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16. Abstract

The delineation of horizontal curves on two-lane rural roads is an important component of safety improvements to reduce run-off-road and head-on crashes. This project assessed four types of vertical delineation in conjunction with edgeline markings through a closed-course nighttime driving test, a survey of drivers using video clips of curves, and a field test of vehicle performance at four sites in rural Texas. The treatments evaluated were standard post-mounted delineators with a single reflector at top and one with retroreflective material the full length of the post, standard chevrons, and chevrons with yellow retroreflective material applied the full length of the post. The results show that vertical delineation of any type improves vehicle lane position at the entry and mid-point of horizontal curves. Fully reflective post-mounted delineators improved lane position and reduced encroachment more than standard posts. The two styles of chevrons performed equally well and both showed significant speed reduction when compared to pavement markings alone.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Susan T. Chrysler.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1: LITERATURE REVIEW

Roadway delineation is a critical roadway characteristic that assists drivers with the control and guidance of their vehicles (*1, 2*). In fact, the proper installation of delineation treatments can lead to a reduction in driver error and benefit traffic flow and safety (*3*). Poor and/or inadequate delineation, on the other hand, may contribute to single vehicle run-off-road crashes. There were 12,527 serious (KAB) crashes of this type on two-lane bidirectional roadways in Texas from 1999 to 2001. A clear understanding of the potential vehicle performance and crash impacts of delineation (along tangents and curves) is one of the key factors in their effective selection and implementation. Several transportation agencies use the *Roadway Delineation Practices Handbook* to assist them with this activity (*1*).

This chapter summarizes literature that focuses on the interaction between roadway delineation, the driver, and the driving task. First, the concept of positive guidance is discussed along with relevant driver needs and behaviors. Then, the results of studies that have evaluated the surrogate safety or operational (e.g., vehicle speed and lateral placement) impacts and direct crash results of delineation treatment(s) are summarized. The treatments evaluated by previous research and contained in this summary include:

- chevrons,
- post-mounted delineators (PMDs),
- raised pavement markers (RPMs), and
- pavement markings: centerlines and edgelines.

Following the summary of research, a short description of delineation cost analysis, standards, and sections of the Texas Manual on Uniform Traffic Control Devices (TMUTCD) are provided.

DELINEATION AND THE DRIVING TASK

The interaction between the driver and roadway delineation can be complex. The following paragraphs summarize those studies that have focused on how drivers use delineation and driver behavior along curves. The concept of positive guidance is discussed and the need for adequate delineation preview distances noted. In addition, the vehicle path selection of drivers along horizontal curves (i.e., corner-flattening) is described along with the need for appropriate delineation treatment contrast and retroreflectivity. Research studies that have considered the driver visualization impacts of curve delineation characteristics are also summarized.

Positive Guidance

The concept of positive guidance was developed by Alexander and Lunenfeld to provide a framework for understanding the driving task (*3*). One of its main tenets is that providing drivers with an obvious path through the use of delineation makes the driving task easier. The driving task includes vehicle control, guidance, and navigation. Control issues consist of interactions between the driver and his/her vehicle (e.g., reading gauges, manipulating the steering wheel, pedals, and gear shift). Guidance tasks consist of maintaining the proper speed and lane placement, and the navigation task includes all aspects of planning a trip (e.g., pre-trip route mapping, reading and interpreting guide signs, and making route changes based on traffic conditions). The theory of positive guidance further states that the three levels of the driving task are related in a hierarchy, with the control task in the prime position, and the navigation task in the lowest position of importance. When a driver is presented with too much information in the roadway environment, he/she will focus on the more important tasks of control and guidance. These are the portions of the driving task that rely on good delineation.

Delineation and Driver Eye Movements

An important study in the 1970s used eye tracking equipment to measure exactly where drivers directed their vision along the tangents and curves of a two-lane rural roadway (*4*). These researchers found that eye movements in curves were frequent and concentrated on roadside cues (e.g., pavement markings and geometry), and the eye scanning process began on the approach to a curve. Along tangent sections drivers fixed their gaze toward the horizon. Both of these behaviors have implications related to the implementation of roadway delineation treatments. For example, it was recommended that sight distance to a curve be maximized and that advisory speed signs, as is currently done, should be before the beginning of the curve. These results also support the idea that there is a need for combinations of "near" and "far" delineation treatments (*2*). A "near" delineation treatment is a longitudinal pavement marking, and chevrons are an example of a "far" delineation treatment.

The visual search patterns and speed choice of drivers through curves are also not symmetrical (*4, 5, 6*). Drivers look more to the right on right-hand curves than they do to the left on left-hand curves (*4*). In addition, a difference between vehicle speeds has also been noted by curve direction. Participants in a closed-course test drove faster on left-hand curves than right-hand curves. It was hypothesized that the drivers might be able to evaluate the curvature of left-hand curves better because they look to the inside of the curve for cues and have an unobstructed view on the curves (*5*). An Australian study supported this finding by showing subjects 35 mm slides of curve approaches and asking them to estimate the curve exit angle (*6*). The drivers studied tended to overestimate the exit angle when shown curves with a smaller (i.e., 8 and 15 degrees) curvature. They were also able to estimate the exit direction of right-hand curves more accurately than left-hand curves (note that Australia is a left-hand drive country).

Driver Vehicle Placement on Curves

A number of studies have also shown that drivers also do not drive a circular horizontal curve along an arc directly in the center of the travel lane (*5, 7*). A large traffic engineering study observed drivers at 46 sites in two states (Georgia and New Mexico) and measured speed and lane placement (*7*). They found that drivers use a curve-flattening strategy. In other words, the driver takes a path that does not follow the radius of the curve. On left-hand curves, the researchers found that vehicles were closer to the centerline of the road at the midpoint of the curve and on right-hand curves they were closer to the edgeline. However, Felipe and Navine found that for curves with larger radii drivers generally did follow the center of the lane in both directions (*5*). Along smaller radii curves the drivers "cut" the curves in both directions. In order to minimize their speed change, the drivers "flattened out the bends" by driving on the shoulder or in the other travel lane.

Visual Needs: Contrast and Retroreflectivity

The visibility of a delineation treatment relates to contrast and retroreflectivity. Contrast is a measurement of the difference between the treatment and its background (e.g., pavement marking and pavement surface). Allen et al. have concluded that a contrast of two was needed for proper visibility of a pavement marking (*8, 9, 10*). This study is described below. Retroreflectivity of pavement markings/markers and roadway is also important. It is the process by which light reflects or returns to the driver from delineation devices. However, a recent study that focused on safety and pavement marking retroreflectivity concluded that additional expenditure of funds to improve the retroreflectivity of pavement markings beyond normal existing maintenance levels was not likely to be cost effective (*11*).

In 1979, Hall summarized a series of research projects that generally focused on the delineation needs and curve negotiation of drivers at night (*10*). One of the studies described by Hall was a contrast visualization analysis completed by Allen et al. for the Federal Highway Administration in 1977 (*8, 9, 10*). First, Allen et al. created a theory of delineation visibility and then conducted a simulation study that attempted to relate driver performance measures to different delineation treatments. The simulations included variations in roadway geometrics (e.g., straight, winding, and occasional curve), visual ranges, and delineation pavement marking (e.g., stripe patterns). Performance measures related to vehicle control (e.g., speed) and driver behavior (e.g., errors) were collected and subjective driver responses tabulated. Not surprisingly, the simulation results showed that as the visual range of drivers decreased, for instance due to fog, the need for good delineation configurations increased. For example, the use of solid edgelines, longer stripe dashes, and shorter gap-stripe cycles can reduce the impact of decreased visibility (e.g., longer stripes can show some roadway curvature). Overall, based on the simulation and field test results, it was concluded that the probability of a vehicle leaving a lane increased rapidly as the delineation to pavement contrast was reduced below 2:1.

Driver Visualization of Curve Delineation Characteristics

In 1986, Zwahlen considered the impact of height, spacing, and lateral offset of flexible PMDs on the detection or recognition of curves by drivers (*12*). Zwahlen evaluated these PMD characteristics using a computer analysis based on driver visibility needs. He then supported his recommendations with a field test evaluation . Zwahlen concluded that height and lateral offset had a negligible impact on delineator detection distance. He recommended a PMD spacing of 275 feet for encapsulated sheeting materials on tangents and 350 to 400 foot spacing for prismatic sheeting . For curvilinear roadway segments Zwahlen provided a series of recommended spacing equations (based on radius) for four-lane divided and two-lane undivided roadways . Another study in 1986, however, did conclude that increasing the height of PMDs around a curve increased the appearance of curve "sharpness" and speed reduction (*13*).

In 1995, Zwahlen and Park focused on the number of chevrons a driver needed to appropriately judge the "sharpness" of a curve (*14*). Ten young drivers were shown slides of a curve with 12 equally spaced chevrons (for two seconds). They were then asked to estimate the "sharpness" of test curves that had one of five radii with two, three, four, or eight equally spaced chevrons (all within an 11 degree viewing range). Zwahlen and Park concluded that the number of correct responses increased until greater than four chevrons were installed along the curve. In other words, there was almost no difference in the correct response level for the four and eight chevron installations. The researchers also found that it was impractical to have more than four chevrons in an 11 degree viewing field. It was concluded that four chevrons within an 11 degree viewing area provided "…adequate curve radius estimation cues…" for unfamiliar drivers.

In 2004, Carlson et al. investigated the spacing practices for chevrons and PMDs (*15*). The chevron field study portion of this project considered vehicle performance impacts and is described in the next section of this document. The PMD portion of the project, on the other hand, was designed to evaluate, among several characteristics, driver opinion of different PMD spacing on the approach to horizontal curves. Twenty-four drivers (ranging in age from 22 to 72 years old) were asked to drive along a closed course where the curve approach spacing of the PMDs, along with the number of reflectors they included, were individually varied. Before each subject entered a curve they were also asked to rate its apparent severity on a five-point scale. They expressed this opinion by choosing one of five radii pictured on a sheet of paper. Overall, it was found that the subjects perceived slightly less curvature with the variable rather than the constant PMD spacing. In addition, curves marked with one three-inch square reflector were perceived to be less sharp than those posts with a 3 x 6 inch rectangular piece of retroreflective material. Not surprisingly, the amount of detection possible was greater at longer distances for the younger drivers.

DELINEATION AND VEHICLE PERFORMANCE MEASURES

A number of studies have measured the impacts of roadway delineation treatments by collecting and comparing the magnitude and variability of vehicle speed, lateral position, speed reduction, and/or centerline and shoulder encroachments. These vehicle performance measures are more easily and quickly collected than crash data, and are considered surrogates for the potential safety improvement impacts of delineation treatments (*2*, *16*, *17*, *18*, *19*). Studies that have attempted to quantify the relationship between vehicle performance measures and crash data, or have tried to evaluate the direct crash impacts of delineation, are described later in this document.

Many of the delineation studies that have focused on vehicle performance measures have attempted to compare the impacts of one or more treatments (e.g., chevrons, PMDs, RPMs, and/or pavement markings). The following discussion of these studies is organized by the delineation treatments they considered and the general focus of their conclusions. Almost all of these studies were completed between 1970 and 1990, and it should be noted that pavement marking and signing installation practices and materials have changed.

Chevrons and Post-Mounted Delineators

The most common vertical delineation devices used in the field are chevron alignment signs (W1-8) and post-mounted delineators (PMD). The MUTCD defines the chevron alignment sign as a warning sign. It states that the chevron alignment signs are intended for additional emphasis and guidance when the horizontal alignment changed. Delineators, on the other hand, are strictly considered a guidance device rather than a warning device.

A study in Australia also found that vehicles on a test track followed a "better" path around curves when chevrons (in addition to edgelines) rather than PMDs were used (*20*). At the same time, higher mean vehicle speeds were found when the chevrons were used (either with or without edgelines) than with the other delineation treatments (e.g., PMDs with or without edgelines). However, the nighttime mean speed was still below that possible in the daytime and the speed increase was considered "adaptive" (i.e., due to increased driver confidence). They also found that mean vehicle speed was the lowest for the treatment that only included a centerline and no overall difference was found between treatments that had PMDs and those that only included edgelines. It should be noted that chevrons were not in use on rural roadways in Australia when this study was conducted.

Jennings and Demetsky studied three different roadside delineation designs: chevrons, PMDs, and a special road edge delineator (a 48 x 6 inch black/white object marker sign) (*21*). In this study the chevrons were installed at a spacing twice that of the PMD spacing, and the five sites were grouped by length, degree of curve, and degree of vertical grade. In addition, speed and lateral placement data were collected in the short-term and several weeks after installations. Overall, the data showed that drivers move away from the edgeline with the addition of roadside delineation. There was also an increase in the daytime speed measured, but this increase was smaller with the chevron installation. The variation in speed, however, was also higher with chevrons than with the PMDs considered. However, at the sites that had a degree of curvature greater than 7 degrees, the chevrons generally produced low encroachment levels, a path closer to the center of the lane, and smaller lateral placement variability. At the three sites with a degree of curvature less than 7 degrees, the standard and special PMDs generally produced more favorable speed, lateral placement, and encroachment results.

In 1986, Agent and Creasey also considered chevrons and PMDs as part of a study that evaluated a range of traffic control measures for horizontal curve delineation (*13*). First, a laboratory evaluation was completed. Forty subjects were shown photographs of a curve with PMDs and chevrons that varied in height, lateral offset, and spacing. Curves were perceived as sharper when the delineators were equally spaced and offset, but with increasing heights. Chevron and PMD installations with constant and increasing heights were then considered in this field. Speed, speed reduction, and encroachment impacts of these treatments were analyzed at two locations. The data showed that average vehicle speed at the point of curvature decreased by 4 miles per hour (mph) or less, and only a few of the chevron installations produced what was determined to be a significant decrease. In most cases the average speed reduction into the curve increased after the installation of PMDs and chevrons, and the percentage of encroachments (almost all over the centerline) experienced a large decrease. The severity (or distance) of the encroachments also decreased. Agent and Creasey concluded that chevron signs have more speed impacts than PMDs, but that pavement delineation (e.g., RPMs) had more impact than either chevrons or PMDs.

Recently, TxDOT changed its chevron standard to a fluorescent yellow microprismatic retroreflective sheeting to provide maximum visibility during the day and night (*15*). In response the Texas Transportation Institute was asked to examine PMD and chevron spacing along horizontal curves. The Texas Transportation Institute study included a chevron field study and a closed-course study of PMDs. The chevron field test was designed to evaluate the vehicle speed impacts of drivers viewing two, three, or four chevrons along horizontal curves. The results of this study showed that the chevron installations that included more than two of these devices produced a small reduction in mean vehicle speed (i.e., 2.6 to 2.8 mph). This reduction in speed appeared to increase at night and as the radius of the curve decreased. Carlson et al. concluded that the data from at least two of the three curves considered did provide "…convincing evidence that increasing the number of chevrons in view on a curve will result in slower speeds around the curve ." The PMD portion of this project had drivers subjectively evaluate the “sharpness” of a curve based on different treatments. Its results were previously described in the “Driver Visualization of Curve Delineation Characteristics” section of this literature review. Carlson et al. recommended a simplified approach to PMD and chevron spacing.

