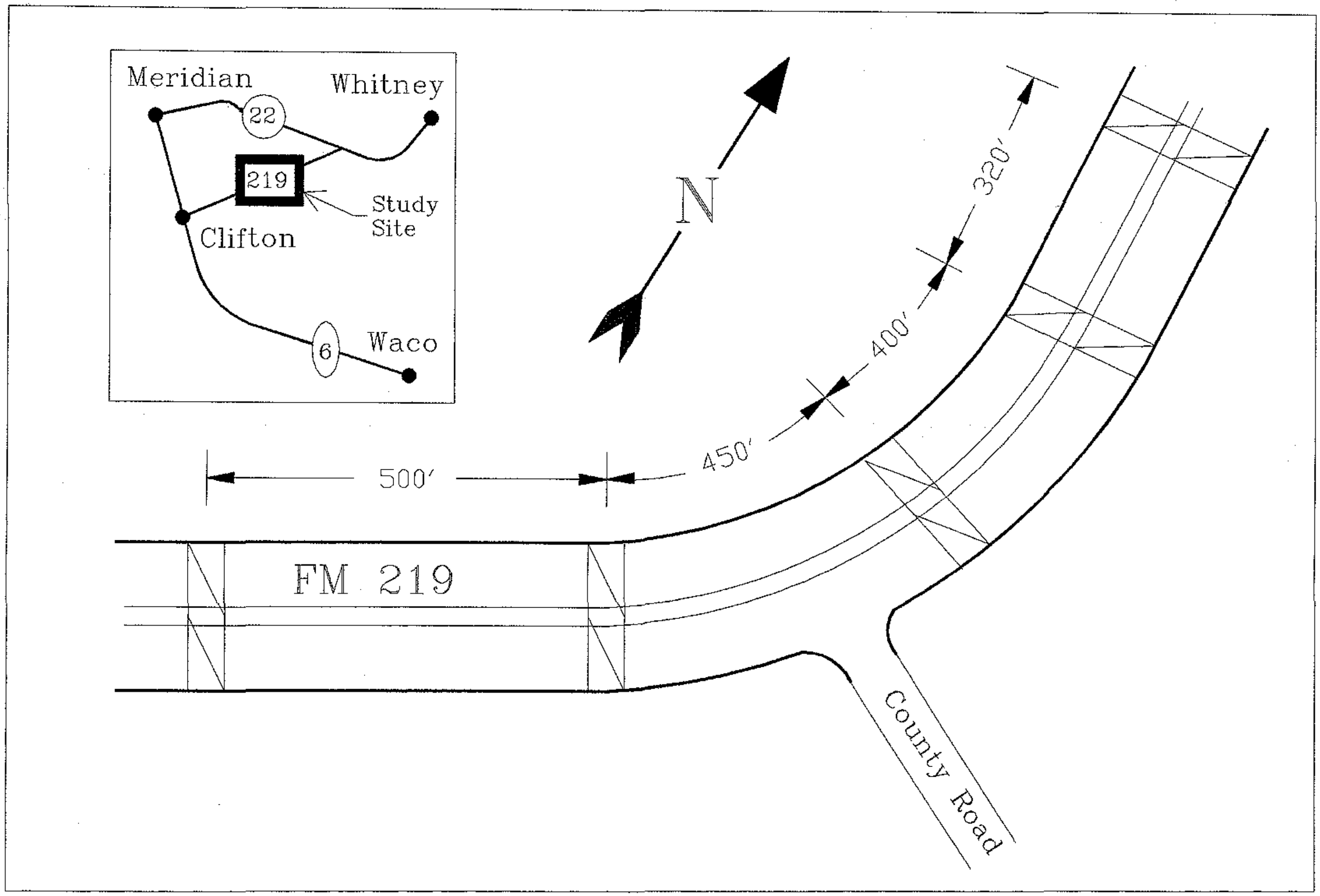


Figure A-4. Schematic of the FM 219 Study Site.

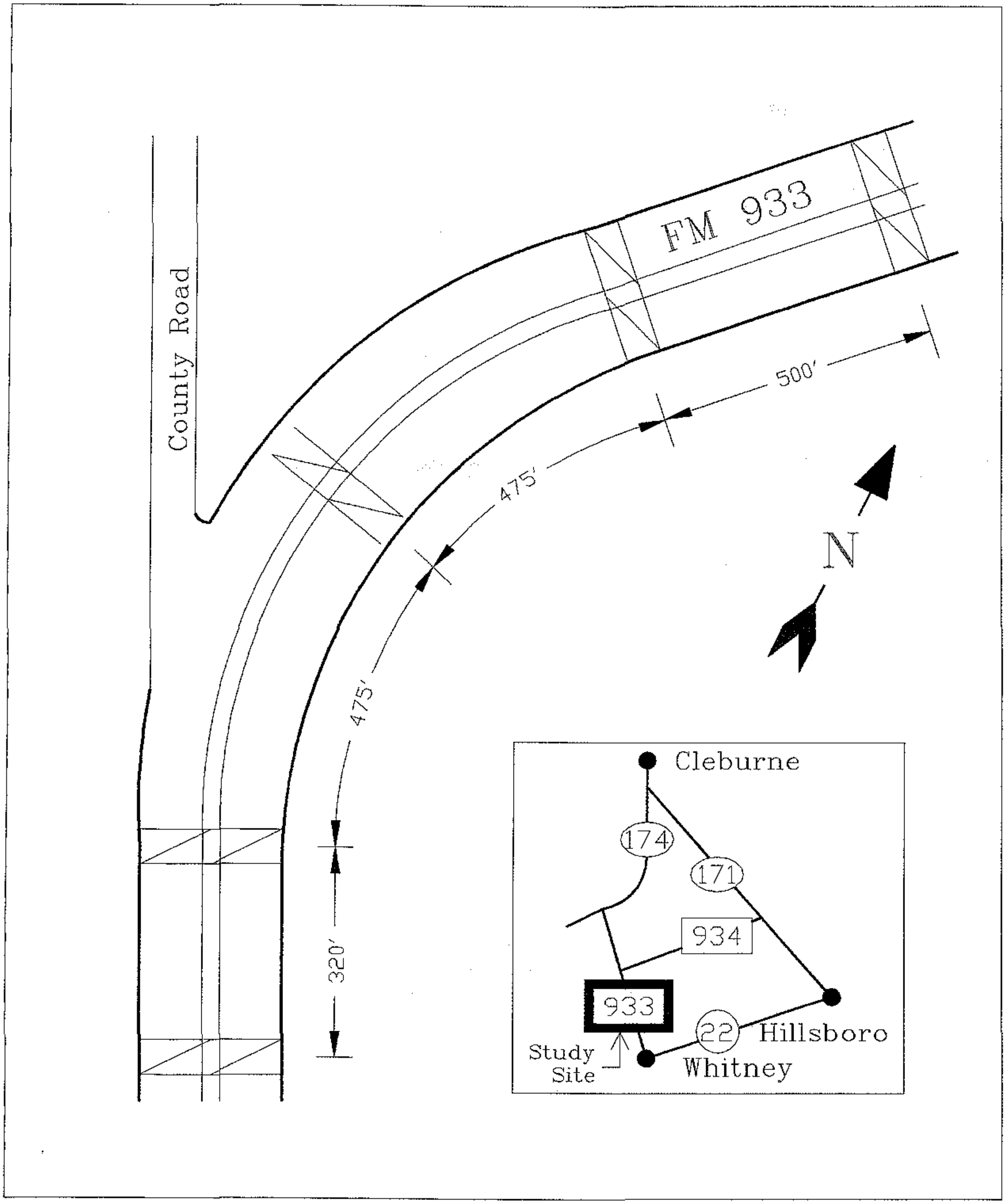


Figure A-5. Schematic of the FM 933 Study Site.

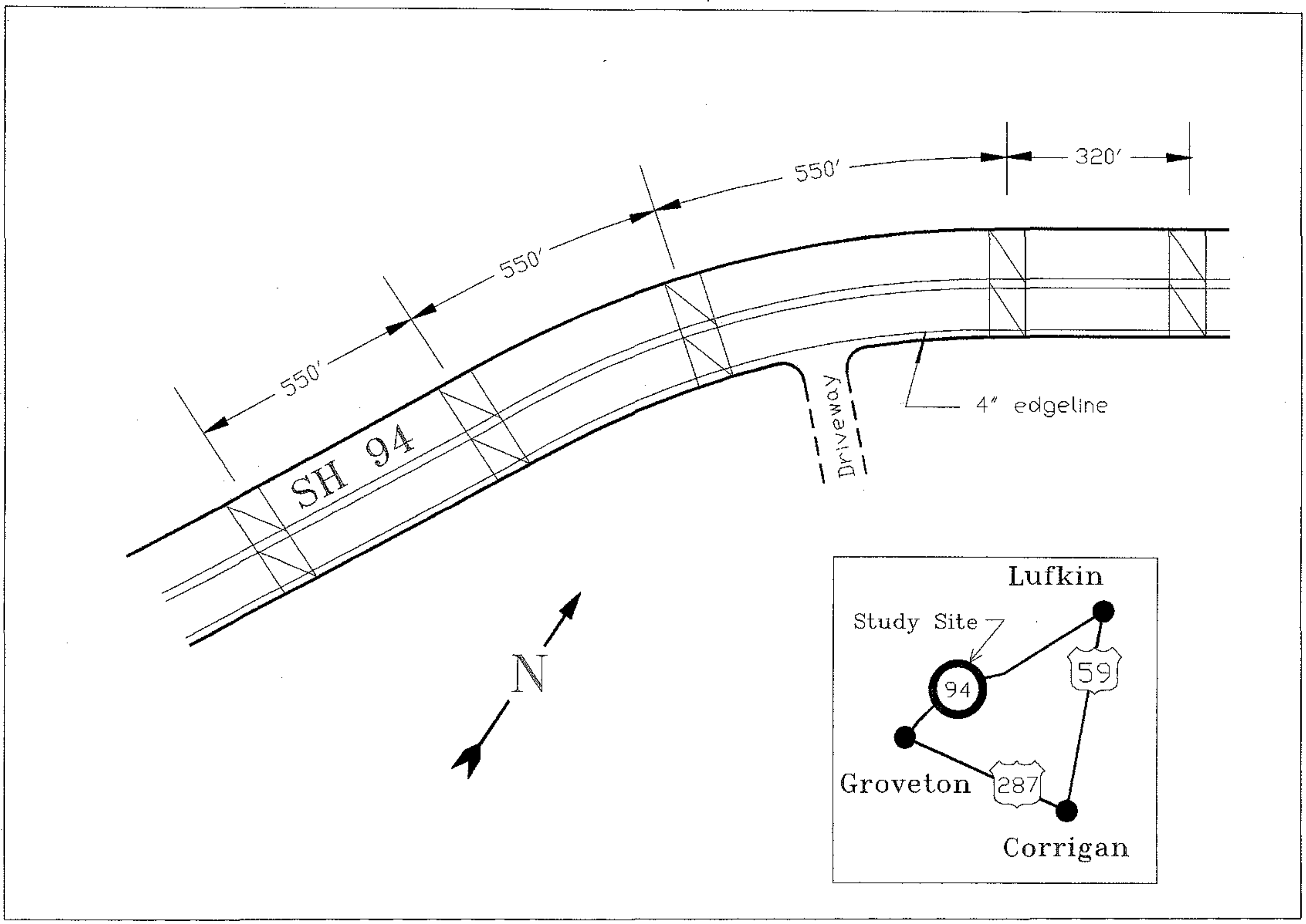


Figure A-6. Schematic of the SH 94 Study Site.

A.7. FM 120 SITE

The FM 120 site was located in Grayson County (District 1), 8 mi west of Denison and 4 mi north of FM 996. Figure A-7 illustrates the data collection setup. A 1050-ft long, 5-degree curve was studied. The approach tangent on the outside lane was 1300 ft long, and the approach tangent on the inside lane was almost 500 ft long. This pavement through the curve was 23 ft wide. The existing delineation consisted of painted centerlines, painted edgelines, and bidirectional PMDs. Within the limits of the study site, there were three residences and a private road. Additionally, at the south end of the section was an entrance to a housing development and further south was an entrance to a resort area. Data were collected with the existing PMDs on June 20, 1988, and with the new RPMs installed on June 21, 1988.

A.8. ACCIDENT EXPERIENCE AT THE STUDY SITES

Table A-1 summarizes the number and type of accidents that occurred at the study sites during the years 1985 through 1988. Accident data were obtained from the Texas Master Accident Data File maintained by the Department of Public Safety. A total of 13 accidents occurred at the 7 study sites during a 3.5-year period prior to the replacement of the existing PMDs with RPMs supplementing the painted centerline. No accidents were reported during the 4-7-month period of 1988 after the RPMs were installed. Most of the accidents at the curves were single vehicle accidents that occurred at night with clear weather conditions. Most of the accidents were not severe, involving either no injury or nonincapacitating injuries.

TABLE A-1. ACCIDENT HISTORY AT STUDY SITES

	Number of Accidents per Year				
Sites	1985	1986	1987	1988	Total
FM 1753					0
FM 730		1			1
FM 2280	1	1	1	1*	4
FM 219	1				1
FM 933			3		3
SH 94			1		1
FM 120		3			3
Total	2	5	5	1	13

* Before RPMs were installed.

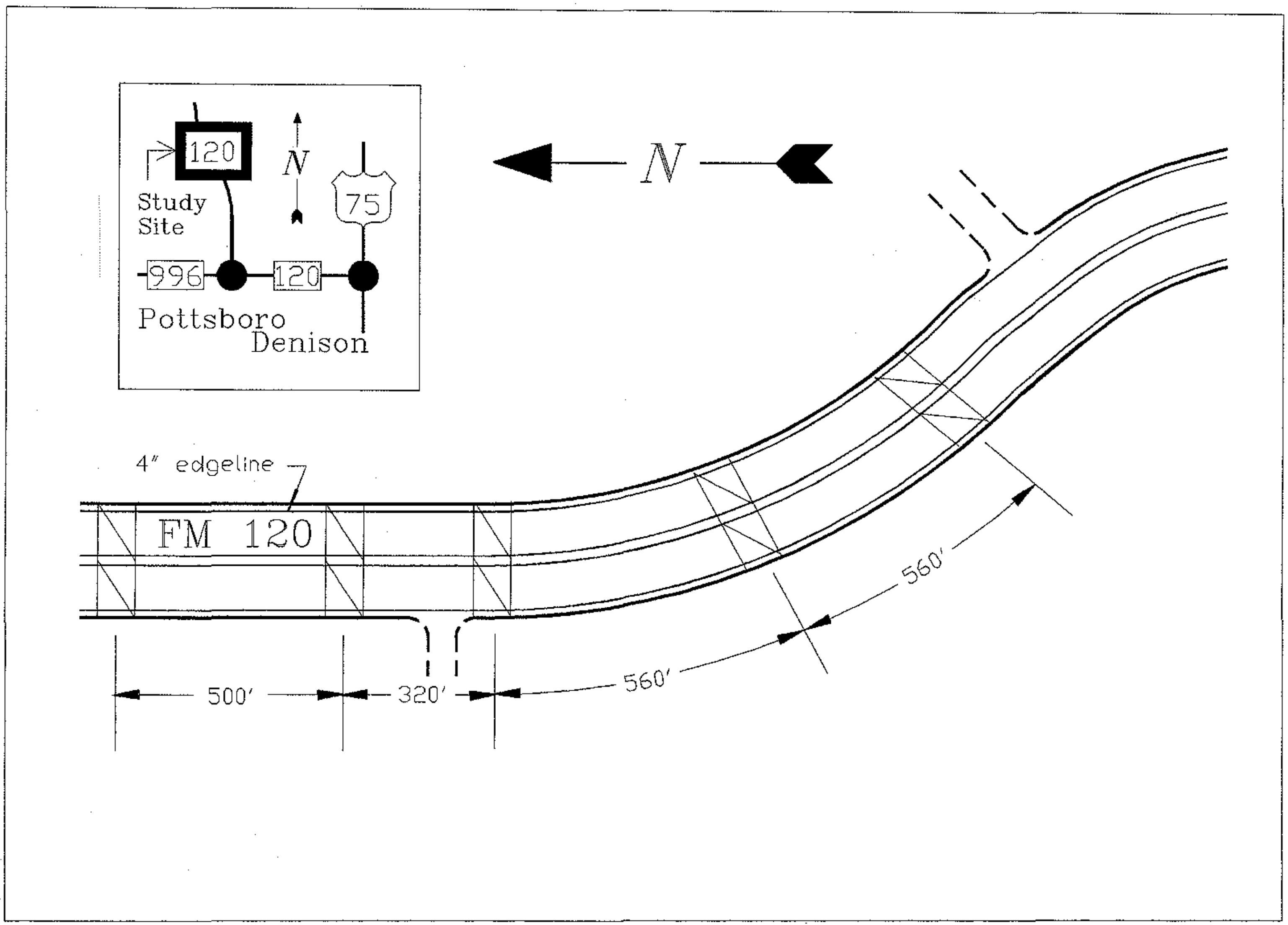


Figure A-7. Schematic of the FM 120 Study Site.

APPENDIX B.

MEAN SPEED AND LATERAL PLACEMENT PROFILES FOR THE STUDY SITES

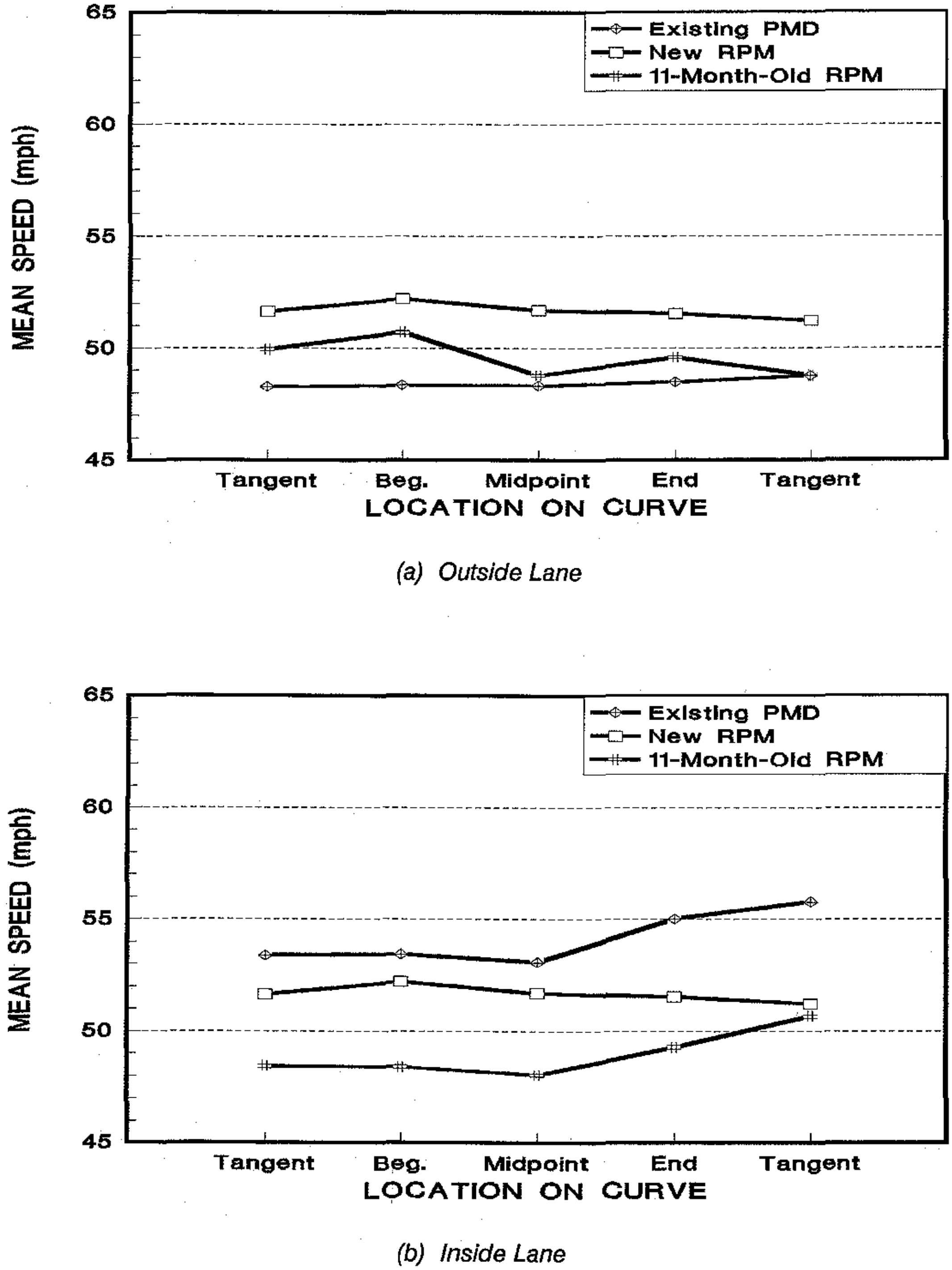
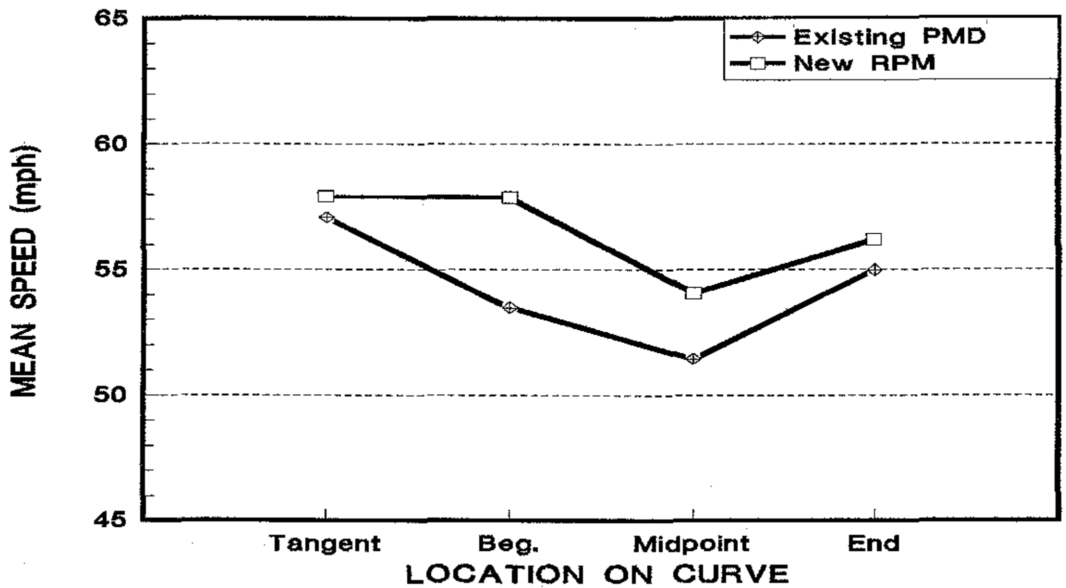
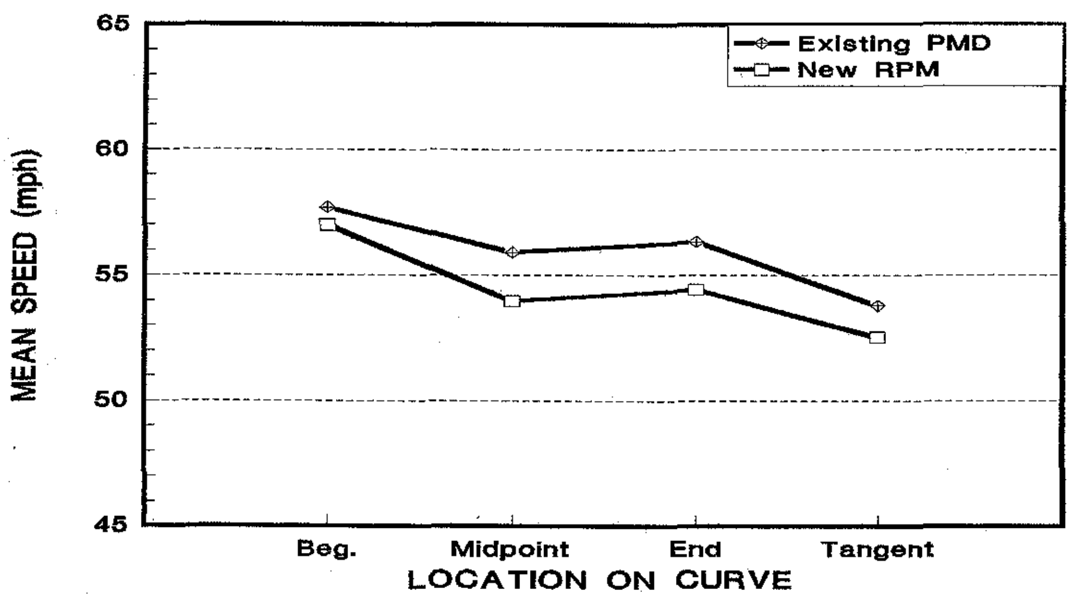


Figure B-1. Mean Speed Profiles at the FM 1753 Study Site.