Post-Mounted Delineators and Raised Pavement Markers

As part of a TxDOT project in the late 1980s, Krammes et al. evaluated the operational impacts and cost effectiveness of RPMs as an alternative to PMDs at horizontal curves (*18, 22*). The operational impacts of switching from PMDs to RPMs were compared by collecting nighttime vehicle speed and lateral placement at seven locations (*18*). The standard deviation of the vehicle lateral placement in the curve was also calculated and vehicle encroachments measured. These data were collected with the PMDs in place, and then re-collected when the RPMs were new (i.e., the evening of placement) and weathered (i.e., at 6 weeks, 10 to 11 weeks, and 11 months). Immediately after the placement of the RPMs, the mean vehicle speeds at the midpoint of the curve were 1 to 3 mph greater than what they had been with the existing PMDs. In addition, the mean lateral placement of the vehicles was consistently 1 to 2 feet further away from the centerline. However, the variability of the lateral placement was smaller with the RPMs and few drivers crossed the centerline. Krammes et al. concluded that RPMs provide better path delineation and this may allow drivers to travel faster. An evaluation of the intermediate term data (i.e., at 6 and 10 to 11 weeks) showed very few changes in vehicle speed and lateral placement. The long-term (i.e., 11 months) lateral placement and encroachment data, collected at only one location and when the RPMs had lost most of their reflectivity, also was not significantly different than when the new RPMs were installed. These measures, along with mean vehicle speed, were also similar to those measured with the PMD installation. A small but statistically significant increase in curve approach vehicle deceleration in the long term may mean the RPMs are providing less advance notice.

Chevrons, Post-Mounted Delineators, and Raised Pavement Markers

In 1987, Zador et al. reported mixed and/or inconclusive results from the speed and lateral placement they collected after the addition of PMDs, chevrons, and RPMs (*7*). These data were collected 100 feet before and after 51 rural horizontal curves in Georgia (n = 46) and New Mexico (n = 5). For some treatment cases, speed increases were measured (the addition of PMDs and RPMs increased speed by 2 to 2.5 feet per second and 1 foot per second, respectively) and in other cases both increases and decreases were measured for the same delineation treatments in different states. Additional delineation treatments increased nighttime speeds by 1 to 3 feet per second, but chevron additions had little impact on this measure in Georgia. Vehicle speed and lateral placement variability were reduced by a small amount when chevrons and RPMs were used. Overall, there was no significant "…evidence to support a preferential choice…" in delineation treatment. In 1993, Zwahlen also found vehicle speed increases and decreases in curve speeds with the addition of chevrons (*12*). The overall average speed reduction he calculated was not statistically significant. Zwahlen concluded that the visual guidance of roadside delineation did not appear to impact driver speed choice. Another reason for these results may be the lack of control in the experimental design for the large impact roadway curve geometry has on vehicle speed and lateral placement choices.

Post-Mounted Delineators, Raised Pavement Markers, and Pavement Markings

In 1972, the National Cooperative Highway Research Program (NCHRP) report *Roadway Delineation Systems* was published (*2, 23*). As part of this project, David attempted to evaluate the impacts of several pavement marking, PMD, and RPM delineation treatments (*23*). Overall, eleven delineation treatment combinations were considered along two two-lane rural roadway horizontal curves. In the first phase, nighttime vehicle speed and lateral placement data were collected after the addition of six PMD treatment variations (one or both sides of roadway, and amber and/or white reflectors). These data were compared to similar measures when only a weathered centerline existed, and none of PMD variations produced a significant impact on either vehicle speed or lateral placement . In the second phase, the impacts of adding RPMs (alone and in combination with PMDs on the outside of the curve), a freshly painted centerline, and a new centerline with PMDs were analyzed. The variance in the vehicle performance data were reduced when the centerline was repainted. The data improved again with the addition of RPMs. In addition, the use of RPMs with PMDs resulted in a smaller lateral placement variance than the application of just a new centerline and PMDs. Based on these project results, David would not recommend one type of delineation treatment design, but he did recommend that RPMs be used at "hazardous" curve locations.

In 1977, a comprehensive study by Stimpson included a large field evaluation of conventional and modified delineation systems (*16, 24*). The systems considered in the study included different combinations and dimensions of painted centerlines, edgelines, and supplemental devices such as RPMs and PMDs. Overall, three or four combinations of these delineation treatments were evaluated at nine study sites. Five of these sites were tangent segments, two were winding roadway segments, and two were isolated curves. In general, no change was found in vehicle placement along straight and winding roadway sections when the centerline or edgelines were reduced from 4 to 2 inches. The existence of PMDs also did not appear to have an impact on vehicle lateral placement when installed along a straight roadway. Along the horizontal curves, on the other hand, the two-way RPMs reduced centerline encroachments (from the outside lane) and the variance in vehicle lateral placement. The application of PMDs only reduced the lateral placement variance along the outside lane. The addition of RPMs and/or PMDs also resulted in lower midcurve vehicle speeds.

Overall, Stimpson et al. recommended that 4-inch centerlines be used with a 10:30 stripe to gap ratio along with 4-inch edgelines (*16, 24*). However, a narrower width of pavement marking and/or smaller stripe to gap ratio could also be applied to reduce costs. RPMs were also recommended along the centerline of general roadway segments if severe visibility reductions occurred frequently. In addition, if RPMs were desirable on a tangent, but could not be implemented due to snowplows, the researchers recommended that PMDs should be installed at a spacing of 400 to 528 feet. RPMs, rather than PMDs, were recommended as the preferred curve delineation treatment.

Chevrons, Post-Mounted Delineators, Raised Pavement Markers, and Pavement Marking

In 1988, Freedman et al. investigated the interaction and impact of the roadway environment on the need for several types of delineation (*25*). Both a simulation and field study were completed as part of this project. First, the Federal Highway Administration (FHWA) Highway Simulator (HYSIM) was used to collect several vehicle performance measures at five roadway locations (i.e., tangents, horizontal curves, turn lanes, lane drops, and bifurcations) that had various delineation treatments. The treatments considered were combinations of centerlines, edgelines, RPMs, chevrons, and PMDs. Overall, 154 scenarios of roadway geometry headlight glare, visual complexity, pavement condition, and treatment type were simulated with a total of 62 subjects. Data were collected about vehicle speed, acceleration, lateral placement, and steering wheel position. The driver ratings of their confidence and feeling of safety were also noted.

Significant differences in the simulation results were only found for the delineation treatments at horizontal curves, left-turn lanes, and bifurcations (*25*). The horizontal curve treatments that included PMDs and/or RPMs were associated with lower vehicle speeds, speed variance, and acceleration (when compared to pavement markings only). In addition, they produced more consistent lane tracking toward the centerline. Large steering wheel movements were less frequent for combinations of pavement marking and PMDs or RPMs. Driver ratings of confidence and safety were the highest for RPMs in wet conditions, and the second highest driver ratings were combinations of pavement markings, RPMs, chevrons, and PMDs. Freedman et al. concluded that treatments combining pavement marking and PMDs or RPMs produced smoother vehicle paths and better lane tracking.

The simulation results were generally supported by the field tests completed as part of the Freedman et al. project (*25*). However, the field test included the comparison of only two delineation treatments at one curve. The baseline condition at this curve consisted of 4-inch preformed polymer stripes along both the centerline and edgeline. The improved treatment included the application of a rubber-base paint over the existing polymer and the addition of centerline RPMs (every 40 feet) and PMDs on the outside of the curve. Two groups of chevron signs were also installed approximately 415 to 455 feet and 1,110 to 1,150 feet from the start of the curve. Vehicle performance data were collected on the approach to and within the curve for 20 nights (12 nights of data with the baseline conditions and then, after one week, eight nights with the upgraded delineation). They found that the vehicle speeds after the upgrade were slightly higher 400 feet before the curve and slightly lower 1,000 feet into the curve (but both were only by about 1 foot per second). The variability in vehicle speed, however, was consistently smaller and decreased in magnitude as the vehicle progressed into the curve. Centerline encroachments and lateral placement decreased after the delineation upgrade. Vehicles were located about 1.5 feet further from centerline after the upgrade.

In the mid-1990s, a comprehensive FHWA-sponsored delineation study was completed by the Pennsylvania Transportation Institute (*26*). This project also had simulation and field study stages. Initially, a simulation study was completed to examine the driver detection distances of 25 horizontal curve delineation combinations. The combinations considered include various centerline pavement markings and/or RPMs; edgeline pavement marking materials, widths, and/or RPMs (with different brightness levels); and chevrons, PMDs or a unique "T-post" delineator. During the simulation study 45 younger and older drivers indicated their detection of the horizontal curve delineation and direction ("…with 100 percent confidence…") by depressing the brake pedal. They were also asked to provide a subjective rating of how well they thought each treatment combination conveyed the curve direction (in comparison to the centerline-only baseline treatment). The six longest recognition distances were for delineation combinations with roadside treatments (e.g., chevrons, PMDs, "T-post"), and the eight combinations with the shortest recognition distances did not include any roadside delineation. The subjective rating results showed little correlation with the detection data, and the researchers hypothesized that this might be the result of the older participants' "…deficiencies in short term memory."

The field study portion of the Pennsylvania Transportation Institute project involved a closed-course evaluation of twelve delineation treatments (*26*). These treatments were selected based on the results of the simulation study and their ease of implementation and cost effectiveness . The delineation considered included combinations of centerlines, edgelines, RPMs, chevrons, different types PMDs, and a "T-post" PMD. In some cases the type of sheeting on the posts was also changed from one delineation combination to another. For each combination the researchers collected recognition distance data, visual occlusion time, and a subjective ranking from 66 drivers (half were older than 45 years of age and half were not). Recognition distances were collected by approaching the curve at 100-foot increments and asking the driver when they were sure the curve turned left or right (guessing was not allowed). The participants were also familiarized with the visual occlusion device and asked to approach the curves with the cruise control engaged at 30 mph (about 1,000 feet from the curve). Approximately 420 feet before the curve their vision was completely blocked and they were asked to open the shield when they felt uncomfortable driving any further. The hypothesis was that effective delineation combinations would allow drivers to advance a longer distance with their vision occluded.

The results of the field study confirmed those produced by the simulation (*26*). Younger drivers recognized curve direction at significantly longer distances than older drivers. In addition, the shortest average recognition distance was produced by the centerline-only treatment and the longest average was produced by the delineation combination including a centerline, edgeline, and "T-post" roadside device. The delineation combinations with the six longest recognition distances, however, were statistically similar. Unfortunately, the visual occlusion results showed only small differences between the delineation treatments and no differences between age groups. The researchers' opinion was that this test measure was not as good an indication of delineation impact as the recognition distance. The results were altered by the various risk-taking tendencies of individual drivers and also by the fact that they knew about the secondary brake. The top three delineation treatments recommended by the researchers all included a centerline and a "T-post" roadside device (two also had high-intensity sheeting on the "T-post"). Only the top-ranked treatment included an edgeline, and the delineation combination ranked third included centerline RPMs. The treatment ranked fourth only included a centerline and chevrons with high-intensity sheeting. The recognition distance for this treatment was not significantly different than the top-ranked delineation combination (i.e., centerline, edgeline, and "T-posts" with engineering-grade sheeting), but it was only about half the cost.

Raised Pavement Markers and Pavement Marking

As part of the efforts related to NCHRP 130 – *Roadway Delineation Systems*, Hultman and McGee analyzed the vehicle speed and lateral placement impacts of installing RPMs along one isolated horizontal curve (with a 289 feet radius and a length of 440 feet) (*2, 27*). The vehicle performance measures with the existing roadway delineation (weathered center and edgelines) were compared to the data collected with RPMs as a double yellow centerline, centerline RPMs with freshly painted edgelines, and just freshly painted center and edgelines (*27*). Based on this comparison, Hultman and McGee concluded that vehicle speed was not "practically" different for any of the four treatments considered. However, there was a trend toward lower speeds when RPMs were used, and the lateral placement of vehicles improved as delineation increased (e.g., RPMs and fresh paint). The combination of RPMs and improved edgeline pavement markings was recommended by the researchers because it reduced vehicle lateral placement variability and resulted in vehicles located closer to the center of the lane. Overall, the use of just centerline RPMs resulted in the longest average vehicle placement distance from the centerline.

Several other studies have also focused solely on the vehicle performance impacts of adding RPMs to curves and tangents (*28, 29, 30, 31*). A study by Khan, as described by Donnell et al., attempted to evaluate the vehicle speed and placement impacts of adding RPMs to the centerline and edgeline. The addition of RPMs along a two-lane rural roadway segment resulted in an increase in the calculated mean and 85th percentile night speeds of 1 to 3 mph. The addition of RPMs to a four-lane undivided roadway segment, however, produced a 1 to 2 mile per hour reduction in mean and 85th percentile speeds. Neither of these changes is practically significant. The vehicle placement data collected showed a mean lateral shift (between 0.2 and 0.8 feet) away from the centerline at night, and the lateral placement variability decreased (*28*). Mullowney, on the other hand, studied vehicle speed after the installation of RPMs along two curves and found a smaller and more consistent speed profile (*29*). He also found a reduction in centerline encroachments. A very good summary of RPM vehicle performance research in the recently completed NCHRP Report 518 – *Safety Evaluation of Permanent Raised Pavement Markers* found the same results: some increases in speed, more consistent speed profile, movement away from the centerline, reductions in encroachments, and decreased lateral placement variability (*30*).

Only one study has considered the vehicle performance impacts of different RPM spacing on tangent sections of roadways (*31*). This study found no significant difference in vehicle speed choice for the spacings considered, but a small and consistent shift away from the centerline of about 5 inches when the RPM spacing was changed from 120 to 60 feet. This benefit was not believed to be worth the extra cost and 120-foot RPM intervals were recommended for tangent roadway sections.

Raised Pavement Markers and Wider Edgelines

In an ongoing but yet unpublished research project, Donnell et al. evaluated different combinations of edgeline width, RPM "brightness" (i.e., filtered and unfiltered), and horizontal signing (e.g., "SLOW") at 16 horizontal curves (*32*). An instrumented vehicle with sixteen drivers (half between 18 and 26 years old and half between 61 and 79 years old), was used to collect nighttime vehicle speed, lane position, and acceleration data related to each delineation combination. The preliminary results indicate that providing improved striping or enhanced markings along the entire roadway segment (versus curves only) may increase vehicle speeds (*32*). There was some concern, however, that the data were impacted by drivers "learning" the route. A statistical analysis revealed that this was not the case. Direction of travel (e.g., geometrics) and driver age, on the other hand, were statistically significant. Younger drivers tended to travel at higher speeds and closer to the centerline.

Donnell et al. also gathered subjective ratings of delineation effectiveness (e.g., seven levels between "not at all effective" to "extremely effective") from the 16 subject drivers (*32*). These ratings were analyzed with nonparametric statistical tests and fuzzy logic, and these analyses showed that the ratings increased when the worn pavement markings were painted and RPMs were added. The 16 drivers in this study, however, appeared to prefer bright centerline paint to RPMs. Overall, the combination of centerline and edgeline treatments had the highest proportion of positive ratings.

Pavement Markings

Several studies have been completed that focus on the vehicle performance impacts of pavement marking as a delineation device. Studies that have considered the influence of adding pavement markings, contrast, and wider edgelines are described below.