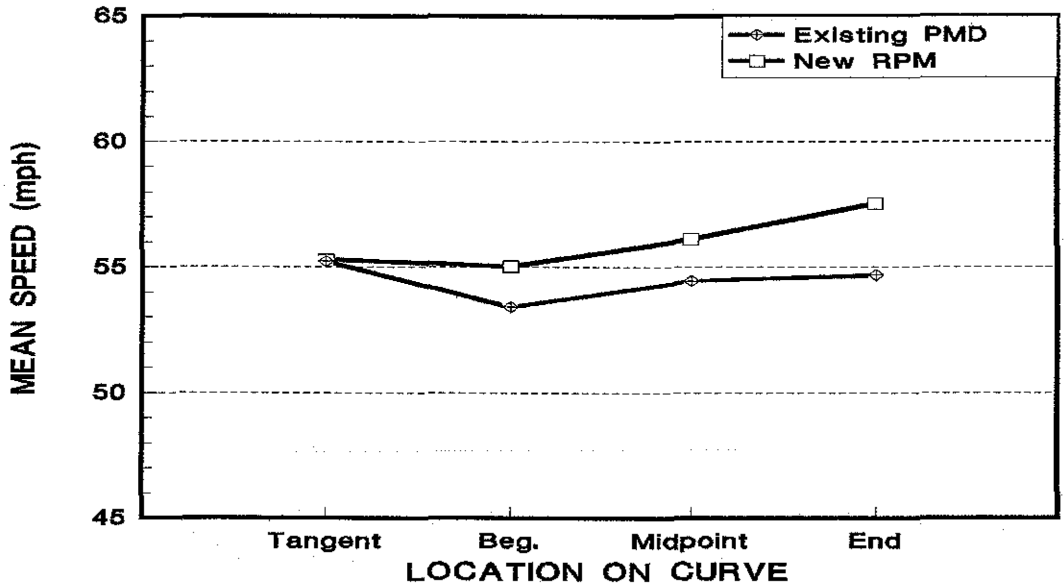


(a) Outside Lane

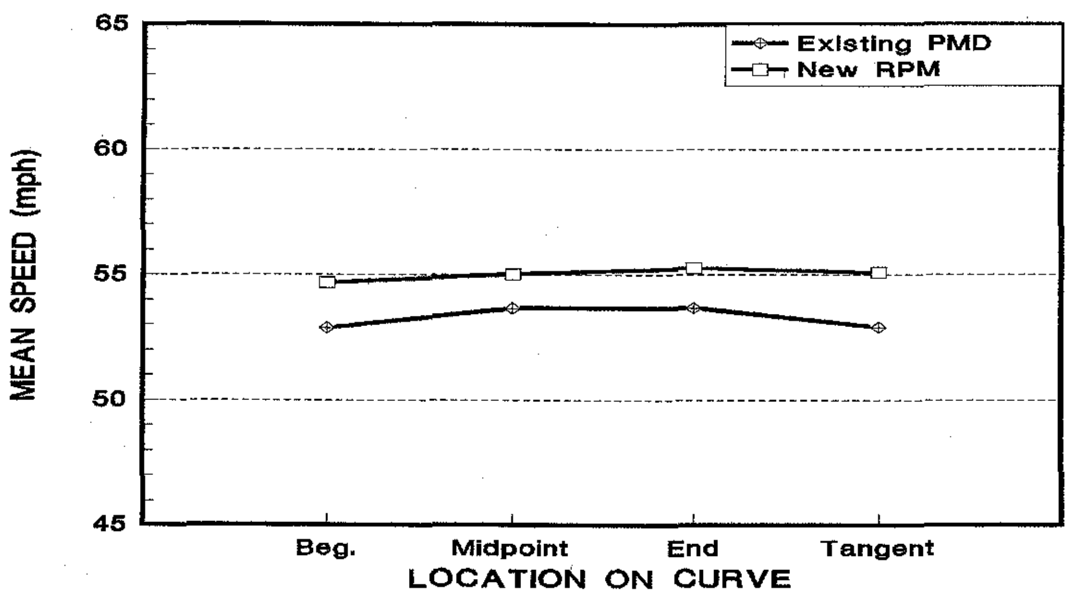


(b) Inside Lane

Figure B-2. Mean Speed Profiles at the FM 730 Study Site.

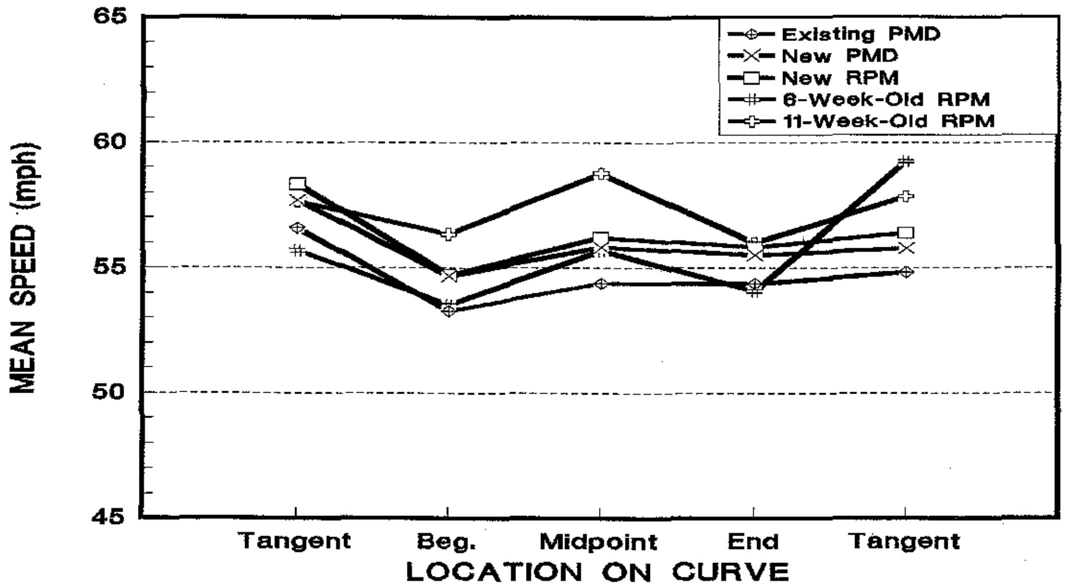


(a) Outside Lane

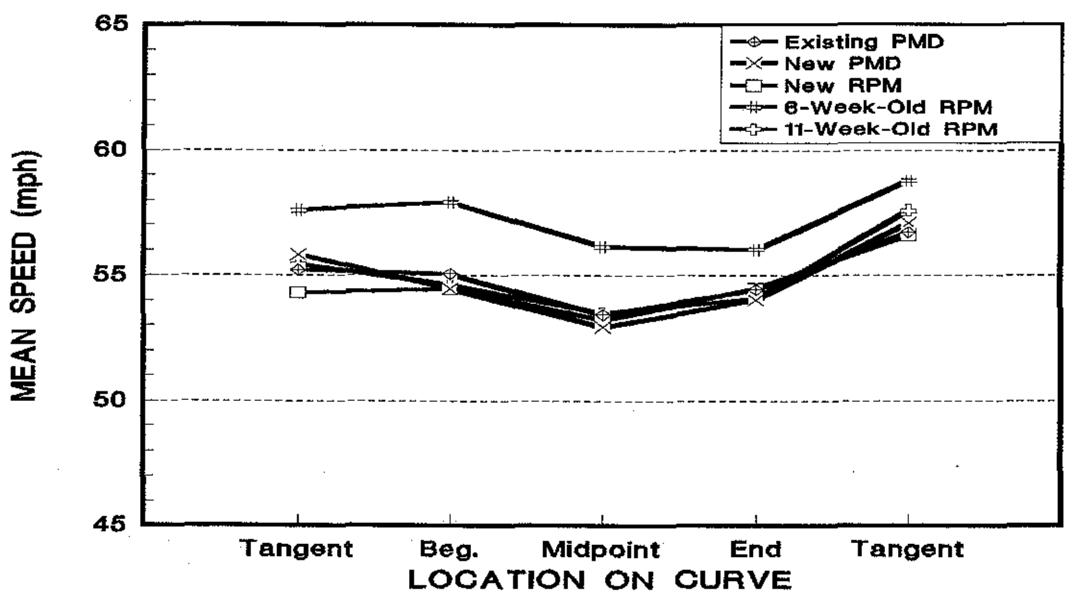


(b) Inside Lane

Figure B-3. Mean Speed Profiles at the FM 2280 Study Site.

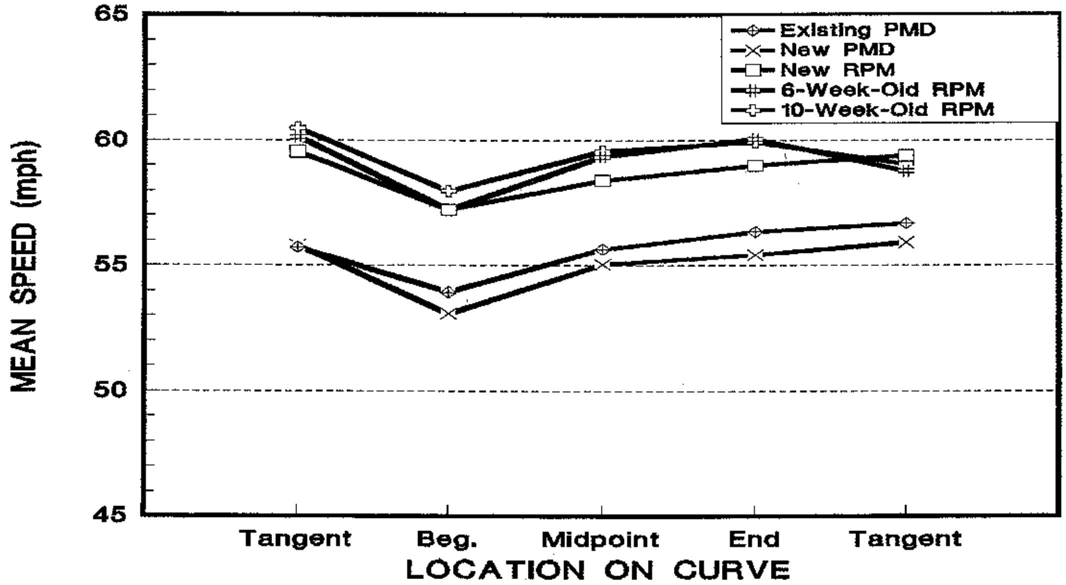


(a) Outside Lane



(b) Inside Lane

Figure B-4. Mean Speed Profiles at the FM 219 Study Site.