Pavement Marking Presence

Styvers and DeWaard collected vehicle placement and speed data after adding dashed and solid edgelines to lower category rural roadways in the Netherlands (*33*). The vehicle placement and speed on these roadways, which were only 13 to 15 feet wide, was compared to the same measures along two control roadways with no lines at all or only a dashed centerline. The addition of the experimental edgelines resulted in vehicle positions closer to the center of the roadway. In addition, vehicle speeds were greater along the roadways with edgelines than along the unlined roadway speeds. The vehicle speeds along the roadways with edgelines, however, were still lower than those along the roadways with just a centerline. The drivers subjectively rated the effort needed to drive as higher along the unlined road. They preferred the edgelines to the unlined roadway, but not more than the roadways with a centerline.

A meta-analysis of edgeline presence studies was also done by van Driel et al. (*34*). This analysis evaluated the vehicle speed and lateral placement impacts reported by 65 previously completed studies from the United States and the Netherlands. Van Driel et al. observed that there was a difference in the study results from the United States and the Netherlands, and only the former are described here. The studies from the United States generally showed a mean increase of less than 0.5 mph in the mean vehicle speed after the addition of an edgeline to roadway with just a centerline. The range of the vehicle speed results, however, was -3.0 to +8.1 mph. The United States studies also showed that the mean lateral position of vehicles along roadways with edgelines was an average of 0.5 inches closer to the centerline (this statistic, however, for the studies evaluated by van Driel et al. ranged from a -10.5 inches toward the centerline to 14 inches away).

Finally in 2005, Sun et al. completed a study in Louisiana that considered the addition of edgelines to narrow (20 to 22 foot pavement widths) rural roadways (*35*). Lateral vehicle placement and speeds were measured with video equipment and automatic traffic recorders, and the researchers concluded from their data that the addition of edgelines resulted in a more central lane position and that this shift was more apparent at night. Drivers generally moved away from the edgeline, and the magnitude of the shift appeared to change with a number of factors (e.g., roadway width, operating speed, time of day, frequency of heavy vehicles, pavement condition, roadway alignment, edge drop-off, and traffic from the opposite direction). The addition of an edgeline had little impact on the mean vehicle speed.

Pavement Marking Contrast

As previously noted, Hall summarized a series of research projects that generally focused on the delineation needs and curve negotiation of drivers at night (*10*). One study, described by Hall, was completed by Allen et al. for the Federal Highway Administration in 1977 (*8, 9, 10*). It focused on contrast and included both simulation and field tests. The driving simulator results generally showed the importance of good delineation when visibility decreases, and this result was used to design two field evaluations. The first field test considered pavement markings with four different bead concentrations, and collected speed and placement data along various sections of a 19.9-mile roadway segment. The data were gathered when there was no striping, the new pavement marking treatments had been applied, after the winter degradation process, and once the pavement markings were repainted with a standard concentration of beads. The second field test, along 24.9 miles of roadway, compared the impacts of a standard centerline treatment with edgelines and PMDs with a similar situation supplemented by RPMs. The vehicle performance impacts of thermoplastic and regular paints were also considered.

The field studies by Allen et al. showed that delineation contrast was systematically related to the standard deviation of vehicle lateral placement (*8, 9, 10*). Lateral placement variance decreased as the contrast increased. In addition, as the contrast was reduced (by wear and tear or rain) drivers shifted toward the center of the lane. The mean speed and lateral placement variance of the vehicles, however, did not appear to be related to the delineation treatments considered. Allen et al. also found no difference in driver performance measures when thermoplastic lines and painted lines were used in dry or wet conditions (the wet weather dataset was very small). They calculated, based on their simulation and field test results, that the probability of a vehicle leaving a lane increased rapidly as the delineation contrast was reduced below 2.

Wider Edgelines

The most universally used form of delineation is longitudinal pavement markings. However, the studies related to the use of wider edgelines, 6-inch or 8-inch, have produced mixed results (*36*). In 1982 for example, Nedas et al. completed a study of vehicle lane position and wider edgelines in New Jersey (*37*). The objective of this study was to compare the lateral placement of vehicles when no edgeline pavement marking was present and also when 4-, 6-, and 8-inch edgelines were used. The study was conducted on a closed course and analyzed the vehicle placement performance of 16 male drivers with three blood alcohol content (BAC) levels. Lateral vehicle positions were photographed every 100 feet as the subjects drove through a course of tangent and curved sections. Overall, the curve data showed that increasing the edgeline width caused drivers to move closer to the centerline, but did not increase centerline encroachments. In addition, the lateral placement of the vehicles was also less variable and more centrally located. The data from the tangent roadway sections, however, were inconclusive.

In the mid-1980s, Cottrell also studied the lateral placement and speed impacts of 8- versus 4-inch edgelines (*38*). Data from 12 two-lane rural roadway sites were collected and compared, but the roadway segments used in the analysis were selected based on the fact that they were high crash locations. Cottrell concluded, based on an analysis of the data, that there was no significant difference in lateral placement after the edgelines were widened. However, the drivers did position themselves closer to the center of the lane when the 8-inch edgelines were in place. In addition, no statistically significant change in centerline encroachments, mean speed, or speed variance was found due to the increase in edgeline width. Behar et al. found that other studies produced similar results (*11*).

In 2006, Donnell et al. also published the results of a wider edgeline study they completed for the Pennsylvania Department of Transportation (*28*). This study focused on the vehicle performance impacts of wider edgelines (8-inch versus 4-inch lines) along horizontal curves. Four treatment and four control sites were used, and the data collected included vehicle speed, encroachment frequency, lateral vehicle position, and the difference in vehicle speed and lateral position from the tangent to the curve midpoint. Donnell et al. concluded that addition of wider edgelines did not result in consistent changes related to encroachments (centerline and edgeline), vehicle speed, or lateral vehicle placement. However, a subjective evaluation of the speed profile data revealed that drivers appeared to recognize the curves at a greater distance with 8-inch edgelines.

VEHICLE PERFORMANCE MEASURES AND CRASH DATA

Two studies have tried to define the relationship between the vehicle performance measures and crash data. Both of these studies were done in the 1970s and followed what was considered to be an acceptable statistical approach for crash data analysis at the time. During the last decade, alternative procedures have been introduced.

In 1972, Pagano attempted to define the potential relationship between the crash data from nine two-lane rural roadway curves and vehicle speed and lateral placement (*2, 39*). Pagano developed a total crash rate model with a linear regression approach that included variables for vehicle deceleration in the first half of the horizontal curve and the ratio of variance in vehicle lateral placement at the middle and beginning of a horizontal curve. The total crash rate increased with both variables. Pagano's model did not improve when only those crashes related to driving a curve (e.g., run-off-the-road) were included rather than the total number of crashes. Good correlations were found, however, between mean vehicle speed and total crash rate. The crash rate increased as the mean vehicle speed decreased at sharp curves.

In 1977, Stimpson,,et al. published the results of a similar effort to define the potential relationship between vehicle performance measures and crash data (*16, 17*). They collected vehicle speed, lateral placement, and crash data at 32 roadway segment sites with an average daily traffic (ADT) of 540 to 5,000 vehicles per day (vpd), and a regular regression approach was used to develop models for nighttime, delineation-related, non-intersection (dry pavement) crash rates along straight and winding road segments. A two-variable model was developed that included variables related to the lateral deviation of vehicles from the center of the lane and lateral placement variance. The crash rate results of the model increased with both variables. Stimpson et al. concluded that the application of this two-variable model (explaining about 66 percent of the data variability) was generally adequate for straight/winding roadways. A five-variable model was also created that explained 81 percent of the data variability, but it was considered less clear and meaningful. This equation included shoulder width, roadway width, and a vehicle speed skewness measure. Therefore, these are some of the geometric design variables that should be considered in the data collection effort of delineation studies.

Delineation and Crash Data

Research has consistently shown an over representation of run-off-the-road accidents in rural areas on horizontal curves (*6*). In some cases, these types of crashes can account for 40 percent of all those reported along rural roadways with nearly half involving personal injury or fatality (*7*). One study found that along two-lane rural roadways the degree of curvature of horizontal curves is the strongest geometric variable related to crash rates (*5*).

Some studies have attempted to directly evaluate the safety impact of delineation through the use of crash data. Many of these studies, past and present, have followed a typical or "naïve" before-after approach for their crash analysis. Directly measuring the crash impacts of delineation can be a difficult endeavor because the small changes it produces can be overwhelmed by the natural variability in crash data and the impacts of other roadway characteristics (e.g., traffic volume). The results of the studies described below, therefore, should be used with some caution. They generally have small sample sizes, fail to consider regression-to-the-mean, and/or may not control, document, and/or account for the large number of other factors that can impact the safety reduction effectiveness of delineation treatments (e.g., volume, time, etc.). The impact that pavement marking may have on crash data, in comparison to other factors, requires a large sample size and more current safety analysis procedures.

Several studies have been completed that have focused on the potential relationship between pavement marking and crash data. The projects described below considered the safety improvements of adding centerlines and normal width or wider edgelines. Studies that evaluated the safety impacts of different pavement marking retroreflectivity and materials are also summarized.

Centerline and Edgeline Presence

Donnell et al. summarized a study by Potters Industries and Carlstadt that concluded two-lane roadways with centerlines had 40 percent fewer total crashes than those same roadways with no centerline (*28*, *32*). The crash data from roadways that had a white centerline changed to yellow (with passing and no-passing zones indicated) were also compared and a 15 percent reduction in total crashes was found (while control roadways had an 18 percent increase in crashes. Unfortunately, this study only considered data from four months before the lane lines were added and eight months after.

In the mid-1980s, Glennon also studied the safety impacts of adding a centerline (with passing and no-passing zones indicated) to previously unmarked roadways (*40*). Crash data from a total of 225 roadway sections were evaluated, and Glennon determined that crashes increased after a centerline was added along those roadways with an annual ADT of 500 vpd or less. Similar results were also found for roadways with an annual ADT of 500 to 1,000 vpd and lane widths of 10-feet or less. Glennon hypothesized that adding a centerline to a roadway might result in drivers forgetting about the fact that more caution is needed on these lower volume, and therefore lower design standard, roadways. Safety improvements were found, for example, after centerlines were added along roadways with an annual ADT of more than 1,000 vpd. Crash reductions were experienced along wider roadways with higher volumes. Glennon recommended that centerlines be added to roadways with a 16 to 18-foot width and an annual ADT more than 1,000 vpd. Similarly, he indicated that centerlines should be added to roadways with a width of 20 feet or greater and an annual ADT greater than 500 vpd.

Finally, Tsyganov et al. completed a study for TxDOT on the safety effects of edgelines along two-lane rural roadways in Texas (*41*). The first-year report included the summary and comparison of crash statistics from 56,285 miles of Texas roadway with and without edgelines. An initial comparison indicated that roadways without edgelines had a lower crash rate than those with edgelines. However, when roadway segments with only two or more crashes (during the four years considered, 1998 to 2001) were compared the results produced the opposite conclusion. Using only the results from this "crash-prone" roadway segment comparison, the researchers concluded that having an edgeline may reduce crash frequency and that the greatest reduction appears to occur along curved segments of narrow roadways (i.e., 9 to 10-foot lanes). In addition, edgelines may also result in fewer speed-related crashes at night.

Wider Edgelines

Documentation for three crash studies that evaluated the crash impacts of wider edgelines was found (*42, 43, 44*). A study by Hall in New Mexico used a before-and-after crash study approach to evaluate the safety impacts of using 8-inch versus 4-inch edgeline pavement markings (*42*). Hall evaluated approximately 530 miles of rural two-lane roadways identified as high single-vehicle run-off-the-road crash locations. Approximately 176 miles of these roadway segments were restriped with 8-inch edgelines and the remainder served as a control. Based on his analysis Hall concluded that wider edgelines did not appear to reduce single vehicle run-off-the-road crashes or opposite-direction collisions. His results were similar for tangent and curved roadway segments . A study by Cottrell used a similar approach to compare the safety of roadways with 4 and 8-inch edgelines (*43*). Approximately 61 miles of two-lane rural roadway were striped with 8-inch wide markings, and two to three years of before-and-after crash data evaluated. The crash types considered were single-vehicle run-off-the-road, impaired drivers, curve locations, nighttime, inclement conditions, and opposite-direction. A comparison of these crashes to those occurring along the control group roadway segments lead Cottrell to conclude that there was no evidence that wide edgelines significantly impacted any of these crash types. Unfortunately, both of these studies are based on a small sample of crash data and they do not appear to control for traffic volume or other roadway variables. Selection of high crash locations for evaluation also leads to typical regression-to-the-mean impacts on the results.

Hughes et al. also conducted a FHWA study of wider edgelines (8 versus 4-inch) along two-lane rural roadways (*44*). The researchers used a before-and-after study design and compared treatment site crash data with similar information from roadway segments in a control group. One to three years of before-and-after crash data were compared for more than 2,000 miles of roadway (in seven states) with either a 4 or 8-inch edgeline. Similar to the two studies above, the results of the analysis indicated there is little evidence to suggest that the addition of 8-inch edgelines produces an incremental reduction in crashes (along two-lane rural roadways with an ADT between 5,000 and 10,000 vpd). Hughes et al. did conclude, however, that wider edgelines might be cost effective on two-lane rural roadways that had ADT volumes between 2,000 and 5,000 vpd; pavement widths equal to 24 feet with unpaved shoulders; and frequent rainfall. In addition, wider edgelines may also be appropriate as spot treatments for isolated sharp horizontal curves and approaches to narrow bridges.

Marking Retroreflectivity

In 1998, Lee et al. attempted to develop a relationship between pavement marking retroreflectivity and crashes (*45*). Three years of nighttime lane departure crash data were collected at 46 sites in four areas of Michigan along with longitudinal retroreflectivity data (collected approximately four times a year for a three year period). The study considered a variety of pavement markings, and a linear regression approach was used to quantify the potential relationship between nighttime crashes and pavement marking retroreflectivity. Unfortunately, no evidence was found that a significant relationship existed between these two factors. Similar results were also found when the researchers attempted to model the potential relationship between the ratio of night to day crashes and retroreflectivity. The amount of crash data used in this study was small and most likely impacted its results.

Abbound and Bowman have also completed a study on the safety impacts of pavement marking retroreflectivity (*46*). This study used nighttime retroreflectivity-related crash data from 1,302 miles of state highways in Alabama. In addition, the pavement marking retroreflectivity from 520 miles of rural roadways were collected (15 m geometry). A critical crash rate (a maximum allowable crash rate that corresponds to minimum acceptable pavement marking retroreflectivity threshold) was calculated for both white paint and thermoplastic. These rates were determined to be 0.220 and 0.103 crashes per million-vehicle-miles for paint and thermoplastic lines, respectively. The crash-based threshold values for retroreflectivity were established at 140 to 156 mcd/m^2/lx, and the researchers recommend the use of 150 mcd/m^2/lx.

A more recent study, using current safety evaluation techniques, was published in April 2006 (*11*) as a web-only document as part of NCHRP 92 – *Pavement Marking Materials and Markers: Real World Relationship between Retroreflectivity and Safety Over Time,* researchers used pavement marking service life information from the National Transportation Product Evaluation Program (NTPEP), and combined it with crash data to evaluate and define the safety impacts of pavement marking retroreflectivity. Behar et al. took a "unique" approach that focused on quantifying the relationship between retroreflectivity and safety over time (but independent of marking and marking material type). The NTPEP data, along with the other information collected, were used to derive models for retroreflectivity performance. The variables and/or categories considered for these models included age, color, marking material type or marker type, climate region, and amount of snow removal. In addition, models were developed for five pavement marking materials (and RPMs) and safety effect multipliers calculated (i.e., factors representing the expected number of crashes due to retroreflectivity). Look-up tables are provided to estimate retroreflectivity and allow the comparison of new and old pavement marking materials. Based on their work, Behar et al. conclude that the "… approach used in this study was found to be reliable and straightforward to implement and is recommended for safety treatments which change over time." However, based on a California application, it was determined that "…the safety difference between high retroreflectivity and low retroreflectivity markings during non-daylight conditions and at non-intersection locations was found to be approximately zero…." They propose that doing something above and beyond normal pavement marking/marker replacement to gain additional retroreflectivity may not be cost-effective.

Marking Types and Materials

In 2000, Migletz et al. completed a study for the FHWA that evaluated the safety impact of all-weather pavement markings (AWPMs) (*47*). AWPMs are defined as pavement markings visible at night under conditions that are dry or up to ¼-inch of rain per hour. They completed a before-after crash study that evaluated three years of data from 85 pavement marking locations in 19 states. More than half of the locations were along freeways, and a range of AWPM materials were included in the study (e.g., epoxy, regular and profiled thermoplastic, regular and profiled polyester, regular and profiled methyl methacrylate, preformed profile tape, and waterborne paint). A paired sign statistical evaluation found an increase in daytime dry-condition crash rates at 53 percent of the sites and a decrease at 47 percent. Similar results were found for the nighttime dry-condition crashes. Daytime and nighttime wet-condition crashes also increased at 40 and 45 percent of the sites, respectively. Overall, nighttime wet-condition crashes increased by 15 percent, but the total number of nighttime crashes (dry- and wet-condition) decreased by 6 percent. None of these changes were statistically significant. A yoked statistical comparison showed that dry-condition crashes were expected to decrease by 1 to 20 percent with the installation of AWPMs and wet-condition crashes could decrease or increase by as much as 5 and 40 percent, respectively. Migletz et al. concluded that the addition of AWPMs might be effective in reducing crashes but they could not prove it statistically.

In 2001, Cottrell and Hanson also attempted to evaluate the safety impacts of different pavement marking materials (*48*). Twenty-two sites with an average length of 3.6 miles were re-marked with paint, thermoplastic, or tape. However, no more than five sites of any one type of pavement marking were available for analysis, and most pavement markings were only installed at two to three locations. In addition, some of the sites were used as a control for comparison purposes (these sites were re-marked with the same pavement marking materials). Cottrell and Hanson analyzed 2.5 years of total, sideswipe same-direction, and run-off-the-road crashes before and after the installation of the new pavement markings at both the control and treatment sites. They concluded that they could not find a statistically significant difference in crash frequencies by type of pavement material.

Raised Pavement Markers and Safety

A good summary of the literature about the safety effectiveness of RPMs is included the report for NCHRP 518: *Safety Evaluation of Permanent Raised Pavement Markers* (*30*). A similar summary, with additional references, will also be included in an upcoming multi-volume FHWA report from Donnell et al. (*32*); the title of this ongoing project is *Methods to Maintain Pavement Marking Retroreflectivity*. A sample of some of the literature that focused on crash data and the addition of RPMs, and was included in these two documents, is provided below (*30*, *32*). Similar studies from the Texas Transportation Institute (TTI) are also summarized (*49*, *50*).

Donnell et al. discussed several before-and-after crash studies of RPM additions (*32*). Two of these studies were completed by Graf et al. and Khan. Graf et al. evaluated before-and-after crash data at three locations in New Jersey. These locations were chosen for RPM installation based on their high number of total, wet-night, night, and fixed-object crashes. Three years of crash data were collected for the period before the implementation, but only one year of data were available after implementation. Overall, 33 crashes per year occurred before the RPMs and 31 crashes after. This difference was not statistically significant. Khan evaluated one year of crash data before and after RPMs were installed at 184 locations in Ohio. These sites were selected if they had four or more delineation-related crashes in the before period. A number of location types were also considered (e.g., horizontal curves, narrow bridges, stop-controlled approaches on two-lane highways, etc.). The results showed that the 38 curve locations experienced a total crash frequency decrease of 2.0 percent, a daytime crash frequency decrease of 4.1 percent, and a nighttime crash frequency increase of 1.9 percent. These percentages were all statistically significant. Unfortunately, the validity of these before-and-after study results is reduced by their small sample sizes, regression-to-the-mean, and/or the lack of control for the safety impacts of other roadway characteristics (e.g., traffic volume).

RPMs are used extensively throughout Texas. In the mid-1980s, two TTI research projects considered the crash impacts of RPMs for TxDOT (*49*, *50*). In 1984, Kugle et al. evaluated the safety impacts of RPMs on two-lane and four-lane roadways (*49*). A total of 452 roadway segments were considered and two years of before-and-after crash data collected (more than 92,000 crashes). Three statistical processes were used to analyze the differences in this crash data, and the daytime crash patterns were used as a control (this assumes RPMs do not impact daytime driving behavior and/or safety). The cross-product analysis found a statistical increase in nighttime crash frequency for all crash types and severity levels, and Gart's procedure (a weighted cross-product) showed a significant increase in total and "preventable" (i.e., head-on, sideswipe, and run-off-the-road) nighttime crashes. The logistic analysis found similar results. It should be noted that 56 percent of the locations considered by Kugle et al. experienced an overall decrease in nighttime crashes after the RPMs were installed, but 10 percent of the locations had very high crash increases. Mak et al. eliminated all but 101 of the sites from Kugle et al. (because of unwanted roadway construction impacts) and only considered non-zero crash locations (these actions reduced the database to 87 sites) (*50*). However, there was no real change in the results. Mak et al. found no statistical difference in nighttime crashes (with daytime patterns as a control) at 74 of the 87 sites. There are a number of variables in the roadway environment that could produce these results found in these two studies (e.g., traffic volume).

NCHRP 518, *Safety Evaluation of Permanent Raised Pavement Markings*, was recently completed (*30*). It includes one of the most thorough discussions and analyses of snowplowable RPM safety impacts. As part of their safety evaluation of RPMs, Behar et al. collected crash, geometry, and traffic volume data from six states and several time periods between 1991 and 2001. They then completed a before-after study analysis, but used the generally accepted empirical Bayesian approach. Overall, Behar et al. found that the existence of RPMs significantly decreased two-lane roadway head-on and wet-weather crashes. This safety benefit also increased with traffic volume. They also found an increase in nighttime crashes after the installation of RPMs at "sharp" two-lane roadway curves and along lower design standard roadways (e.g., narrow pavement width). Along four-lane freeways the addition of RPMs decreased nighttime and wet-weather crashes, but their calculations indicated that RPMs may not be effective along these roadways if their ADT is less than 20,000 vpd. The accident modification factors (for the installation of a snowplowable RPM) calculated by Behar et al. result in a lower number of expected crashes along two-lane roadways with an ADT greater than 5,000 vpd (and a degree of curvature less than 3.5 degrees). A decrease in expected crashes would also occur if their accident modification factors for four-lane freeways with an ADT greater than 20,000 vpd are applied. These results show that RPMs increase crashes in some situations and decrease crashes in others.

Chevrons and Post-Mounted Delineators

In 1983, Niessner summarized several field studies that focused on the safety impact of chevrons and PMDs (*51*). During this project it appears that several individual analyses were performed by different agencies in eight separate states. Based on the results of these analyses, Niessner concluded that flexible post PMDs were twice as expensive as the standard "U-channel" post, but that where posts were knocked down frequently the flexible version may be more cost effective. The cost difference between these posts may have changed in the last 20 years. Niessner also determined that the results of his analysis could not support a conclusion that PMDs reduced run-off-the-road crashes for all roadway conditions. However, he did believe the crash data showed a decreasing trend with the addition of PMDs. An analysis of safety data before and after the addition of chevrons, on the other hand, revealed a significant reduction in fatal crash rate and a general reduction in overall crash rate. Unfortunately, the experimental design used in these studies was not documented and the validity of all these crash rate comparisons, especially the fatal crash rate analysis, is questionable.

Post-Mounted Delineators, Raised Pavement Markers, and Pavement Markings

In the late 1970s, Bali et al. studied the general safety impacts along two-lane rural roadways with different types of delineation (*52*). During this project researchers collected and analyzed crash data from more than 500 sites in 10 states, and the data were categorized by straight and winding roadway segments and isolated curves. They analyzed this data and estimated the mean crash rate for different delineation treatments within various highway situations and environmental conditions. The researchers recognized some of the weaknesses in their before-after approach (e.g., delineation effectiveness changes with time, the variety of combined sites, and various crash reporting approaches). The data showed that for straight and winding roadway segments the crash rates on two-lane roadways with a centerline were lower than those with no lines at all. The two-lane roadway segments with RPMs had even lower crash rates, and those with PMDs had lower crash rates than those without PMDs (with or without edgelines). The horizontal curve results were not as definitive, but there was an indication that the crash rate on curves with PMDs was lower than those without PMDs.

In addition, the crash rates at curves with a centerline appear to be lower than those without a centerline. The researchers acknowledge that the relationships indicated above are not definitive but they do believe the crash reduction measures calculated during their project could be applied in the field.

DELINEATION COST COMPARISONS

The selection and implementation of many roadway design features are based on cost-effectiveness calculations and comparisons. There are a number of transportation-related documents that describe the basic steps to this process (*1*, *13*, *32*). If several potential improvements, like various delineation treatments, can address a particular safety problem, a cost-benefit comparison can be critical to the decision-making process.

The selection of individual or combined delineation treatments to address a safety concern along roadway tangents or curves can be a complicated decision. Limited funds require a decision that produces the largest safety impact for the smallest amount of money (i.e., has a good benefit-cost ratio). However, to calculate a benefit-cost ratio for individual delineation measures an adequate estimation of its crash reduction benefits is needed. Unfortunately, as shown by this literature, valid estimates of chevron, PMD, pavement marking, and/or RPM crash impacts, can be difficult to calculate. Several attempts have been made to measure the crash impacts of delineation treatments or relate delineation-related vehicle performance measures to crash records. These projects have had questionable success.

A decision about the delineation combinations to consider during this project should be based on the benefit and/or cost information TxDOT currently uses in their decision-making. Pavement marking and signing service life (or replacement schedules), and materials, installation, and maintenance costs are needed. A consistent approach to the calculation and comparison of benefit-cost ratios will allow a proper decision to be made about the appropriate delineation treatment systems to test. Testing the validity of any economic analysis inputs or results is beyond the scope of this project.

SUMMARY OF FINDINGS

A wide range of research project results have been discussed in this literature review. In some cases similar studies even appear to produce conflicting conclusions. The following summary contains a description of the general findings or trends from past research efforts. Based on these findings, suggestions are also provided for the next stage of this research project.

Driving Task Research

Studies have shown that the interaction between drivers and delineation treatments can be relatively complex. It is clear, however, that a straightforward and understandable delineation of the vehicle path is critical for vehicle guidance, curve detection, and roadway safety. The proper application of positive guidance has clear benefits, but its impacts can be difficult to quantify.

Several studies have focused on how drivers visualize and proceed through horizontal curves. These studies have shown that drivers do not view delineation and drive curves in the same manner in each direction. In addition, they do not follow a circular path along a curve, and appear to need three to four chevrons to properly evaluate curve "sharpness". Changing the height of PMDs around the curve may also produce the same result. Drivers also need minimal levels of delineation treatment contrast and retroreflectivity, but a recent study concluded that the current approach to pavement marking replacement (due to reduced retroreflectivity) appears to be adequate and cost-effective from a safety point of view.

Vehicle Performance Impacts Research

A significant number of studies have focused on the vehicle performance impacts of delineation treatments and their characteristics. Far fewer have evaluated delineation applications along tangents or tangent-curve combinations. Some of the more significant efforts, like this project, have evaluated a large number of delineation treatments or devices with simulation/closed-course activities, and then applied a limited number of combinations in the field.

A comparison of the project results summarized in this literature review is difficult. There is a high level of variability in the study experimental designs, data collection locations, and the treatment combinations considered. The general trends from the study results, however, have led to the following conclusions:

- Combinations of pavement marking/markers and roadside devices appear to have larger vehicle performance impacts than the application of individual treatments along horizontal curves. For example, studies have suggested that adding RPMs to chevron or PMD installations can result in better vehicle path and lateral placement. Other studies recommend the use of RPMs and edgelines along curves (due to improvements in vehicle location and path).
- Although their results vary, delineation studies generally show that the addition of chevrons, PMDs, and/or RPMs can result in higher vehicle speeds, a smoother vehicle path, and reductions in lane encroachments and vehicle speed variance. Nighttime vehicle speeds after the addition of delineation, however, are still typically below those occurring during the day. The direction and magnitude of the measured impacts can be influenced by many factors (including research study design) and can be insignificant from a practical point of view (e.g., less than 3 mph or 0.5-foot shift).
- The magnitude of the vehicle performance impacts due to individual delineation treatments also varies. Chevrons and/or RPMs, for example, have more beneficial impacts than PMDs along horizontal curves, and more than two chevrons produces greater vehicle speed reductions. A study that replaced PMDs with RPMs along horizontal curves also produced higher vehicle speeds and a lateral shift of the vehicles away from the centerline. The variability in the vehicle lane placement and encroachments was also smaller with the RPMs.
- The addition of roadside delineation (e.g., chevrons and PMDs) and edgelines generally moves the vehicle path away from the roadway edge. However, these installations do not appear to increase centerline encroachments, and a more centralized lane location is considered a benefit

along both tangents and curves. Roadside delineation (e.g. chevrons and PMDs) also increases curve detection distance.

- The addition of centerlines increases vehicle speed and driver comfort. Speed may also increase with the addition of an edgeline (with or without a centerline), but these speeds are still generally lower than along roadways with just a centerline. A meta-analysis of several study results has shown that the mean speed impacts and lateral placement shift (toward the center of lane or roadway) due to edgelines is typically small but highly variable. The addition of wider edgelines produced similar lateral shifts but no increase in centerline encroachments. Vehicle path variability, however, is reduced with wider edgelines and there is no apparent impact on vehicle speed or speed variance.

Crash Impacts Research

Vehicle performance measures, like those described above, can be collected almost immediately after the installation of delineation treatments. Crash data, on the other hand, requires several years before an adequate before-and-after analysis can be completed. Two studies have developed models relating vehicle performance measures and crash data. These models show that crash rate increases with vehicle deceleration and lateral placement variability. Both models were, however, developed using a typical multiple linear regression approach. This type of application is no longer generally accepted practice.

Studies that have attempted to evaluate the crash impacts of delineation have produced varied results. This variability is not surprising. There are many roadway factors that may have a much larger influence on the occurrence of a crash than delineation treatments (e.g., roadway geometry or traffic volume). Delineation crash studies, however, have shown that the addition of centerlines generally benefits wider (e.g., 10-foot lanes) roadways with higher volumes (e.g., greater than 500 vpd). The addition of edgelines may also result in smaller crash frequencies. Small, highly variable, or inconclusive safety results, however, have been found for the addition of PMDs, chevrons, wider edgelines, pavement marking retroreflectivity (above and beyond typical replacement activities), and different pavement marking materials. RPM safety studies showed crash increases in the past, but a more recent study (using current statistical procedures) has produced a mixture of results. Decreases in the expected number of crashes were calculated for two-lane roadways with an ADT greater than 5,000 vpd (and a degree of curvature less than 3.5 degrees) and four-lane freeways with an ADT greater than 20,000 vpd.