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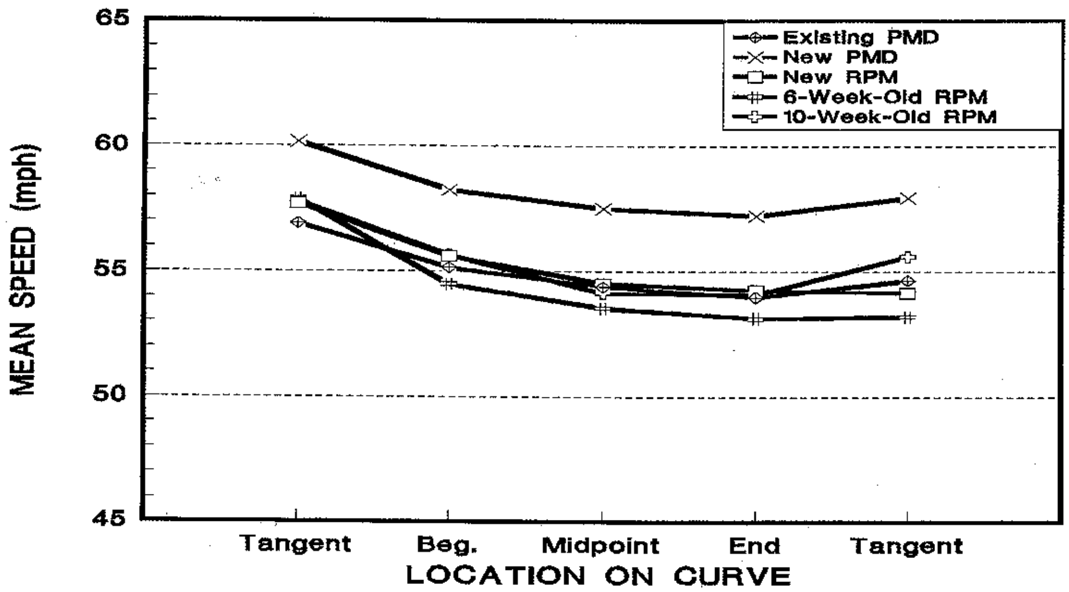
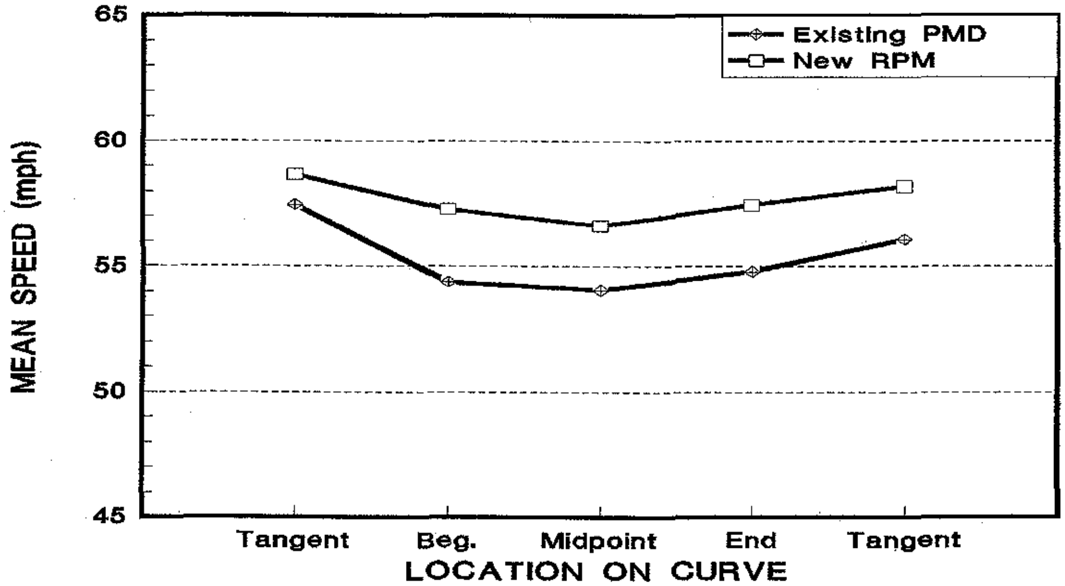
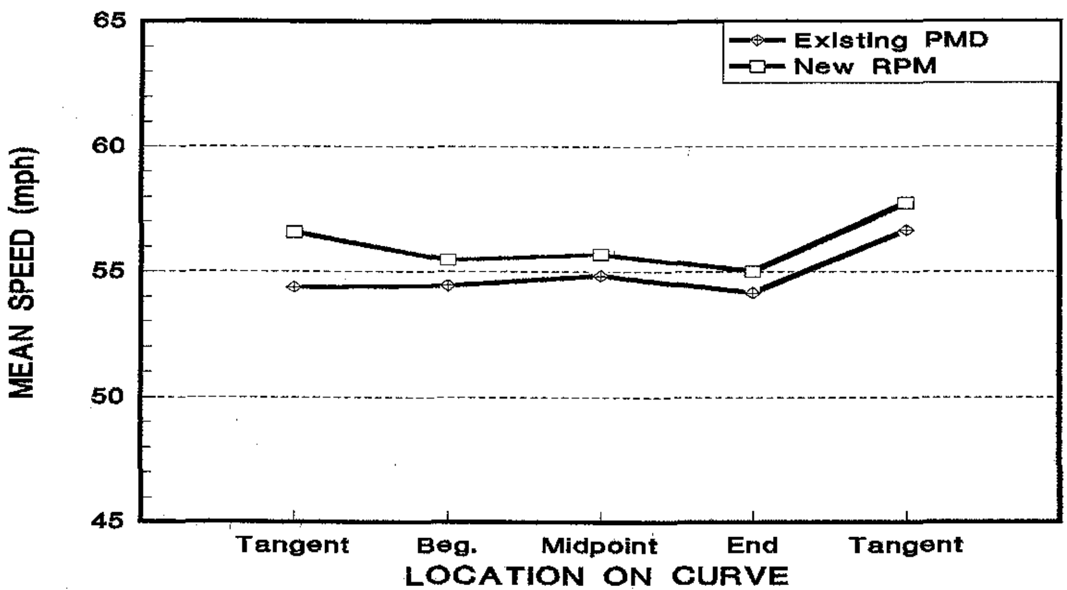


(b) Inside Lane

Figure B-5. Mean Speed Profiles at the FM 933 Study Site.

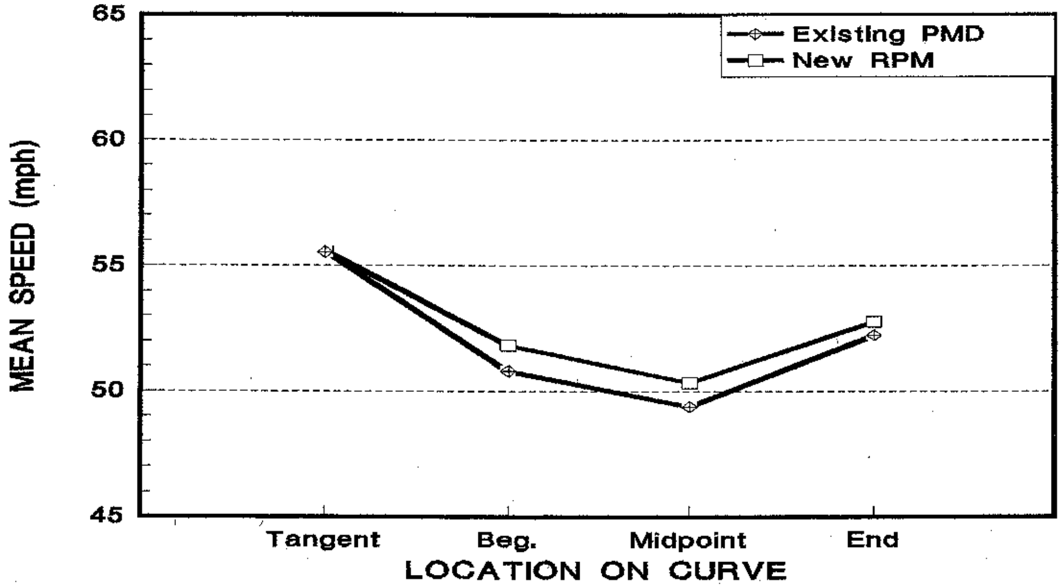


(a) Outside Lane



(b) Inside Lane

Figure B-6. Mean Speed Profiles at the SH 94 Study Site.



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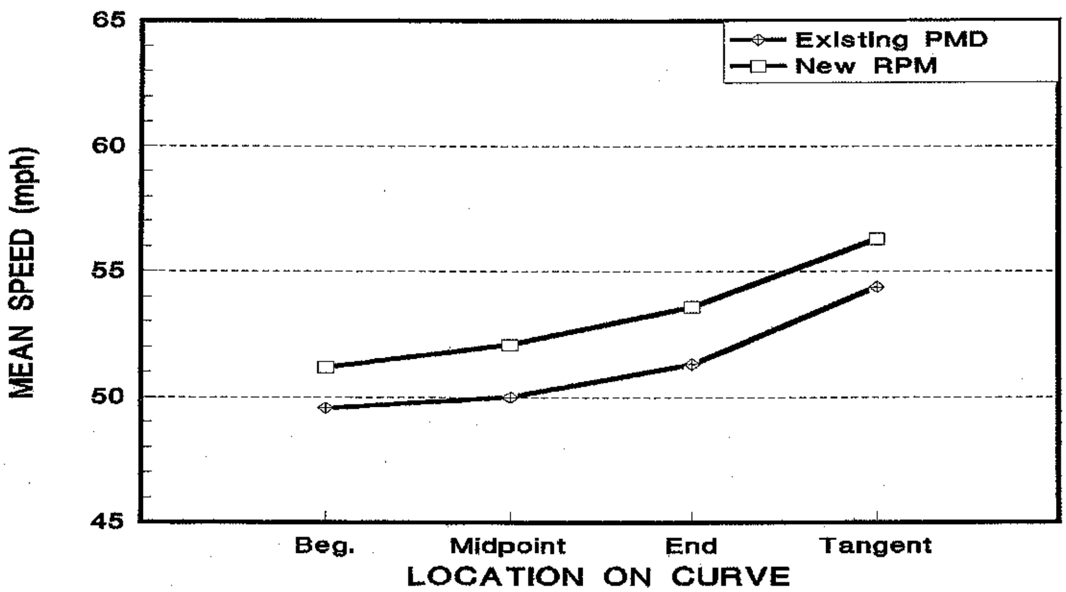
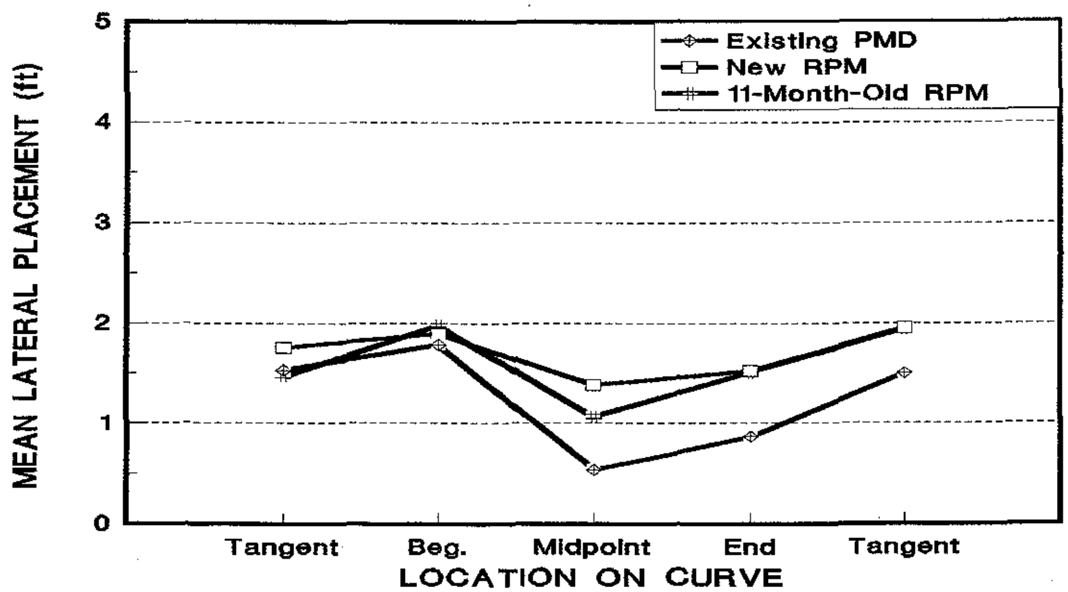


(b) Inside Lane

Figure B-7. Mean Speed Profiles at the FM 120 Study Site.



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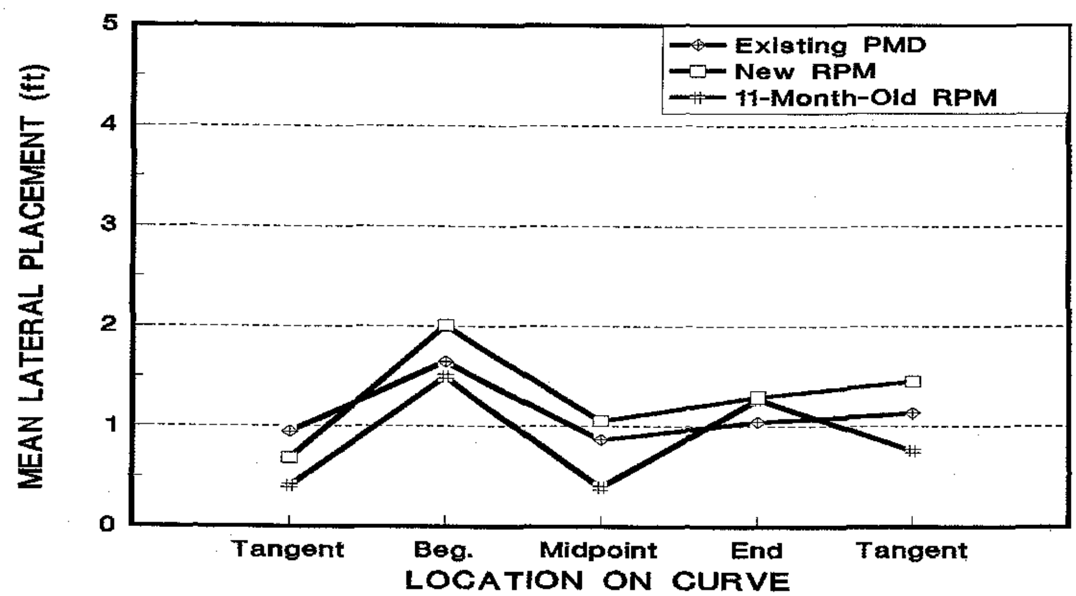
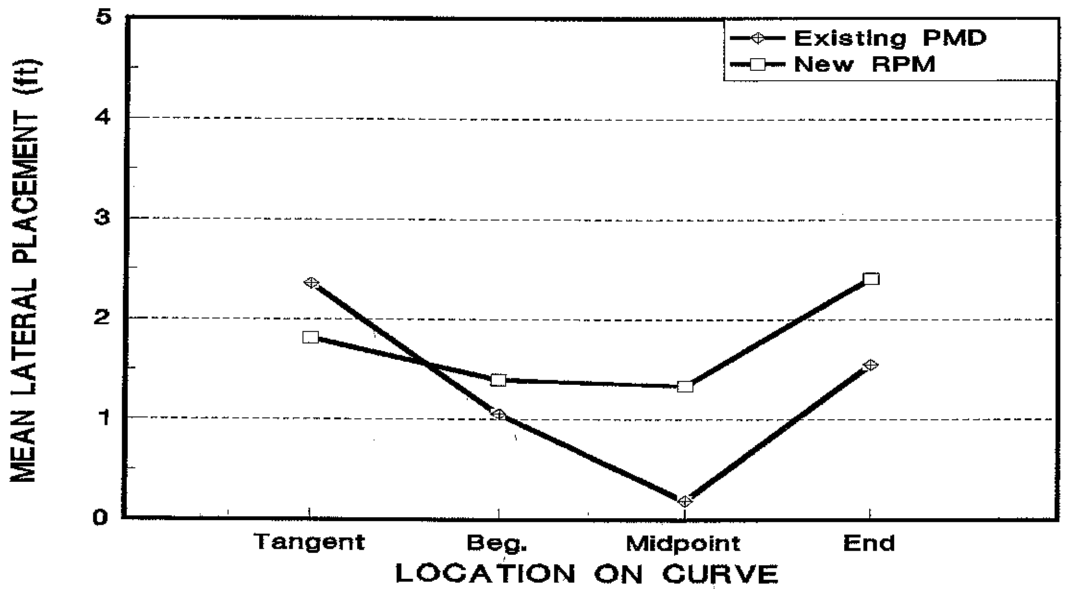


(b) Inside Lane

Figure B-8. Mean Lateral Placement Profiles at the FM 1753 Study Site.