Almost all of the delineation crash studies described in this literature review have used a typical before-and-after approach, had small sample sizes, and/or failed to control for important roadway factors and/or potential regression-to-the-mean impacts. Their results, therefore, should be used with caution.

EXISTING STANDARDS

In addition to the research literature, the project team also reviewed existing standards from the TMUTCD, MUTCD, TxDOT Standards Sheets, and TxDOT Traffic Operations Division Signs and Markings Manual. These are summarized in Appendix A.

One of the main purposes of this review was to find any guidance concerning combinations of treatments. Very little guidance concerning the tradeoffs among delineation options exists, which further supports the current research project. In addition, guidance given in certain sources conflicts with values in other sources. The guidance that does exist is summarized in Appendix A. Note that the TxDOT Traffic Operations Manual Signs and Markings Volume states the edgelines are required for all roads wider than 20 feet, which is conflict with the Texas MUTCD.

CHAPTER 2: CLOSED-COURSE NIGHTTIME HUMAN FACTORS STUDY

A closed-course study was conducted at TTI's Riverside test track facility in order to evaluate candidate delineation treatments and select those to be tested in subsequent field studies. The testing was completed during the period August – October 2007. All testing was completed at night.

Participant Recruitment and Screening

Participants were recruited from the Bryan-College Station area. Twenty people participated, all under nighttime conditions. The participants were required to have a current valid driver's license and be at least 18 years old. Each session took approximately 2 hours and participants were paid $40.00 each.

Test Materials

Study Location

Researchers conducted the closed-course study at the Texas A&M University Riverside Campus, a 2000-acre complex of research and training facilities situated 10 miles northwest of the University's main campus. The site, formerly an Air Force Base, has large expanses of concrete runways and parking aprons which are ideally suited for experimental research and testing in the areas of vehicle performance and handling.

Development of Driving Course

It was believed participants would navigate a curve differently if they knew they had driven through it before, and unfortunately the Riverside Campus runways could only contain four curves of the necessary size. Because of this limitation, it was determined that participants would drive through the same four curves repeatedly. To try to disguise this fact, the route was altered each lap. This was made easier as the landscape on the runways at the Riverside Campus has very few landmarks.

Based on the available space, and the layout of the runways, four curves were chosen to be the curves of interest for this experiment. Lane lines were installed on these curves, and during the data collection, these curves would be delineated with the different treatments chosen to be evaluated. In Figure 1, these four curves are indicated with the numbers 1, 2, 3, and 4.

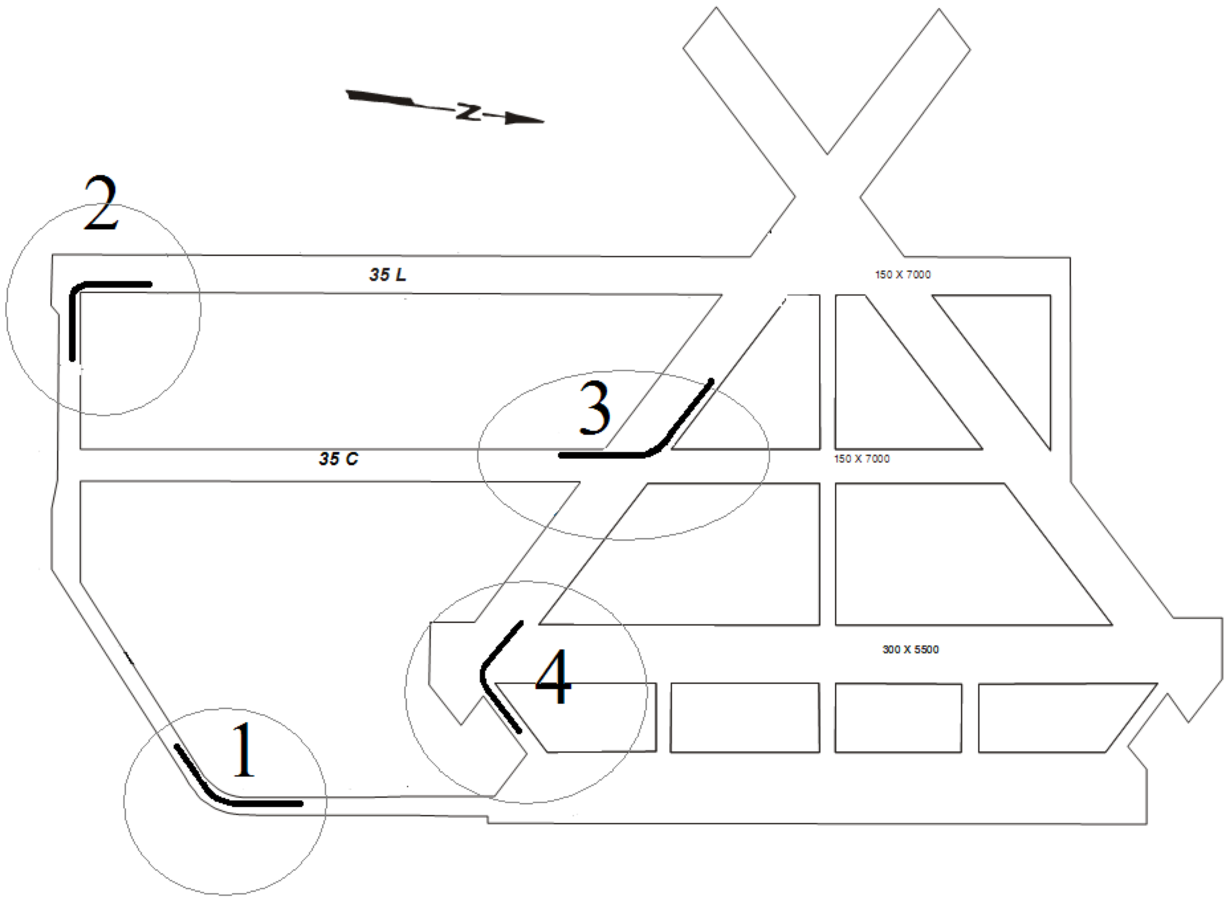

Figure 1. Map of Driving Course with Four Curves Labeled.

These specific areas were chosen to be the sites of the curves of interest for a number of reasons including:

- adequate sight distance in the run-up to the curves from both directions,
- absence of extreme elevation changes, and
- available to be used consistently over the course of the data collection.

Design of Curves

All four curves had lengths of 250 feet from the Point-of-Curvature (PC) to the Point-of-Tangent (PT). The striping extended 300 feet past the PC and the PT. In all four locations an 850-foot section was striped with at least a yellow double center line.

Curve 1 and Curve 3 both had deflection angle of 51 degrees and a radius of curvature of 280.9 feet. Curve 2 and Curve 4 both had a deflection angle of 90 degrees and a radius of curvature of 159.2 feet. These dimensions can be found in Table 1.

Table 1. Dimensions for Four Curves.

Curve 1 and 3		Curve 2 and 4	
L	250.0	**L**	250.0
Δ	51	**Δ**	90
D_{100}	20.4	**D_{100}**	36
R	280.9	**R**	159.2
T	134.0	**T**	159.2
E	30.3	**E**	65.9
M	27.4	**M**	46.6
LC	241.8	**LC**	225.1

The primary difference in terms of the preparation of the curves was the presence of an edgeline on Curves 3 and 4, and the absence of an edgeline on Curves 1 and 2. Comparisons between these two sets should reveal some information on the usefulness of edgelines when negotiating curves at night.

Edgelines and centerlines were created using adhesive, foil-backed temporary tape with embedded glass beads. The white edgelines were measured to have an average retroreflectance of 93 cd/lux*m^2. The yellow centerline was measured to have an average retroreflectance of 134 cd/lux*m^2. In summary, information on the curves is listed in Table 2.

Table 2. Summary Curve Information.

	Curve 1	Curve 2	Curve 3	Curve 4
Curve Radius	280.9	159.2	280.9	159.2
Curve Deflection Angle	51	90	51	90
Edgeline	N	N	Y	Y

Delineation Treatments Tested

Baseline Treatment. The Baseline treatment included no vertical delineation. On Curves 1 and 2, the baseline treatment was simply a yellow, double centerline. On Curves 3 and 4, the baseline treatment added white edgelines to the yellow, double centerline. In all cases, yellow RPMs were placed at 40-foot intervals between the yellow centerlines for the entire length of the lines. A picture of Curve 1 (no edgeline, 51 degree deflection) is presented in Figure 2. A picture of Curve 4 (edgeline present, 90 degree deflection) is presented in Figure 3.

Figure 2. Curve 1 at Dusk with Baseline Treatment.

Figure 3. Curve 4 at Dusk with Baseline Treatment.

Post-Mounted Delineation. Two different styles of post-mounted delineators (PMDs) were tested. Both were mounted on 4-foot tall, 4-inch wide, white, Carsonite™ posts. Wood bases were fabricated and painted black to allow the PMDs to stand on the concrete runways. The two PMD treatments used were called "Fully-reflectorized post-mounted delineators" (Full PMD) and "Dot-reflectorized post-mounted delineators" (Dot PMD.)

The Full PMDs' entire surface (48 inches tall x 3 inches wide) was covered with TxDOT Type C retroreflective sheeting. The Dot PMDs had only a 3 x 8 inch piece of TXDOT Type C retroreflective sheeting placed at the top of the post. This represents the current Texas standard post-mounted delineator according to the Texas MUTCD. Pictures of both a Full PMD and a Dot PMD are presented in Figure 4.

Figure 4. "Dot" Post-Mounted Delineator and "Full" Post-Mounted Delineator.

In order to save materials and facilitate easier on-the-fly set-up and tear-down, the PMDs were made with one side of the Carsonite™ post being fully-reflectorized and the other side having only the retroreflective "dot." Depending on which direction the Participant's vehicle approached the curve, the posts were deployed so that only one side was visible as the curve was negotiated.

In both cases, 12 post-mounted delineators were used to mark the curves in the trials which presented either of these treatments. The PMDs were positioned 16 feet from the centerline with the faces normal to the edgeline. From the PC to the PT, the PMDs were positioned at 50-foot intervals. Outside the PT and PC, the PMDs were positioned at 100-foot intervals out to 300 feet before the PC and continuing 300 feet after the PT. This was based on the design lay-out for a curve with a 25 mph advisory speed in the Texas MUTCD. A diagram of the layout for the PMDs is presented in Figure 5. A photo of this layout with Full PMDs is displayed in Figure 6 and with Dot PMDs in Figure 7.

Advisory Speed (MPH)	Spacing in Curve	Spacing in Strtawy	Chevron Spacing in Curve
	A	2xA	B
65	130	260	
60	110	220	
55	100	200	160
50	85	170	160
45	75	150	160
40	70	140	120
35	60	120	120
30	55	110	80
25	50	100	80
20	40	80	80
15	35	70	40

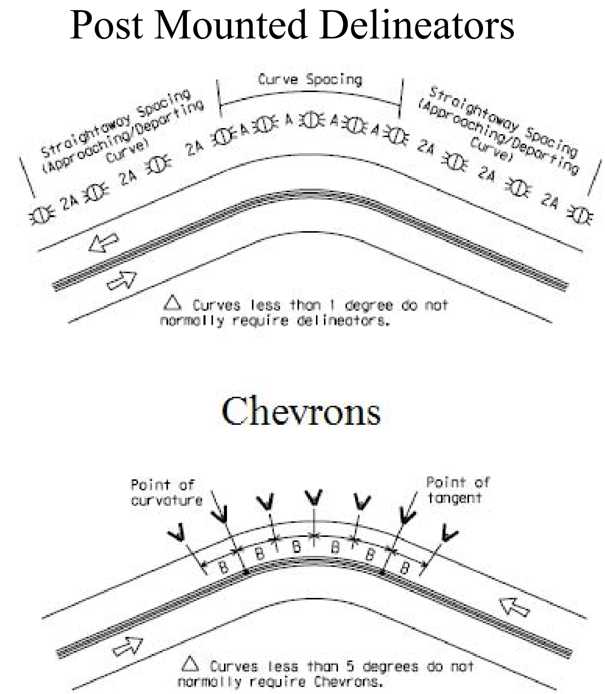

Figure 5. Table and Diagram for Positioning PMDs and Chevrons around Each Curve.

Figure 6. Photo of Curve 1 with Fully-Reflectorized Post-Mounted Delineators.


Figure 7. Photo of Curve 2 with Dot-Reflectorized Post-Mounted Delineators.

Chevrons. The final two treatments both presented the driver with five chevron signs lining the curve. The chevron sign faces were 30 in. tall by 24 in. wide and mounted on movable bases with the bottom of the sign face 7 ft. above the ground. The sign faces themselves were secured with a single bolt in the center of the sign face so that they could be rotated and used to mark either a left-hand or a right-hand curve. A picture of a chevron signs laid-out around a curve is presented in Figure 8. The chevrons were manufactured with Type C prismatic high intensity sheeting

Figure 8. Chevrons Laid-out around Curve 1.

The other treatment employing the chevron signs added fully-reflectorized posts to the chevron sign stands (this treatment will be referred to as "ChevFull"). In practice, the vertical posts were not actually covered with the retroreflective material. Instead PVC tubes, (4-in. diameter) covered with yellow TxDOT Type C retroreflective sheeting were attached to the front of the vertical sign stand posts. The tubes were 6-ft. long, so that when attached to the posts, they stretched from just below the bottom of the sign face down almost to the ground. A picture of a ChevFull signs with fully-reflectorized poles laid-out around a curve is presented in Figure 9.

Figure 9. Chevron Signs with Fully-Reflectorized Posts on Curve 1.

In both cases, five chevrons (or ChevFulls) were used to mark curves in the trials which presented either of these treatments. The chevron stands were positioned 16 feet from the centerline, with the faces facing normal to the approach direction. The chevrons were spaced at 80-foot intervals, with the first one placed at the PC, and the fifth one placed 80 feet after the PT. This spacing was based on the table and diagram displayed previously in Figure 5.

Instrumented Vehicle

All test participants drove a 2006 Toyota Highlander which had been instrumented to collect various driving performance data. All data collected by the vehicle were synchronized by the DEWE5000 data acquisition system. Specifically for this experiment, data collected included brake pedal and accelerator pedal displacement, lateral acceleration, and Global Positioning System (GPS) location information (see Figure 10).

Figure 10. Inside View of Instrumented Vehicle.

Two Advantage Motorsports Throttle Position sensors were used to measure the displacement of the pedals and to output a representative voltage (0–5 volts) to the DEWE5000's Analog to Digital board. Here the pedal position data streams were digitized and integrated into the comprehensive data file.

A Crossbow LP-series accelerometer was used to measure the lateral acceleration experienced within the vehicle. This analog data were also digitized and integrated by the DEWE5000. A Trimble DSM 232 DGPS system was used to report GPS position data. This system is accurate to less than 1 meter and outputs position data at 10 Hz. A simple push-button switch was also wired into the DEWE5000 to allow the experimenter to mark positions around the course in the data file.

Experimental Design

Based on the number of treatments (five), the number of curves (four) and the fact that left curves versus right curves would likely elicit different behaviors, 40 trials would be necessary to expose each participant to all conditions and combinations. With four unique curves, participants could drive 10 laps around the runways and see all 40 combinations as shown in Table 3.

Table 3. Experimental Design Matrix.

	Left				Right			
	51 °	90 °	51 °	90 °	51 °	90 °	51 °	90 °
	CL Only	CL Only	CL + EL	CL + EL	CL Only	CL Only	CL + EL	CL + EL
Markings Only								
Dot PMD								
Full PMD								
Chevron								
Full Chev								

The map of one of the laps is presented in Figure 11. Each lap had a unique route through the four curves (with the exception of laps 5 and 7.) Many factors influenced the design of the routes. Primarily, it was critical that the routes on any two consecutive laps were different enough that participants would be unlikely to make the connection that they were driving through the same curves. Also important was determining the deployment of the treatments in a method and order that allowed the delineation to be set up and correctly positioned to be viewed in a short time frame, and then taken down or changed again quickly.

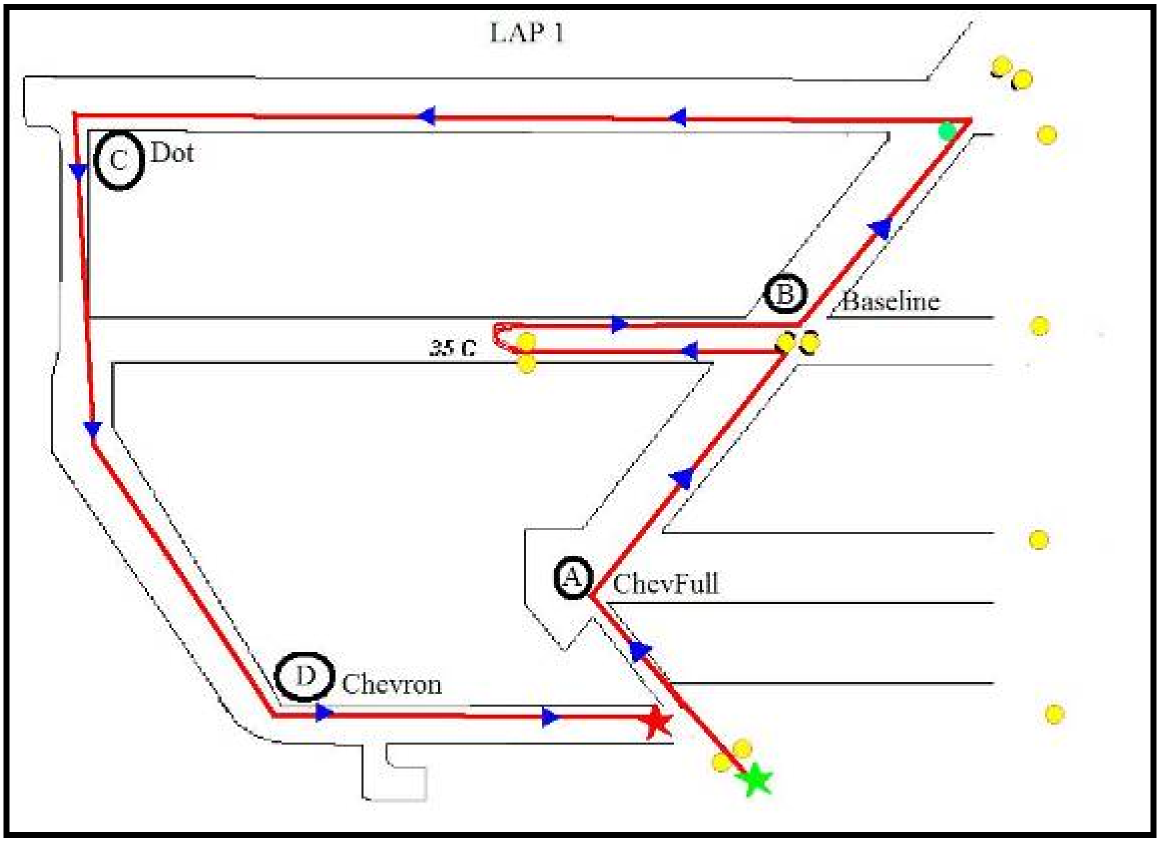

Figure 11. Route Map for Lap 1 of 10.

Test Procedure

Two participants were scheduled to be run each night. Participants were met at the entrance to the testing facility and taken to the intake office where they completed an Informed Consent form, a demographics questionnaire, and a visual-acuity test.

Participants were then given some brief instructions which mentioned that they would be driving a predetermined route lined with raised reflective pavement markers, and that they would be directed to look at some objects around the course as they drove. Participants were intentionally kept unaware that curve delineation was being evaluated. Participants were also given the impression that they would be driving over a huge area, and never told that they would be essentially driving the same course (and viewing the same four curves) 10 times. The participant was then led outside to the instrumented vehicle and allowed to adjust the mirrors, seat, etc.

Once the testing was ready to begin, participants were instructed to drive 45 miles per hour. Speed limits signs reinforcing this were located at two locations around the course. After a short practice drive out to the start of the course, the participant began driving along the route marked with RPMs.

For the first 5 laps, participants simply drove the course by following the RPMs and occasionally received navigational instructions from the experimenter in the back seat. The experimenter's roll during this stage was simply to communicate with the field crews to ensure that the correct treatments would be set up before the participant came upon them.

After the fifth lap, additional tasks were given to the participant. For the final five laps, the participant was asked to indicate by saying "Now" at what point they felt confident that they were able to judge the sharpness of the curve and how fast they should be driving while navigating it. Also, after navigating the curve, they were asked to rate their choice of speed on a scale of 1 to 5, with 1 indicating "I went too fast" through the curve and 5 indicating "I could've gone faster" through the curve.

Data Reduction and Analysis

In order to analyze the participants' reactions to the curve delineations, researchers collected the following data:

- The movements of the brake and gas pedals were recorded in order to determine the earliest moment subjects changed their behavior after recognizing a curve
- The lateral acceleration experienced as the participant drove through the curve
- The speed of the vehicle
- The path of the vehicle as recorded by the GPS unit
- Participants were asked to announce when they were confident they knew how sharp the curve was. This location was marked in the GPS data stream

After the driving portion of the study was completed, subjects were asked to view 3 x 5 inch color prints of still photographs of the five delineation treatments taken at dusk. They were asked to rank order the five photos from best to worst as to the effectiveness of the treatment in conveying the curve sharpness.

Results

Curve Sharpness Detection Distances

Participants were asked to announce when they were confident they knew how sharp the curve was. This location was marked in the GPS data stream. The distances from the midpoint of each curve at which the subject responded were compiled and are displayed in Figure 12-14.

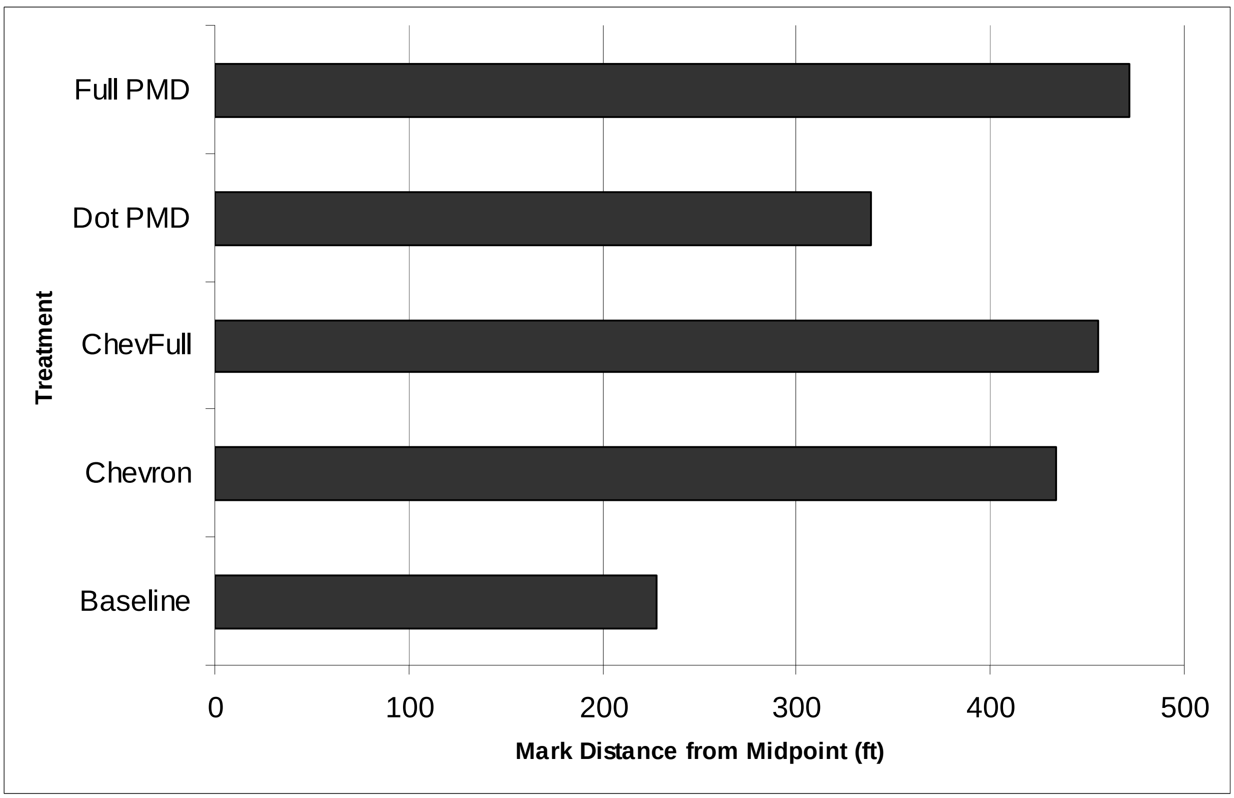

Figure 12. Mark Distance by Treatment.

Based on the data presented in Figure 12, one can see that participants could assess the sharpness of the curve earliest when the Full PMDs were presented. The baseline treatment conditions resulted in the shortest recognition distances. The Dot PMD treatment also performed worse than the other non-baseline treatments.

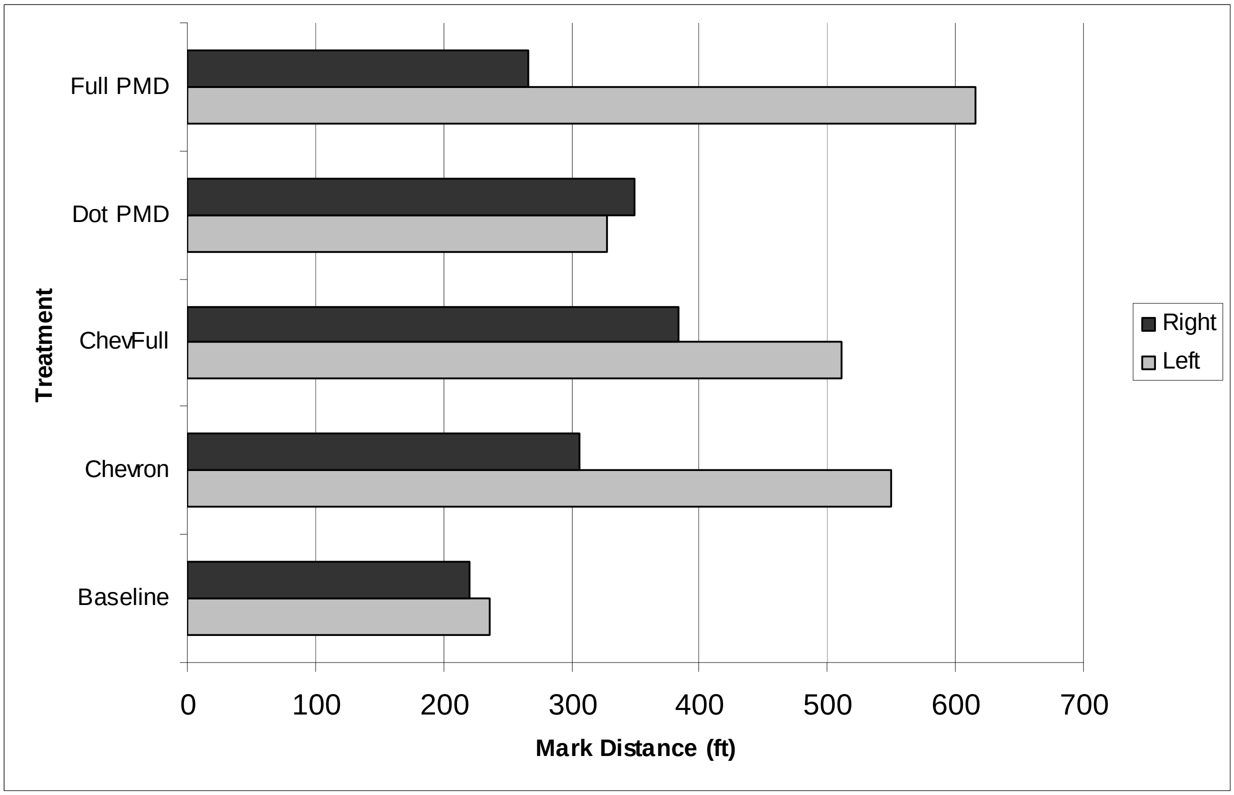

Figure 13. Mark Distance by Treatment, Direction.

In the case of four of the five treatments presented, participants were able to judge the sharpness of left curves earlier than they were able to judge the sharpness of right curves. This was most pronounced in the case of the Full PMD treatment.

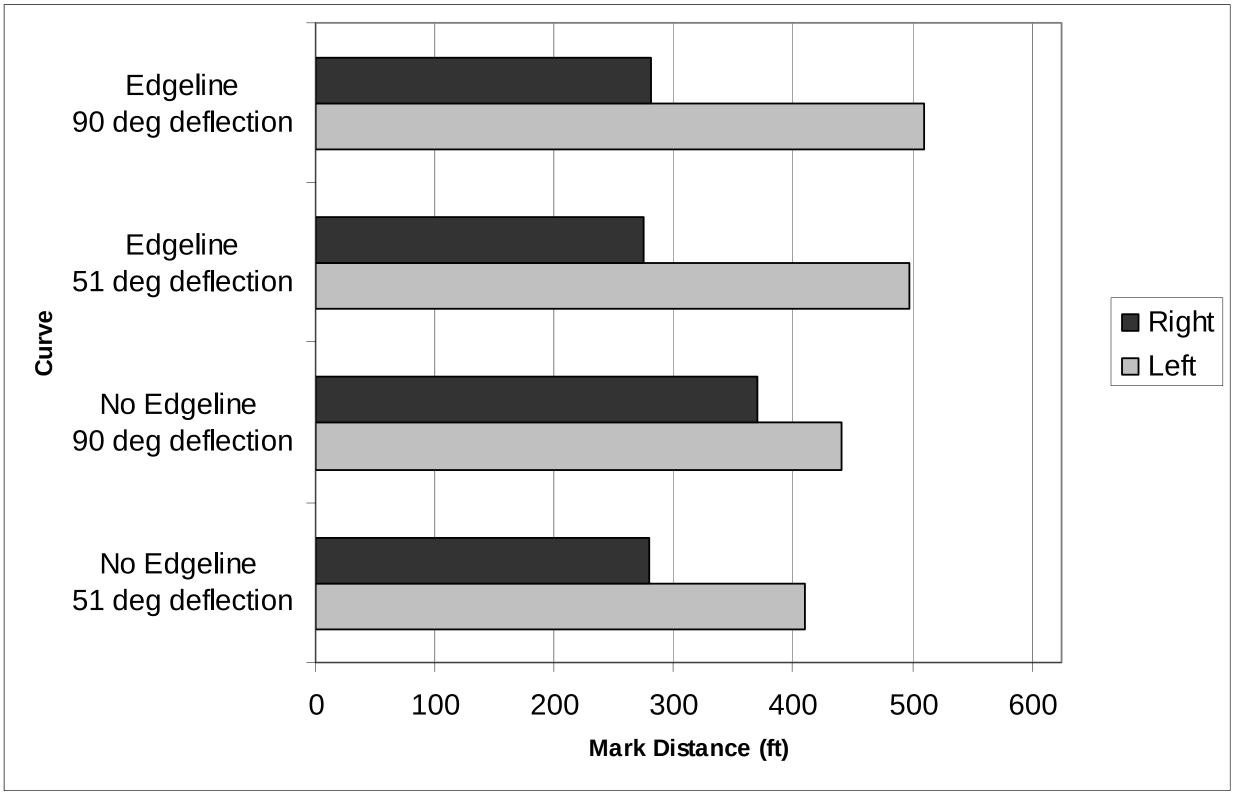

Figure 14. Mark Distance by Curve and Direction.