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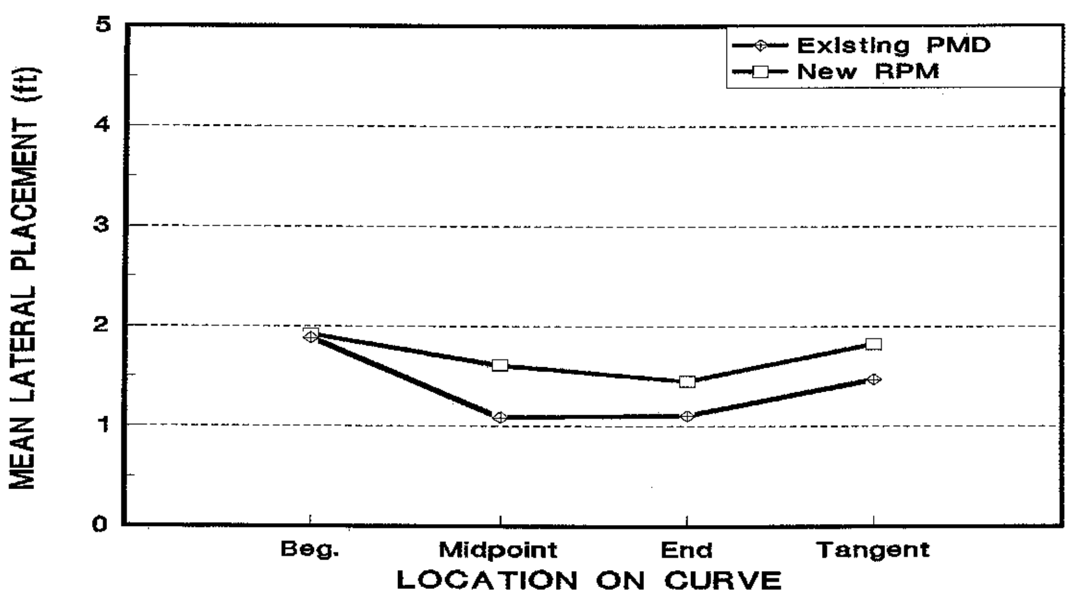
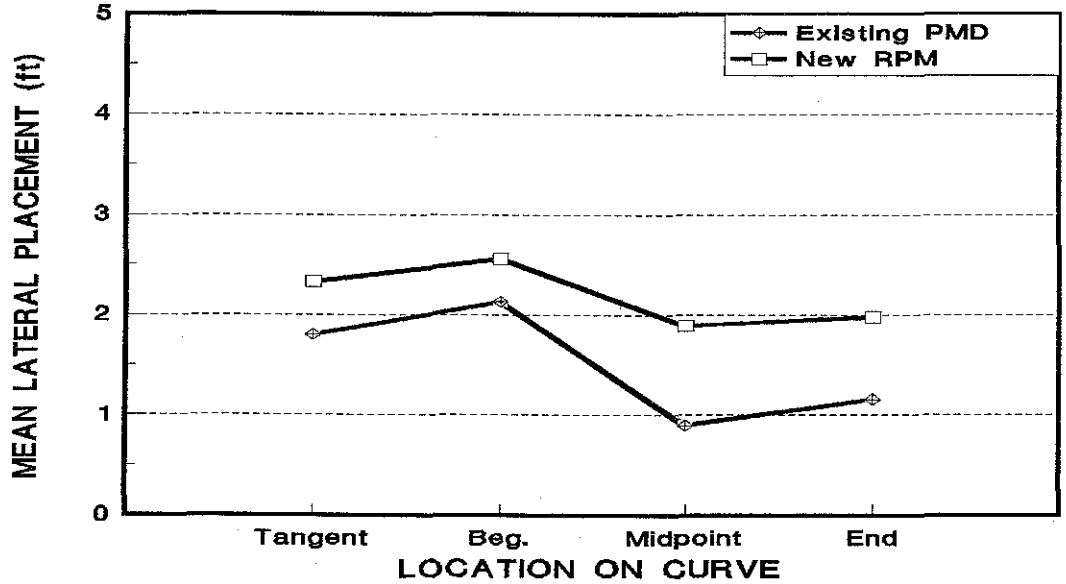


(b) Inside Lane

Figure B-9. Mean Lateral Placement Profiles at the FM 730 Study Site.



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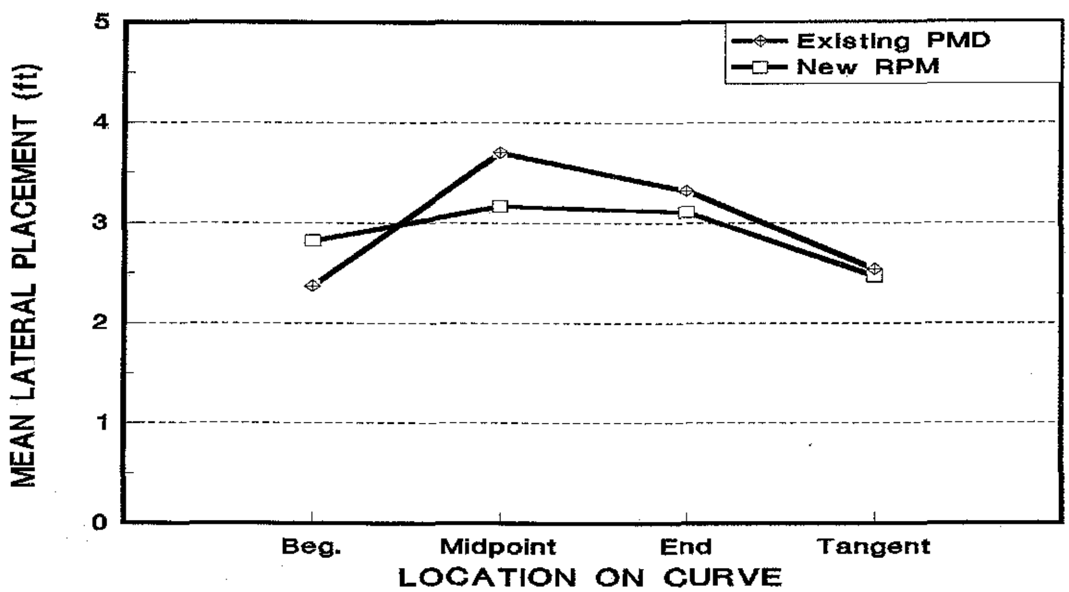
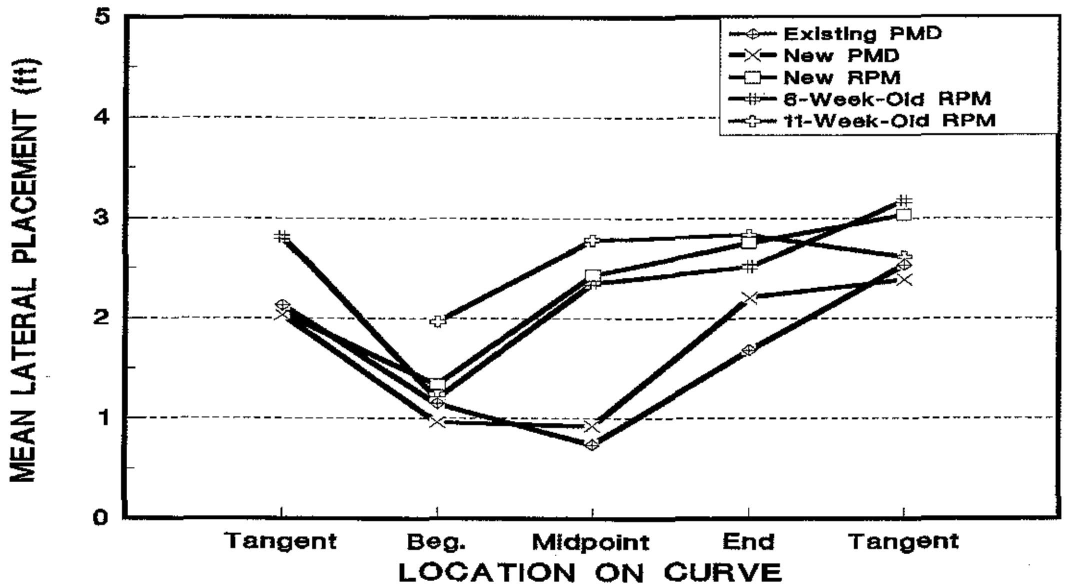
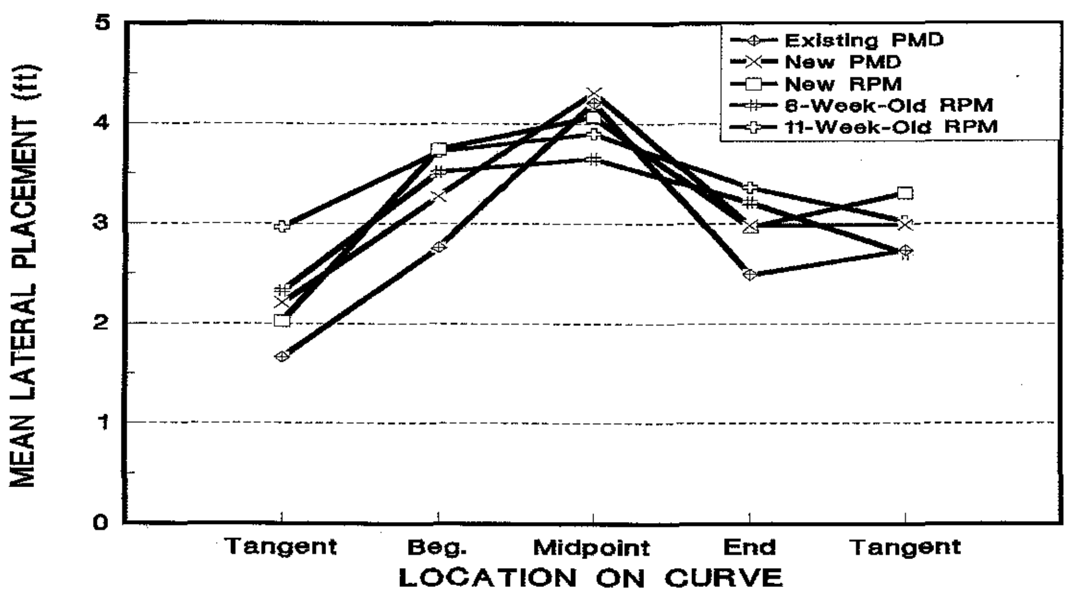


(b) Inside Lane

Figure B-10. Mean Lateral Placement Profiles at the FM 2280 Study Site.