In general, from Figure 14, it appears that the presence of an edgeline may help drivers when navigating a left turn, but not necessarily a right turn.

Brake and Throttle Data

As the participants approached each curve, at some point they were forced to release the accelerator and press the brake pedal to slow the vehicle to safely navigate the curve. Figure 15 and Figure 16 display data on this behavior broken down by curve treatment.

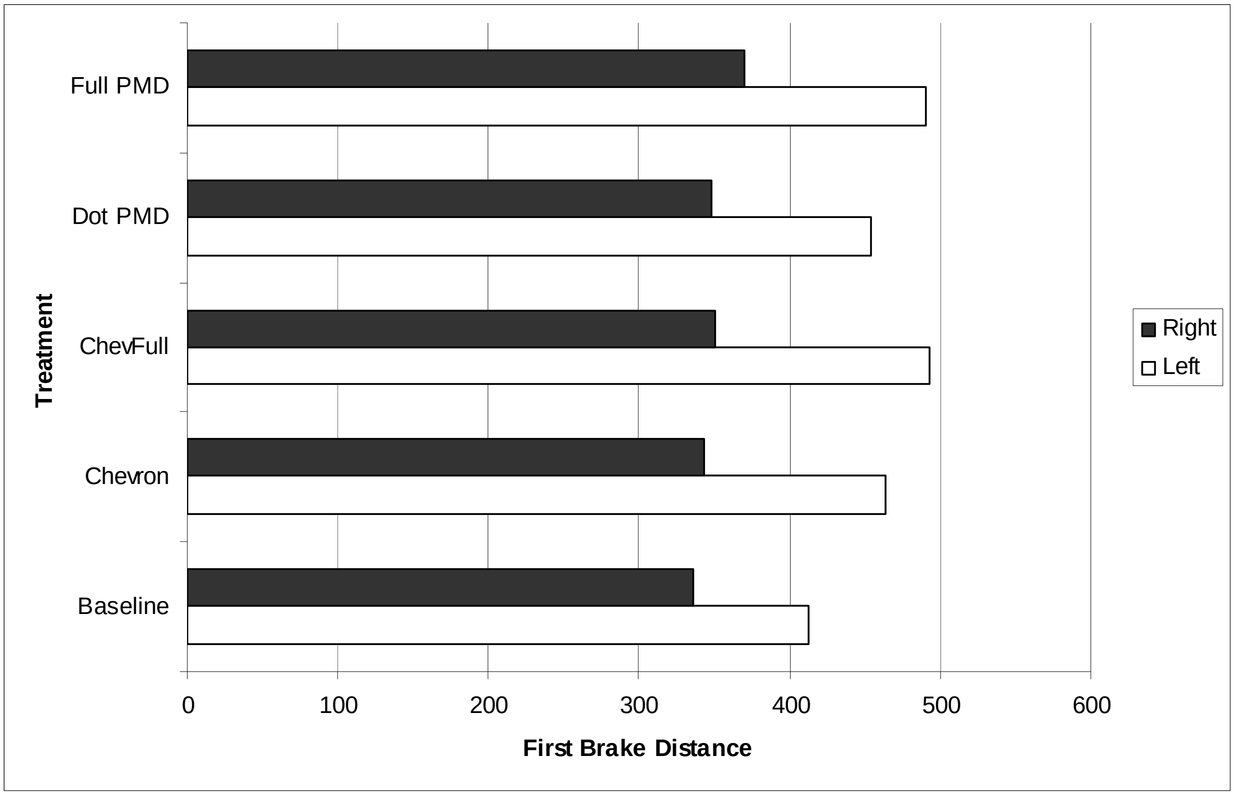

Figure 15. Distance from Midpoint at First Brake.

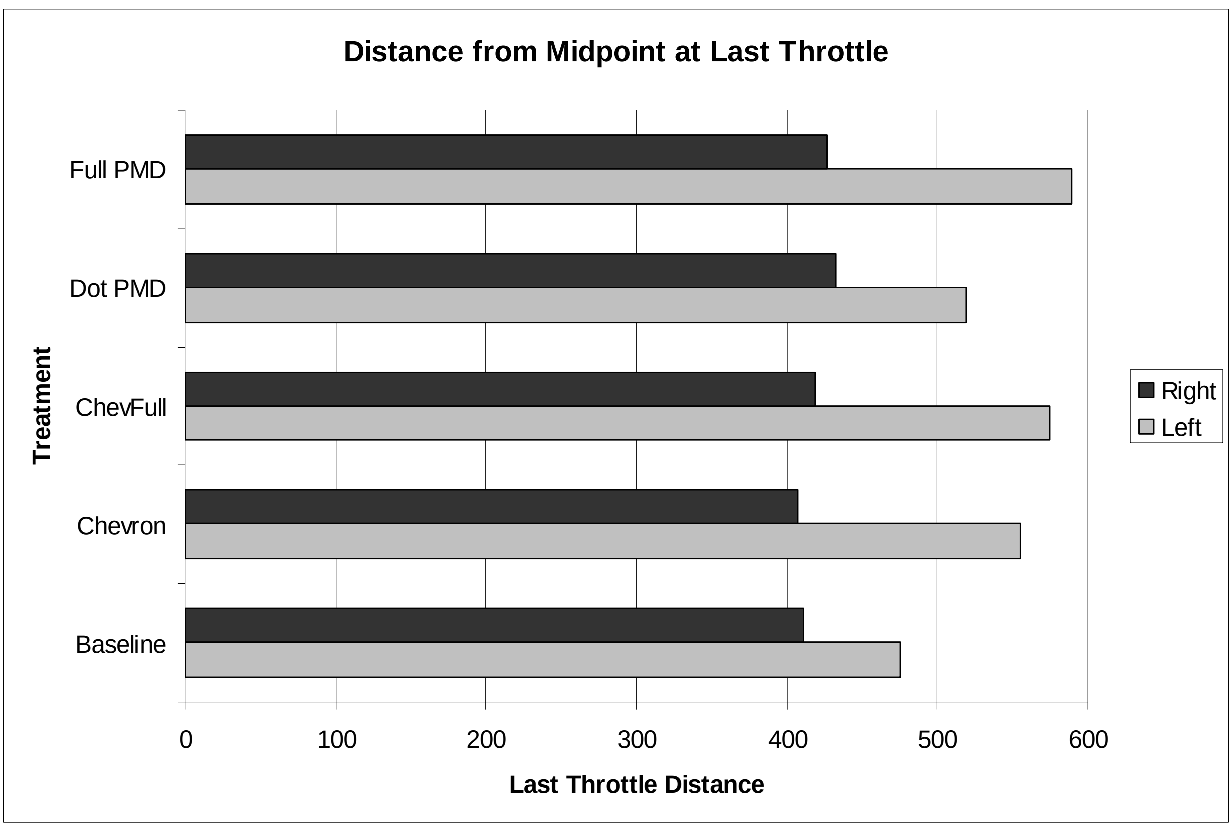

Figure 16. Distance from Midpoint at Last Throttle.

Similar to the data presented in Figure 13, treatment seemed to only have an effect on the participants' ability to judge sharpness when presented with a left turn. These figures essentially display the objective counterpart to the subjective data presented in Figures 13 and 14, and the same relationship of treatment to (mark, brake) distance is seen. From a cursory examination it appears "First Brake" distance may be more sensitive to treatment than "Last Throttle."

Participants behaved in different ways while navigating the curves based on the treatment presented. Figure 17 displays the average maximum brake pedal displacement for participants as they navigated curves marked with each treatment. Figure 18 displays the average maximum lateral acceleration felt by each participant as they navigated curves marked with each treatment.

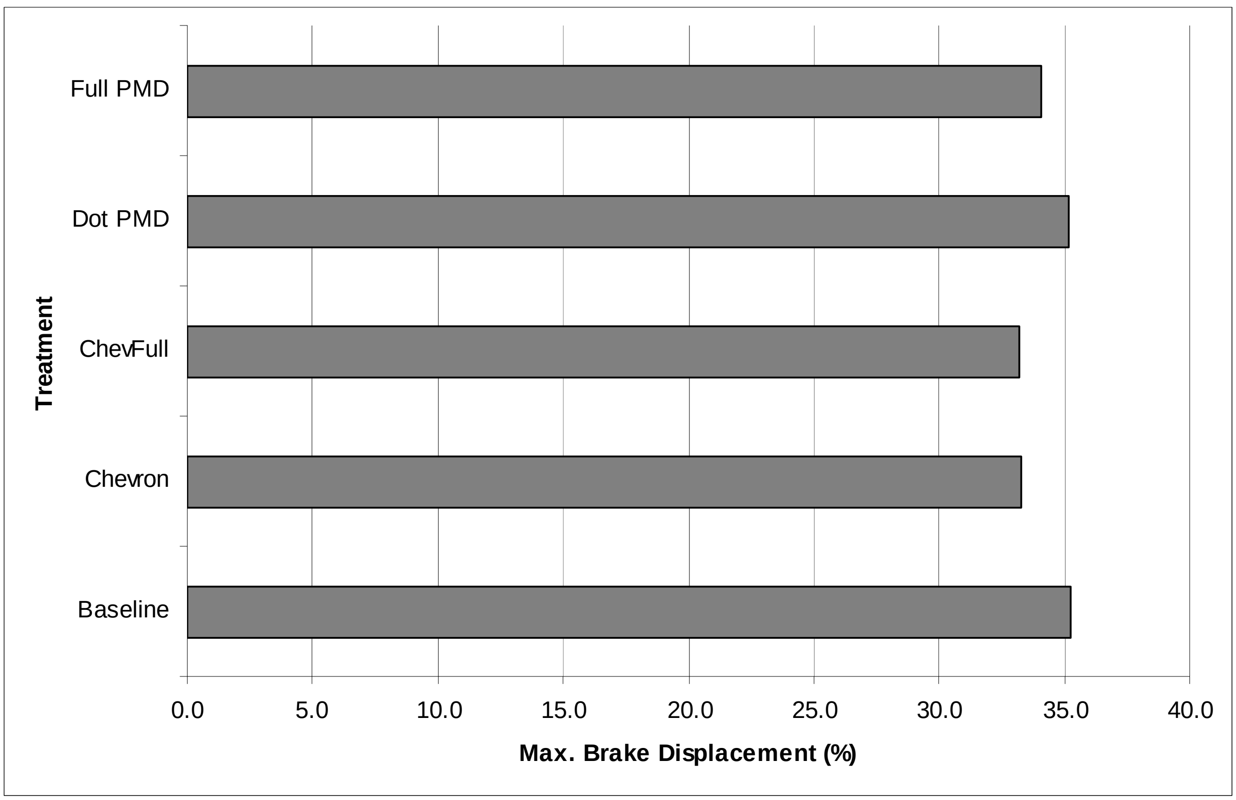

Figure 17. Maximum Brake Pedal Displacement by Treatment.

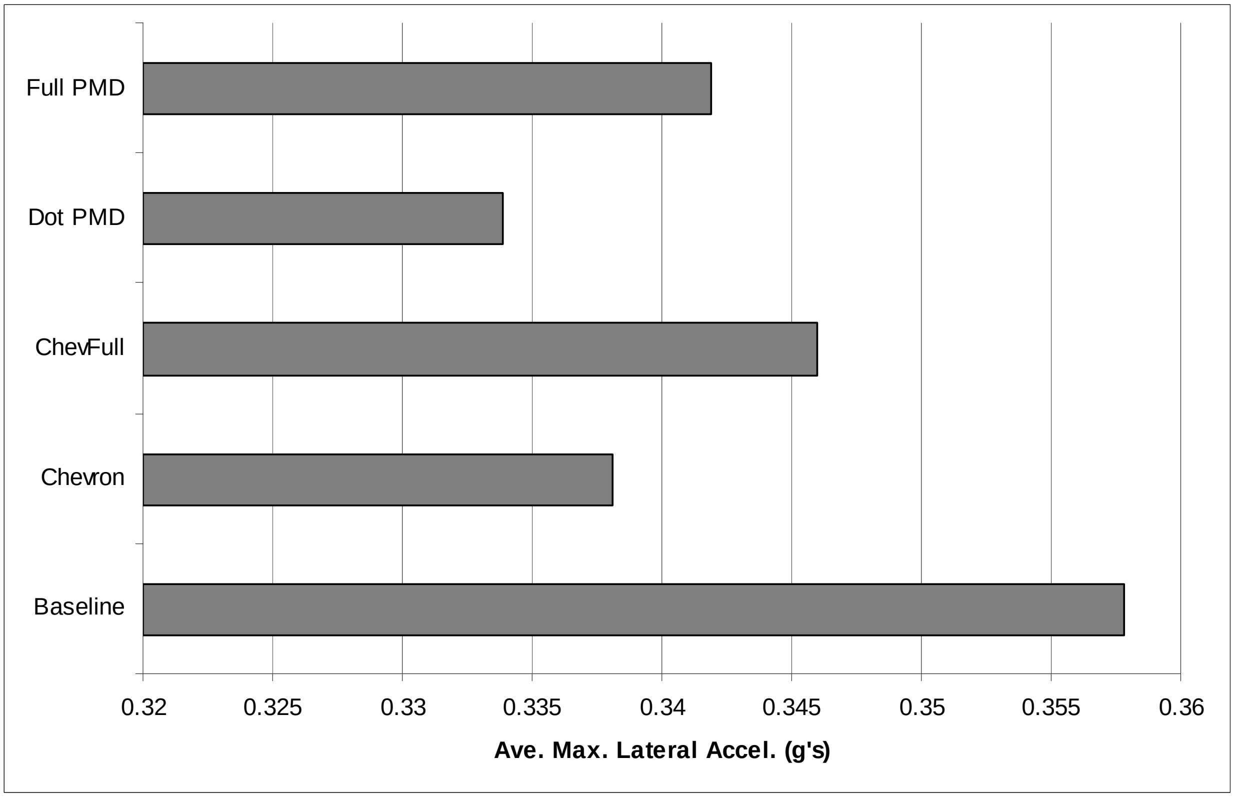

Figure 18. Average Maximum Lateral Acceleration by Treatment.

Velocity

The velocity of the vehicle as it navigated the curves was also of interest. Velocity data are presented in Figure 19 and Figure 20.