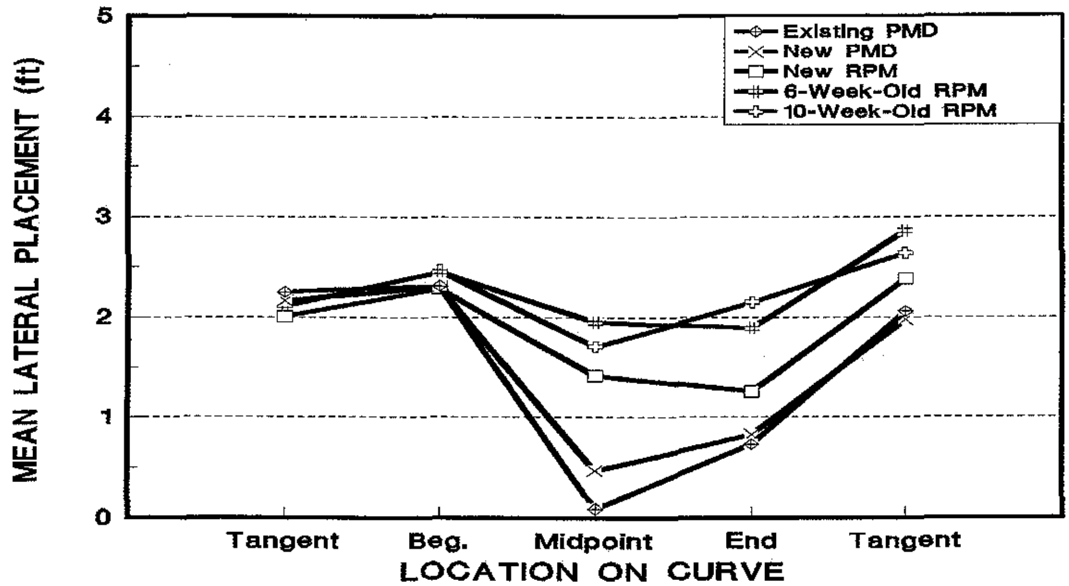


(a) Outside Lane

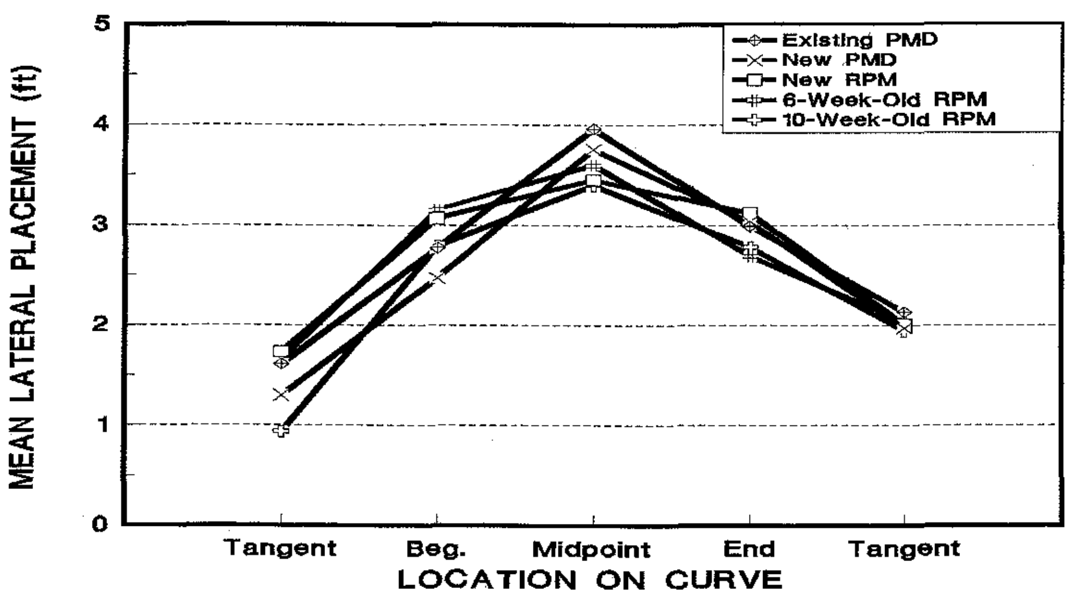


(b) Inside Lane

Figure B-11. Mean Lateral Placement Profiles at the FM 219 Study Site.

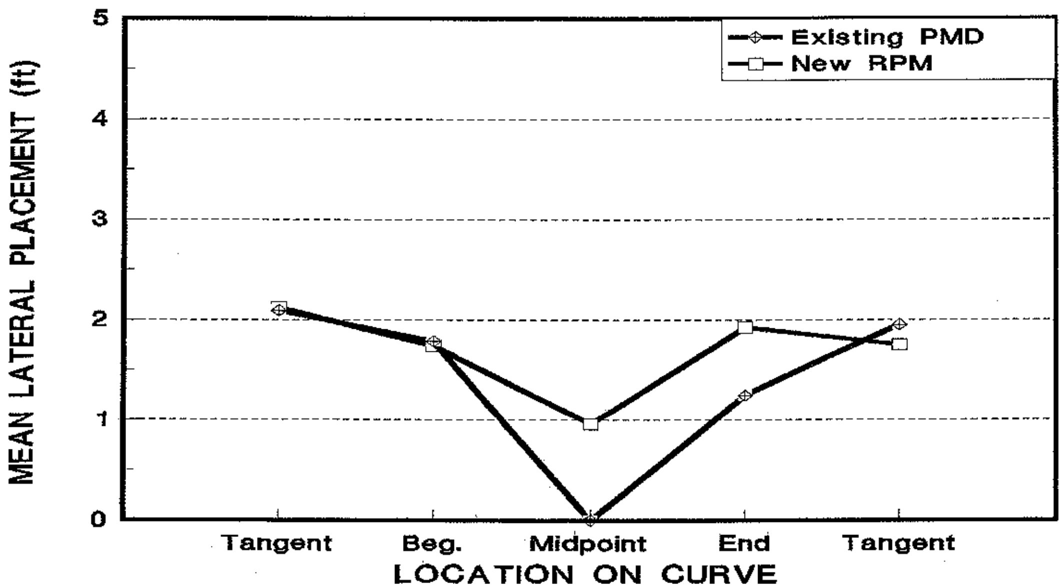


(a) Outside Lane

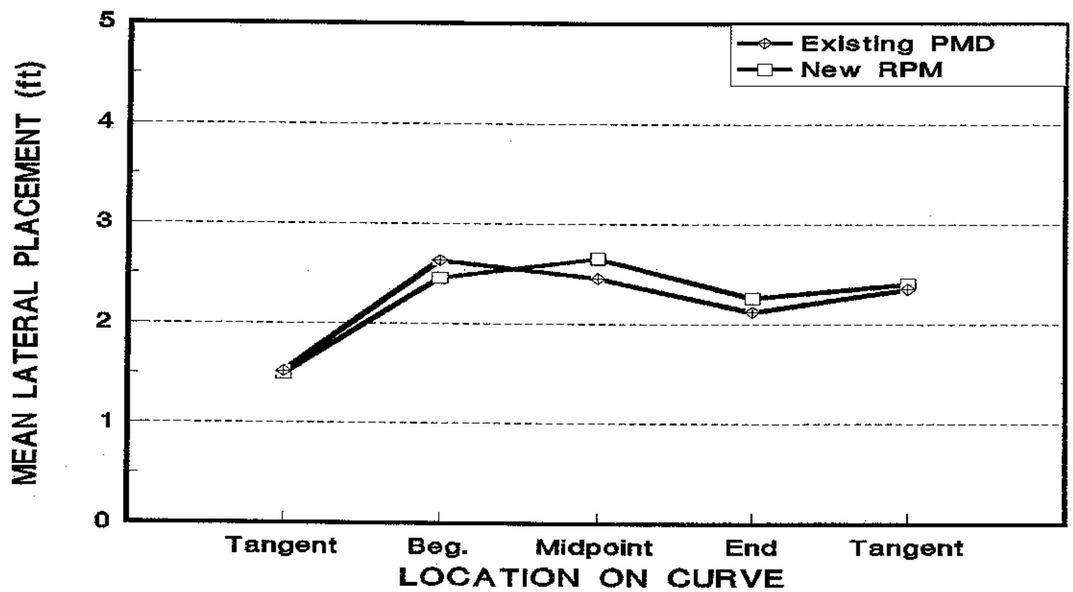


(b) Inside Lane

Figure B-12. Mean Lateral Placement Profiles at the FM 933 Study Site.

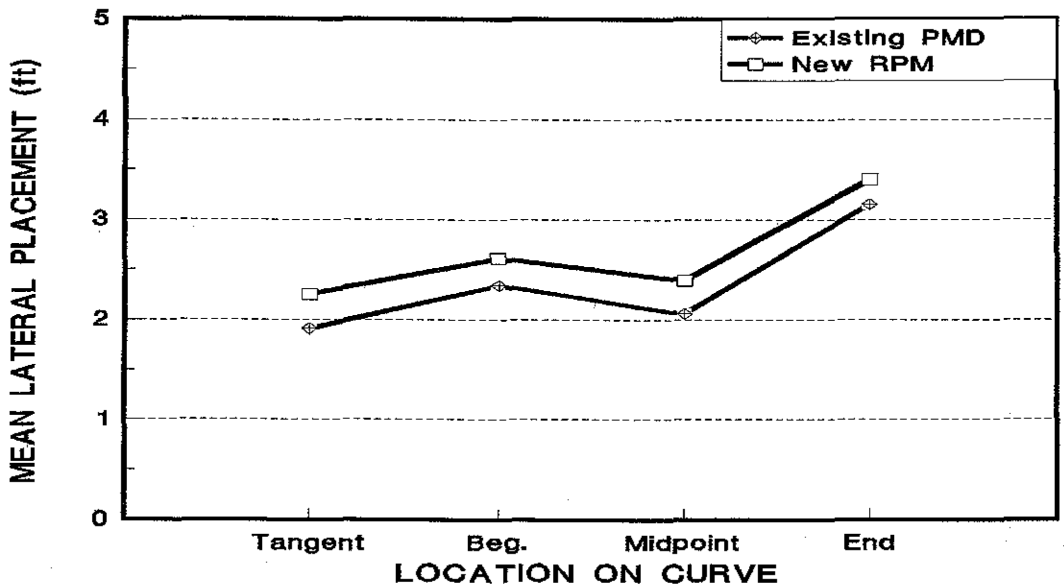


(a) Outside Lane

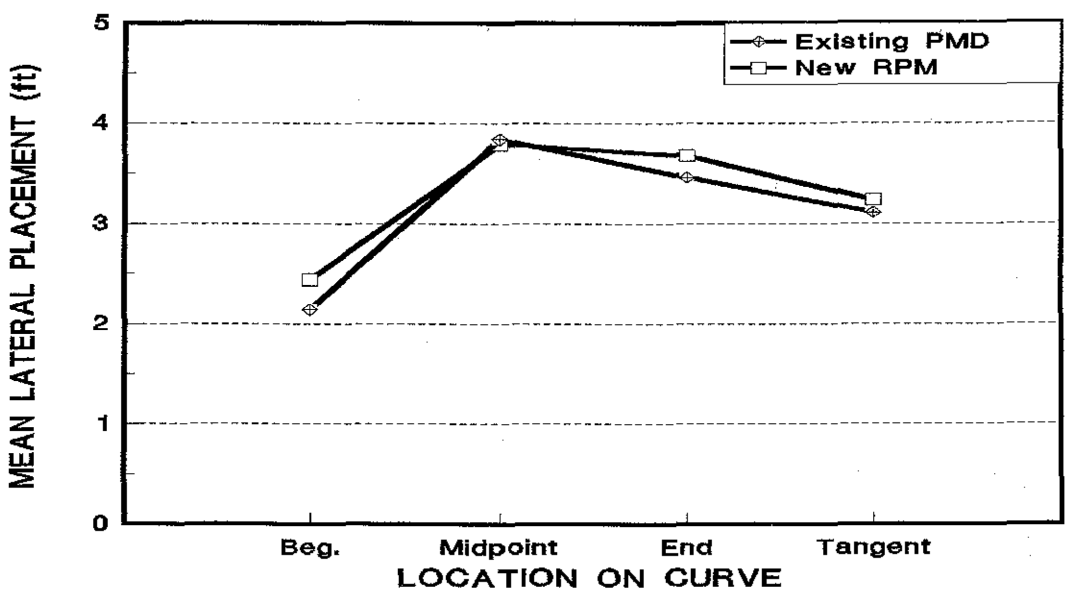


(b) Inside Lane

Figure B-13. Mean Lateral Placement Profiles at the SH 94 Study Site.



(a) Outside Lane



(b) Inside Lane

Figure B-14. Mean Lateral Placement Profiles at the FM 120 Study Site.

APPENDIX C.

RESULTS OF THE STATISTICAL ANALYSIS OF SHORT- AND LONG-TERM OPERATIONAL DATA

TABLE C-1. MEAN SPEEDS AT THE CONTROL POINT OF THE CURVE: OUTSIDE AND INSIDE LANES

	Outside Lane (mph)			Inside Lane (mph)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753	48.8	51.2	2.4	53.4	52.9	-.5
FM 730	57.1	57.9	.8	53.8	52.5	-1.3
FM 2280	55.2	55.3	.1	52.9	55.0	2.1
FM 219	56.6	58.4	1.8	56.7	56.6	-.1
FM 933	55.7	59.6	3.9 *	54.7	54.2	-.5
SH 94	56.1	58.2	2.1	54.4	56.6	2.2
FM 120	55.5	55.6	.1	54.4	56.3	1.9

* Differences are statistically significant at a 0.05 significance level based upon two-sample t-tests.

TABLE C-2. MEAN LATERAL PLACEMENT AT THE CONTROL POINT OF THE CURVE: OUTSIDE AND INSIDE LANES

	Outside Lane (ft)			Inside Lane (ft)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753	1.5	2.0	.5 *	.9	.7	-.2
FM 730	2.4	1.8	-.6	1.5	1.8	.3 *
FM 2280	1.8	2.3	.5 *	2.5	2.5	.0
FM 219	2.1	2.0	-.1	2.7	3.3	.6 *
FM 933	2.2	2.2	.0	2.2	2.0	-.2
SH 94	1.9	1.5	-.4	1.5	1.5	.0
FM 120	1.9	3.1	1.2 *	3.1	3.2	.1

* Differences are statistically significant at a 0.05 significance level based upon two-sample t-tests.

TABLE C-3. SHORT-TERM ANALYSIS OF SPEEDS AT THE MIDPOINT OF THE CURVE: OUTSIDE LANE

	Mean (mph)			Standard Deviation (mph)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753	48.3	51.7	3.4 *	5.4	6.5	1.1
FM 730	51.4	54.1	2.7	6.8	9.2	2.4
FM 2280	54.5	56.1	1.6	5.1	4.8	-.3
FM 219	54.4	56.2	1.8	7.8	8.0	.2
FM 933	55.6	58.4	2.8 *	7.7	5.9	-1.8
SH 94	54.0	56.6	2.6	6.4	5.3	-1.1
FM 120	49.4	50.3	.9	5.9	6.1	.2

* Differences are statistically significant at a 0.05 significance level based upon t-tests for the means and F-tests for the standard deviations.

TABLE C-4. SHORT-TERM ANALYSIS OF SPEEDS AT THE MIDPOINT OF THE CURVE: INSIDE LANE

	Mean (mph)			Standard Deviation (mph)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753	53.1	52.1	-1.0	6.9	4.6	-2.3
FM 730	55.9	54.0	-1.9	6.2	7.5	1.3
FM 2280	53.6	55.0	1.4	5.3	6.9	1.6
FM 219	53.4	53.2	-.2	8.1	7.2	-.9
FM 933	54.4	54.5	.1	7.7	6.6	-1.1
SH 94	54.8	55.7	.9	7.2	5.8	-1.4
FM 120	50.0	52.1	2.1 *	5.9	6.1	.2

* Differences are statistically significant at a 0.05 significance level based upon t-tests for the means and F-tests for the standard deviations.

TABLE C-5. SHORT-TERM ANALYSIS OF SPEED CHANGES FROM THE BEGINNING TO THE MIDPOINT OF THE CURVE: OUTSIDE LANE

	Mean (mph)			Standard Deviation (mph)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753	.0	-.5	-.5	2.1	2.0	-.1
FM 730	-2.0	-3.8	-1.8	2.8	4.3	1.5
FM 2280	1.0	1.1	.1	2.3	1.8	-.5
FM 219	1.1	1.5	.4	2.3	1.8	-.5
FM 933	1.7	1.2	-.5	2.2	2.1	-.1
SH 94	-.3	-.7	-.4	1.6	1.7	.1
FM 120	-1.4	-1.5	-.1	2.3	4.4	2.1 *

* Differences are statistically significant at a 0.05 significance level based upon t-tests for the means and F-tests for the standard deviations.

TABLE C-6. SHORT-TERM ANALYSIS OF SPEED CHANGES FROM THE BEGINNING TO THE MIDPOINT OF THE CURVE: INSIDE LANE

	Mean (mph)			Standard Deviation (mph)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753.	-.4	-.6	-.2	2.6	2.6	.0
FM 730	-1.8	-3.0	-1.2	5.9	3.9	-2.0 *
FM 2280	.8	.3	-.5	4.2	3.0	-1.2
FM 219	-1.6	-1.2	.4	2.2	1.9	-.3
FM 933	-.8	-1.1	-.3	1.3	1.5	.2
SH 94	.4	.2	-.2	1.4	2.1	.7 *
FM 120	.4	.9	.5	2.4	3.7	1.3 *

* Differences are statistically significant at a 0.05 significance level based upon t-tests for the means and F-tests for the standard deviations.

TABLE C-7. SHORT-TERM ANALYSIS OF LATERAL PLACEMENTS AT THE MIDPOINT OF THE CURVE: OUTSIDE LANE

	Mean (ft)			Standard Deviation (ft)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753	.5	1.4	.9 *	1.3	.8	-.5 *
FM 730	.2	1.3	1.1	1.7	.7	-1.0 *
FM 2280	.9	1.9	1.0 *	1.2	1.0	-.2
FM 219	.7	2.4	1.7 *	2.6	1.9	-.7
FM 933	.1	1.4	1.3 *	1.7	2.0	.3
SH 94	-.1	1.0	1.1 *	1.7	.7	-1.0 *
FM 120	2.1	2.4	.3	1.1	.6	-.5 *

* Differences are statistically significant at a 0.05 significance level based upon t-tests for the means and F-tests for the standard deviations.

TABLE C-8. SHORT-TERM ANALYSIS OF LATERAL PLACEMENTS AT THE MIDPOINT OF THE CURVE: INSIDE LANE

	Mean (ft)			Standard Deviation (ft)		
Site	Existing PMD	New RPM	Difference	Existing PMD	New RPM	Difference
FM 1753	.9	1.1	.2	1.5	1.5	.0
FM 730	1.1	1.6	.5 *	.8	1.2	.4
FM 2280	3.7	3.2	-.5	.9	1.1	.2
FM 219	4.2	4.1	-.1	1.3	1.2	-.1
FM 933	4.0	3.5	-.5	.9	1.4	.5
SH 94	2.5	2.7	.2	.8	1.0	.2
FM 120	3.8	3.8	.0	.9	.9	.0

* Differences are statistically significant at a 0.05 significance level based upon t-tests for the means and F-tests for the standard deviations.

TABLE C-9. SHORT-TERM ANALYSIS OF VEHICLE ENCROACHMENTS: OUTSIDE LANE (NUMBER OF VEHICLES)

	Existing PMDs			New RPMs		
Site	Encroached	Did Not Encroach	Total	Encroached	Did Not Encroach	Total
FM 1753*	17	35	52	1	32	33
FM 730*	4	4	8	1	23	24
FM 2280*	11	51	62	1	33	34
FM 219	8	20	28	3	28	31
FM 933*	18	29	47	8	48	56
SH 94	10	17	27	5	24	29
FM 120	0	39	39	0	31	31
TOTAL	68	195	263	19	219	238

* The differences between the two delineation treatments are statistically significant at a 0.05 significance level based upon chi-squared tests.

TABLE C-10. SHORT-TERM ANALYSIS OF VEHICLE ENCROACHMENTS: INSIDE LANE (NUMBER OF VEHICLES)

	Existing PMDs			New RPMs		
Site	Encroached	Did Not Encroach	Total	Encroached	Did Not Encroach	Total
FM 1753	6	22	28	3	10	13
FM 730	3	24	27	1	44	45
FM 2280	0	11	11	1	21	22
FM 219	0	39	39	0	27	27
FM 933	0	27	27	1	27	28
SH 94	0	37	37	1	32	33
FM 120	0	47	47	0	45	45
TOTAL	9	207	216	7	206	213

Note: No statistically significant differences between the two delineation treatments (at a 0.05 significance level) were identified at any of the sites based upon chi-squared tests.

TABLE C-11. LONG-TERM ANALYSIS OF SPEEDS AT THE MIDPOINT OF THE CURVE: OUTSIDE LANE (MPH)

a. FM 1753 Site	Existing PMD	11-Month-Old RPM	New RPM
Mean	48.3	48.8	51.7
Std. Dev.	5.4	6.0	6.5

b. FM 219 Site	Existing PMD	6-Week-Old RPM	New PMD	New RPM	11-Week-Old RPM
Mean	54.4	55.7	55.8	56.2	58.8
Std. Dev	7.8	6.4	5.1	8.0	7.8

c. FM 933 Site	New PMD	Existing PMD	New RPM	6-Week-Old RPM	10-Week-Old RPM
Mean	55.0	55.6	58.4	59.4	59.6
Std. Dev.	7.4	7.7	5.9	5.6	7.3

Note: Underlined treatments do not have significantly different means at a 0.05 significance level based upon single-factor ANOVA and pairwise (least-significant-difference) t-tests.

TABLE C-12. LONG-TERM ANALYSIS OF SPEEDS AT THE MIDPOINT OF THE CURVE: INSIDE LANE (MPH)

a. FM 1753 Site	11-Month-Old RPM	New RPM	Existing PMD
Mean	48.0	52.1	53.1
Std. Dev.	5.4	4.6	6.9

b. FM 219 Site	New PMD	New RPM	Existing PMD	11-Week-Old RPM	6-Week-Old RPM
Mean	52.9	53.2	53.4	53.5	56.1
Std. Dev	8.4	7.2	8.1	4.7	7.2

c. FM 933 Site	6-Week-Old RPM	10-Week-Old RPM	Existing PMD	New RPM	New PMD
Mean	53.5	54.1	54.4	54.5	57.5
Std. Dev.	4.9	5.9	7.7	6.6	7.5

Note: Underlined treatments do not have significantly different means at a 0.05 significance level based upon single-factor ANOVA and pairwise (least-significant-difference) t-tests.

TABLE C-13. LONG-TERM ANALYSIS OF SPEED CHANGES FROM THE BEGINNING TO THE MIDPOINT OF THE CURVE: OUTSIDE LANE (MPH)

a. FM 1753 Site	11-Month-Old RPM	New RPM	Existing PMD
Mean	-1.9	-.5	.0
Std. Dev.	1.5	2.0	2.1

b. FM 219 Site	Existing PMD	New PMD	New RPM	6-Week-Old RPM	11-Week-Old RPM
Mean	1.1	1.2	1.5	2.2	2.4
Std. Dev.	2.3	2.3	1.8	1.5	2.1

c. FM 933 Site	New RPM	10-Week-Old RPM	Existing PMD	New PMD	6-Week-Old RPM
Mean	1.2	1.6	1.7	2.0	2.1
Std. Dev.	2.1	2.2	2.2	1.9	2.5

Note: Underlined treatments do not have significantly different means at a 0.05 significance level based upon single-factor ANOVA and pairwise (least-significant-difference) t-tests.

TABLE C-14. LONG-TERM ANALYSIS OF SPEED CHANGES FROM THE BEGINNING TO THE MIDPOINT OF THE CURVE: INSIDE LANE (MPH)

a. FM 1753 Site	New RPM	11-Month-Old RPM	Existing PMD
Mean	-.6	-.4	-.4
Std. Dev.	2.6	2.8	2.6

b. FM 219 Site	6-Week-Old RPM	Existing PMD	New PMD	New RPM	11-Week-Old RPM
Mean	-1.8	-1.6	-1.5	-1.2	-1.1
Std. Dev.	2.1	2.2	2.2	1.9	1.9

c. FM 933 Site	10-Week-Old RPM	New RPM	6-Week-Old RPM	Existing PMD	New PMD
Mean	-1.5	-1.1	-1.0	-.8	-.7
Std. Dev.	1.5	1.5	1.6	1.3	1.4

Note: Underlined treatments do not have significantly different means at a 0.05 significance level based upon single-factor ANOVA and pairwise (least-significant-difference) t-tests.

TABLE C-15. LONG-TERM ANALYSIS OF LATERAL PLACEMENT AT THE MIDPOINT OF THE CURVE: OUTSIDE LANE (FT)

a. FM 1753 Site	Existing PMD	11-Month-Old RPM	New RPM
Mean	.5	1.1	1.4
Std. Dev.	1.3	.7	.8

b. FM 219 Site	Existing PMD	New PMD	6-Week-Old RPM	New RPM	11-Week-Old RPM
Mean	.7	.9	2.4	2.4	2.8
Std. Dev.	2.6	2.1	2.6	1.9	1.2

c. FM 933 Site	Existing PMD	New PMD	New RPM	10-Week-Old RPM	6-Week-Old RPM
Mean	.1	.5	1.4	1.7	2.0
Std. Dev.	1.7	1.2	2.0	1.1	1.3

Note: Underlined treatments do not have significantly different means at a 0.05 significance level based upon single-factor ANOVA and pairwise (least-significant-difference) t-tests.

TABLE C-16. LONG-TERM ANALYSIS OF LATERAL PLACEMENT AT THE MIDPOINT OF THE CURVE: INSIDE LANE (FT)

a. FM 1753 Site	11-Month-Old RPM	Existing PMD	New RPM
Mean	.4	.9	1.1
Std. Dev.	1.4	1.5	1.5

b. FM 219 Site	6-Week-Old RPM	11-Week-Old RPM	New RPM	Existing PMD	New PMD
Mean	3.6	3.9	4.1	4.2	4.3
Std. Dev.	1.5	1.0	1.2	1.3	1.1

c. FM 933 Site	10-Week-Old RPM	New RPM	6-Week-Old RPM	New PMD	Existing PMD
Mean	3.4	3.5	3.6	3.8	4.0
Std. Dev.	1.1	1.4	1.3	.8	.9

Note: Underlined treatments do not have significantly different means at a 0.05 significance level based upon single-factor ANOVA and pairwise (least-significant-difference) t-tests.

TABLE C-17. LONG-TERM ANALYSIS OF VEHICLE ENCROACHMENTS: OUTSIDE LANE

a. FM 1753 Site	Existing PMD	New RPM	11-Month-Old RPM
Encroached	17	1	2
Did Not Encroach	35	32	25
Total	52	33	27

b. FM 219 Site	Existing PMD	New PMD	New RPM	6-Week-Old RPM	11-Week-Old RPM
Encroached	8	8	3	1	0
Did Not Encroach	20	20	28	27	35
Total	28	28	31	28	35

c. FM 933 Site	Existing PMD	New PMD	New RPM	6-Week-Old RPM	10-Week-Old RPM
Encroached	18	16	8	2	4
Did Not Encroach	29	34	48	44	31
Total	47	50	56	46	35

Note: The results of the chi-squared test indicated that there were differences among the treatments at a 0.05 significance level at all three sites.

TABLE C-18. LONG-TERM ANALYSIS OF VEHICLE ENCROACHMENTS: INSIDE LANE

a. FM 1753 Site	Existing PMD	New RPM	11-Month-Old RPM
Encroached	6	3	4
Did Not Encroach	22	10	8
Total	28	13	12

b. FM 219 Site	Existing PMD	New PMD	New RPM	6-Week-Old RPM	11-Week-Old RPM
Encroached	0	0	0	1	0
Did Not Encroach	39	28	27	26	30
Total	39	28	27	27	30

c. FM 933 Site	Existing PMD	New PMD	New RPM	6-Week-Old RPM	10-Week-Old RPM
Encroached	0	0	1	0	0
Did Not Encroach	27	27	27	28	24
Total	27	27	28	28	24

Note: The results of the chi-squared test indicated that there were differences among the treatments at a 0.05 significance level at all three sites.

APPENDIX D.

DISTRICT RESPONSE TO TTI SURVEY

D.1. INTRODUCTION

Appendix D documents the responses to a telephone survey conducted as part of Study 1145. Districts 1, 2, 7, 9, 10, 15, 17, 18, and 19 provided information regarding current costs of RPMs and PMDs. It proved very difficult to quantify the total costs of using RPMs and PMDs with current maintenance record-keeping practices. Labor, equipment, and overhead costs are particularly difficult to estimate for the installation of delineation devices. Districts were asked to provide estimates for the installation of RPMS and PMDs on isolated curves only. However, Districts were able to provide costs based upon their experiences with installing delineation treatments for an entire length of roadway. Costs are documented for installing these devices by either contractor or state personnel. Contractor costs are considered more reliable because of the difficulties in assigning all relevant costs to the installation of delineation devices by state forces.

The SDHPT purchases delineators and posts to be stored in regional warehouses for use by individual districts. Costs of these materials only in fiscal year 1989 are provided in Table D-1.

TABLE D-1. FISCAL YEAR 1989 COSTS OF POSTS AND DELINEATORS

ITEM	AVE. PRICE	QUANTITY
Post, Galvanized, 5 1/2 foot, 1.12 lb./ft.	$2.69	47,285
Post, Galvanized, 6 foot, 1.12 lb./ft.	$3.08	73,100
Post, Plastic, 5 1/2 foot, flexible	$4.91	26,300
Post, Plastic, 6 foot, flexible	$4.62	20,229
4"X4" Hi-Intensity Delineators, White	$0.72	123,074
4"X4" Hi-Intensity Delineators, Amber	$0.73	170,784
3-inch Centermount Plastic, White	$0.25	62,432
3-inch Centermount Plastic, Amber	$0.26	92,366

D.2. DISTRICT DELINEATION COSTS

D.2.1. District 1 Delineation Costs

District 1 is now replacing RPMs after 1.5 to 2 years in service as a general rule on moderate to high volume roadways. Contractors are hired to install devices on curves that have a relatively high degree of curvature and/or poor sight distance. Flexible delineator posts (plastic or fiberglass) are being used near narrow bridges or other confined areas because they get hit so often. Provision must be made for the movement of large farm equipment which sometimes hits the posts. During the past two years, District 1 has been replacing PMDs with RPMs, especially in Grayson County, except in locations where a lateral clearance problem exists. The following cost estimates were provided by District 1 personnel for the installation of RPMs and PMDs by state forces:

Cost to install RPMs

1.	RPM	$0.91
2.	Adhesive per unit	$0.04
3.	Labor per unit	$0.51
4.	Equipment per unit	$0.06
	Unit cost of installed RPMs (state forces)	$1.52

Cost to install PMDs

1.	Metal Post	$ 2.81
2.	Labor per unit	$ 4.81
3.	Equipment (30 miles @ $0.43/mi.)	$12.90
	Unit cost of installed PMDs (state forces)	$20.52

District 1 personnel estimated that hand trimming on mowing contracts increased the cost of mowing by approximately $1.00 per acre. However, the removal of PMDs will have little effect on herbicide costs in the District. Their herbicide program is mainly Bermuda Release covering an area approximately 30 ft wide adjacent to the roadway.

D.2.2. District 2 Delineation Costs

RPMs have not been widely used on Farm-to-Market (FM) roads in District 2. Only a few of their FM roads have had traffic problems, and thus few have been treated with RPMs. District 2 typically replaces RPMs only when doing a seal coat. Replacement costs per unit are lower if an entire road is being treated as opposed to just the curves.

The cost estimates provided by District 2 assume that a four-man crew installs RPMs all day long, and that they can install 1,000 RPMs in an 8-hour day. The District representative contacted admitted this may be a little high. The standard installation crew in District 2 consisted of one person for each of the following tasks: mark the roadway, drive the pickup, operate the machine, and maintain traffic control from rear. District 2 estimated that the unit cost of installing RPMs by state forces would be as follows:

1.	RPM	$0.87
2.	Bitumen per unit	$0.06
3.	Labor per unit	$0.39
4.	Equipment per unit	$0.13
	Unit cost of installed RPMs (state forces)	$1.45

Information regarding a recent bid letting for the installation of RPMs is given below. The contract was for labor and equipment only; the District supplied the RPMs and bitumen. The low bid was $0.84 per RPM, which was much lower than anticipated. Other bids shown below are closer to the expected range.

Bid A:	$1.90 for Type II C-R
	$1.70 for 4" round
Bid B:	$2.37 for all types

The District 2 representative expected the low bid to be around $1.50 per RPM for installation only. Using this value and the other costs provided above, the estimated unit cost of installing RPMs by contractor are as follows:

1.	RPM	$0.87
2.	Bitumen per unit	$0.06
3.	Labor per unit	$1.50
4.	Equipment per unit	$0.13
	Unit cost of installed RPMs (contractor)	$2.56

D.2.3. District 7 Delineation Costs

District 7 has not used contractors for installing RPMs or PMDs. Therefore, they provided costs only for installation by state forces. District 7 has removed practically all PMDs in response to a 1980 directive. Therefore, the only cost information available was for RPMs, and those costs were for an entire stretch of roadway as opposed to curves only. The most representative total cost, including labor, materials, and equipment is $35.10 per lane-mile, or $70.21 per total mile (two-lane). If this total per-mile cost is used directly for a curve plus approach length of 1,640 feet, the cost is $21.81.

D.2.4. District 9 Delineation Costs

District 9 provided a copy of "Average Low Bid Unit Prices" dated March 31, 1989. The costs of RPMs and PMDs were extracted from that list.

	Quantity	Average Bid
Type IIAA Reflective Raised Pavement Markers	139,677	$ 2.25
Delineators and Object Markers (D-DW)(A)	221	$ 4.09
Winged Channel Posts (1.12 LB) (7.0 FT)	3,697	13.52
Unit cost of installed PMD (contractor)		$17.61

D.2.5. District 10 Delineation Costs

In District 10, the cost of furnishing and installing RPMs is $2.47 per marker when done by contractor. District 10 uses hot bitumen as an adhesive. They conduct a sign and traffic marker inspection twice a year. On low-volume roads, they typically replace RPMs every two years. District 10 does not use PMDs on FM roads because so much maintenance (straightening after being hit) is required. They use them on higher volume roads, such as Interstates, but this would not provide a fair comparison. The district uses some flexible posts on low-volume roads, but only on a very limited basis.

D.2.6. District 15 Delineation Costs

A District 15 sign shop representative provided cost estimates for RPMs and PMDs. He estimated that the unit cost of installing RPMs by state forces was $1.38. Recent costs for installing RPMs by contracter were $2.40 per RPM. RPMs have a life on low volume (FM) roads of about 3 years.

In farming areas, delineator posts are a definite maintenance problem because they get hit more often. District 15 has used flexible posts, but after they are hit a couple of times they get loose and have a tendency to lean. For cost comparisons, the maintenance required to straighten the posts is important.

Because part of this district is hilly, special problems can occur. In the hill country on a few "hairpin" curves, RPMs may not function as well as PMDs. One example cited involved a crest vertical curve that caused drivers to lose sight of the roadway alignment to a worse degree when PMDs were replaced with RPMs. The District carefully considered the implications and decided not to remove PMDs in those situations.

Information on installing PMDs by state forces was not available from District 15. However, the District provided a unit cost for contractor installation of PMDs of $18.72.

D.2.7. District 17 Delineation Costs

District 17 uses 6-ft posts for PMDs on rural two-lane roads. The posts are driven into the ground to a depth of 28 inches. Some of the PMDs now in use in District 17 have bidirectional delineators on the outside of the curve. Recently, they have begun placing PMDs on both sides of the roadway with delineators in one direction only. The range in costs for PMDs in District 17 is $13 to $15 installed. Average costs of posts and bi-directional reflectors installed are $10 and $5, respectively. The District is using some flexible posts, but no costs were provided.

District 17 personnel also gave information on costs of installing RPMs by contract. For a fairly large job (contract amount $100,000 or more) involving the installation of delineation treatments, they stated that the average unit cost of RPMs is about $2.25. For extremely large projects, installed RPMs may cost as little as $1.85 to $2.00 apiece. Larger quantities cause the unit price to be reduced.

The cost of mobilization is now authorized by law as an item in the bid. The typical amount budgeted for mobilization is 10 percent unless the job is unusually large. For contracts involving only pavement delineation, 10 percent is a good rule of thumb. Sometimes these smaller projects are combined with other residencies to make the overall job worth at least $100,000. For jobs of this size (around $100,000), the District allows 30 working days (they typically assume 15 working days per month) for completion. The time period is important in determining the total cost of traffic control because traffic control is usually bid on a per month basis. In District 17, traffic control for this size job is typically $1,500 to $2,000 per month.

D.2.8. District 18 Delineation Costs

District 18 provided information prepared by two residencies on the costs of installing PMDs by state forces. This information is presented below.

Residency "A":

1.	Post per unit	$2.49
2.	Delineator per unit	0.70
3.	Labor per unit	10.00
	Unit cost of installed PMDs (state forces)	$13.19

Residency "B":

1.	Material per unit	$3.27
2.	Labor per unit	5.18
3.	Equipment per unit	4.25
	Unit cost of installed PMDs (state forces)	$12.70

District 18 also provided information on several "routine maintenance contracts" for the replacement of missing or damaged RPMs. The costs are is shown in Table D-2. Variables included the job size and distance required for the contractor to travel between and within job sites. The unit bid price includes such items as equipment costs, labor, traffic control, travel, insurance, and bonding. It does not include any materials cost. No additional mobilization charges are assessed in these contracts.

The cost of installing RPMs on curves only on two-lane roadways is expected to be similar to the costs in Table D-2. Due to the larger amount of travel required in comparison to that required for treating the entire roadway, the costs would be expected to increase. To make a fair comparison with PMDs, however, a similar replacement cost for PMDs would also be needed. No estimate of this type is available. Districts typically replace missing or damaged PMDs by state forces. These costs are not as easily substantiated as when contractors do the work. However, District 18 costs estimated by two individual residencies were $13.19 and $12.70. This is considerably less than the $18 to $20 range typically bid by contractors.

TABLE D-2. DISTRICT 18 UNIT BID PRICES FOR INSTALLING RPMs

Contract No.	Type of Marker	Quantity	Unit Bid Price
1	IA, IIAA, IICR	13,650	$1.30
2	IA, IIAA, IC, IICR	12,320	$1.95
3	IICR	20,710	$2.15
4	IA, IIAA, IICR	27,155	$1.90
5	IA, IIAA, IC, IICR	11,130	$2.00
6	IA, IIA, IICR	28,300	$1.69
	Weighted Average Unit Cost		$1.84

When the cost of materials is added to the RPM installation costs in Table D-2, a more complete cost evaluation can be conducted. However, the overhead cost of moving, handling, and storage of the materials remains unknown. Total cost of the installation, excluding material overhead, is:

1.	RPM	$0.91
2.	Bitumen per unit	$0.04
3.	Weighted Average Unit Installation Cost	$1.84
	Unit cost of installed RPMs (contractor)	$2.79

D.2.9. District 19 Delineation Costs

District 19 provided the following "typical costs" of PMDs based on past experience:

1.	Delineators	$0.32 to $0.36
2.	Bracket (if 2)	$0.18 to $0.20
3.	Post (1.12 lb./ft)	$5.00
	Unit cost of PMDs (materials only)	$5.50 to $5.56

The District 19 construction office provided information on a recent succssful bid for installing RPMs by contract. The total cost of materials and installation, including mobilization and traffic control, was $2.22 per RPM.