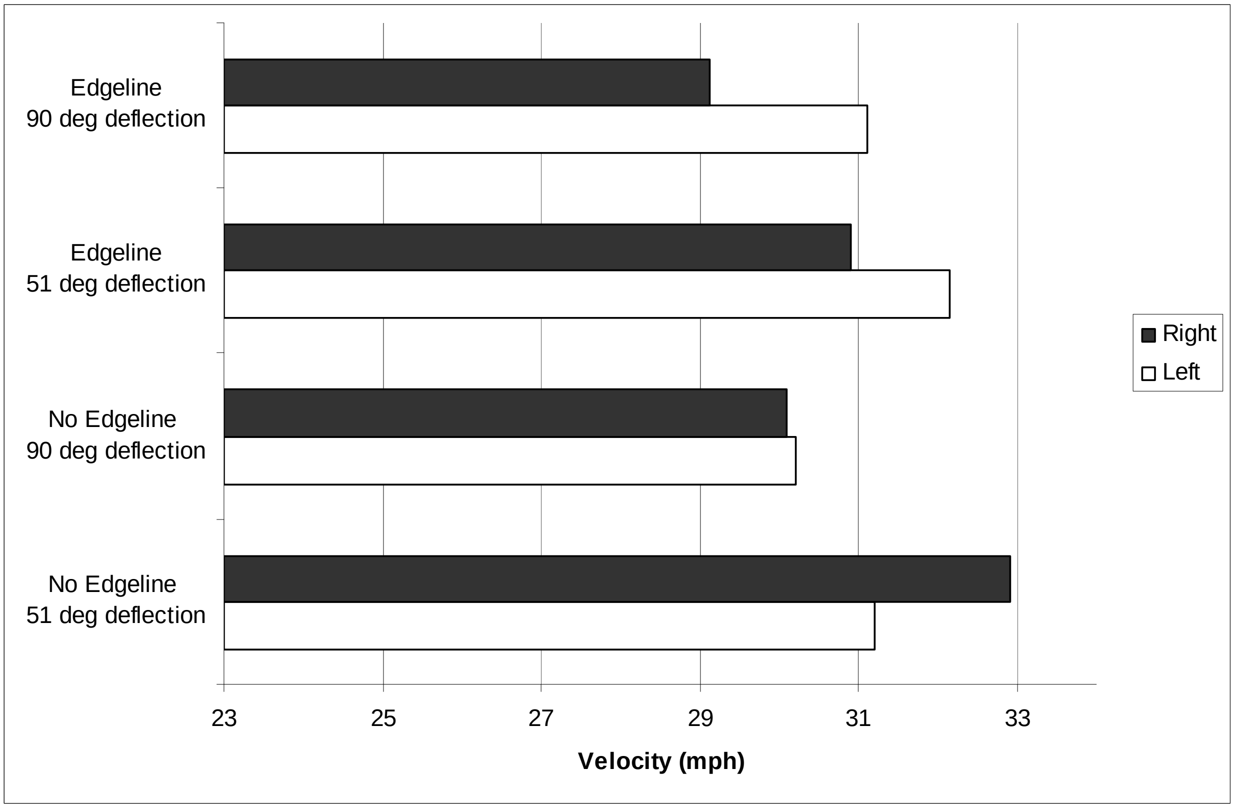

Figure 19. Average Velocity at the PC by Curve, Direction.

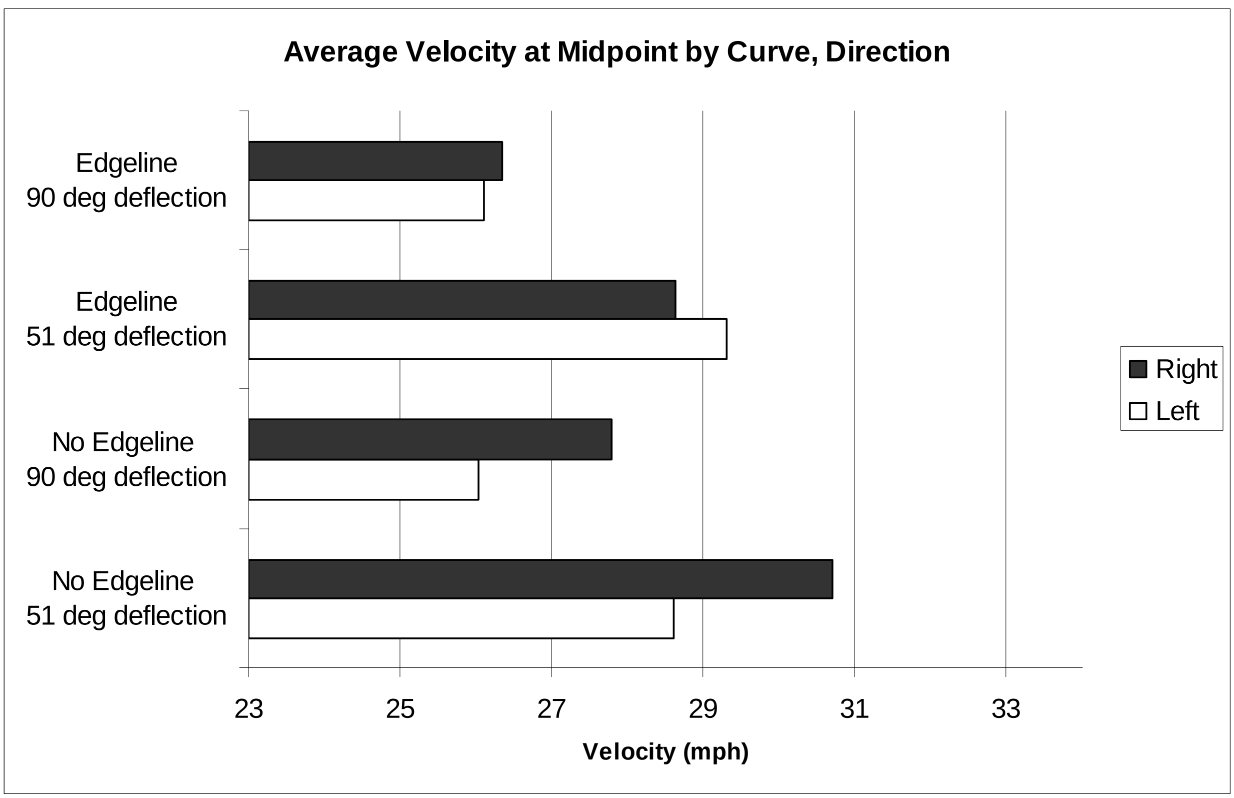

Figure 20. Average Velocity at the Midpoint by Curve, Direction.

Driver Preferences

After the participants completed their drive, they returned to the TTI office for one last task. Participants were handed five 4 in. x 6 in. color photographs each showing a nighttime view of the same test curve with each of the five treatment conditions. Participants were asked to rank these photos in order of their preference for the quality of delineation they provided and how well they defined the sharpness of the upcoming curves. Figure 21 shows the average rankings. As the figure shows, the baseline condition with no edgeline was consistently ranked the worst.

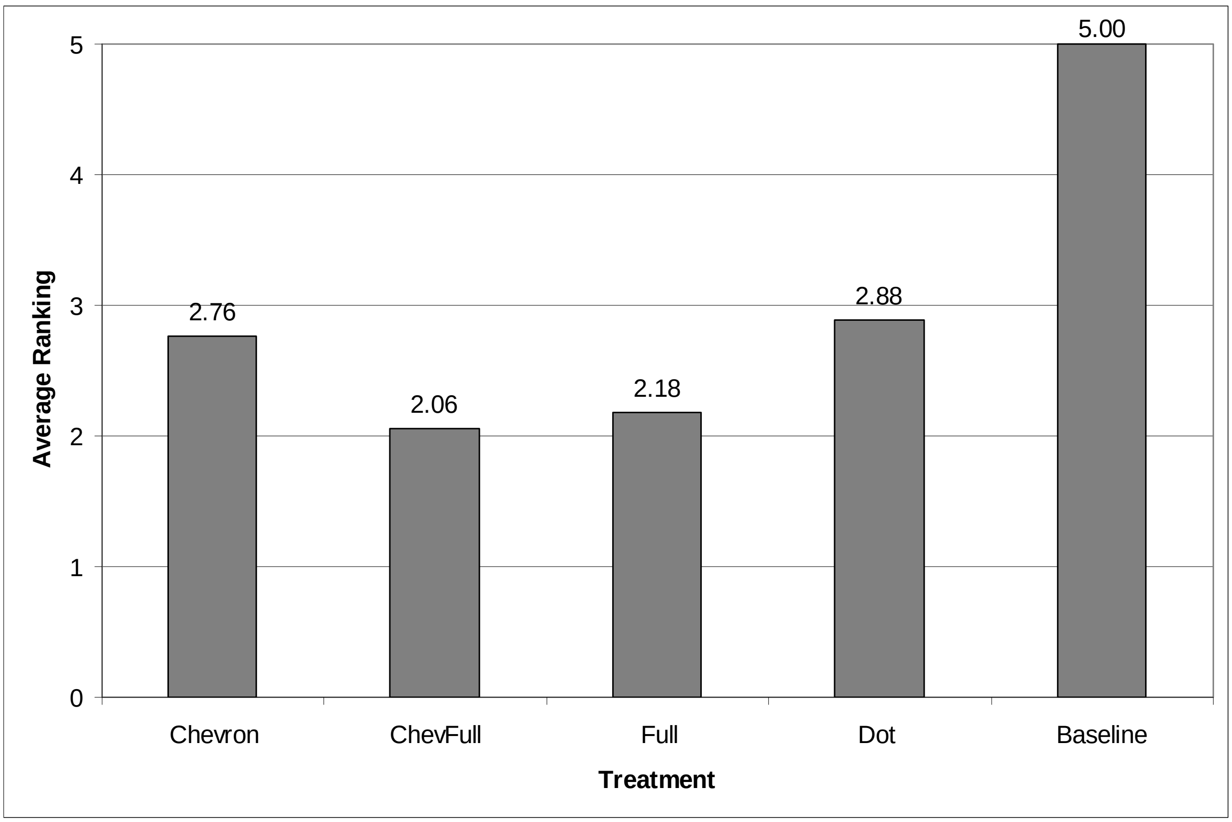

Figure 21. Average Preference Rankings for All Treatments.

DISCUSSION OF CLOSED-COURSE STUDY

The results of Task 2 showed that the fully reflectorized post-mounted delineators showed great promise as an effective delineation treatment. In addition, reflectorizing the chevron posts also provides a slight advantage over the standard chevrons, though the effect is not as strong as for the PMDs. These treatments were selected to be included in the field study (see Chapter 4).

The closed course showed consistent differences between inside (right-hand) and outside (left-hand) curves in terms of speed and curvature detection. These differences need to be considered when designing future closed-course and field studies. Care must be taken not to test one treatment in one approach direction and another treatment in another direction of the same curve. Results that are due to the direction of the curve could be misinterpreted as due to some treatment. This finding also contributed to the design of the field test reported in Chapter 4.

CHAPTER 3: DRIVER SURVEY OF CURVE PERCEPTION

This survey was a follow up to the on-road, closed-course study performed in 2007 and was completed in the spring of 2008. During the previous study, while the curve treatments were still in place, drivers were filmed including both curve radii, in both the left and right directions, and with each delineator treatment. A professional video camera mounted on the hood of the car was used for the filming, with low beam headlamps as illumination. The footage was shot from the driver's perspective at a speed of 35 mph. These video clips were then used to create a computer-based survey, aimed at obtaining responses from new participants that mimicked the data from the on-road study.

EXPERIMENTAL DESIGN AND PROCEDURE

The SuperLab™ software allows measurement of response time (in milliseconds) and keystrokes and controlled presentation of photographs, text, and video. The software will create a unique random order of presentation of test items, or can be programmed to follow a prescribed order.

Design

For this study, there were forty possible video clips to view, which would have been too long and confusing for any one participant to view. In order to shorten the experimental time, curve direction and deflection angle were fixed for each participant, who then viewed the ten delineation treatments on a particular curve. The experimental design is shown in Table 4.

Table 4. Experimental Design for Survey.

	Left Curve				Right Curve			
	45 degree deflection		90 degree deflection		45 degree deflection		90 degree deflection	
	No Edge	Edgeline	No Edge	Edgeline	No Edge	Edgeline	No Edge	Edgeline
1	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
2	Chevron	Chevron	Chevron	Chevron	Chevron	Chevron	Chevron	Chevron
3	Chevron Full	Chevron Full	Chevron Full	Chevron Full	Chevron Full	Chevron Full	Chevron Full	Chevron Full
4	Standard PMD	Standard PMD	Standard PMD	Standard PMD	Standard PMD	Standard PMD	Standard PMD	Standard PMD
5	Full PMD	Full PMD	Full PMD	Full PMD	Full PMD	Full PMD	Full PMD	Full PMD

The participants were asked to watch the videos on a laptop computer and to press the space bar as soon as they could perceive the sharpness of the curve. This question was analogous to that asked in the closed-course study where drivers indicated the same moment of judgment while driving. Also similar to the closed-course task, survey participants were asked to rate the speed at which the filming vehicle traversed the curve.

Participants

Researchers surveyed 197 participants in four total cites, two rural and two urban. The cities were Austin, Houston, Odessa, and College Station.

Demographic Questions

After reading and signing a consent form, the survey began asking each participant to enter information about them. Gender, age, how long have they been driving, their highest level of education were the questions asked. The breakdown of these questions can be found at Table 5, all of the participants reported beginning driving before age 18, the vast majority at 16. Along with providing valuable information about them, this portion of the survey allowed the participants to become more familiar and comfortable with the laptop and the interaction the survey would require. This is important to prevent operator error, especially with older participant who may be unfamiliar and/or uncomfortable using computer equipment.

Table 5. Demographic Information for Survey Participants.

	18-25	**26-59**	**60+**		
Age	29	147	21		
Gender	**Male**	**Female**	**Did not answer**		
	65	130	2		
Education Level					
Some High School	**High School Grad**	**Some College**	**College Graduate**	**Some Graduate School**	**Graduate Degree**
14	26	72	53	5	27

Survey Questions

Video Clip Response and Question

After the demographic questions, instruction was given concerning the video clips with a practice question following. The participants read the following instructions themselves from the computer screen:

> *"Here is a practice video for you to watch. While watching the video, hit the space bar when you feel you can accurately judge the sharpness of the curve. The video will play until completion and then a question and instructions will follow. Hit the Space Bar to continue. The video will start immediately"*

At this point a researcher was available to answer any questions or to clarify the instructions. They stayed with the participant and watched over them while they completed the practice task. Once the participant watched the video and gave their space bar response, the following follow-up question appeared on the screen.

"Here is a practice question. After the test videos the same question will appear. If you were driving through the turn, would you have driven

1. *A lot faster?*
2. *A little faster?*
3. *About the same?*
4. *A little slower?*
5. *A lot Slower?*

Please type your information in the box."

After completing the practice exercise and having their questions answered, the participant continued the survey and completed watching 10 similar videos with the same follow-up question as above.

Still Shot Preference Questions

After the video portion of the survey, participants viewed still shots of the different treatments (similar to Figure 6) and were asked preference questions. All five treatment options were shown on the screen simultaneously to allow side-by-side comparisons.

"Please study the following 5 pictures and note the different treatments for the roadway. Press the Space Bar to continue to the pictures. Please rate the 5 treatments for the roadway markings in the order you prefer them. Best to worst.

Example: 2 1 4 5 3 or 5 3 4 2 1"

RESULTS

The measures of effectiveness for the video clips are the time to judge the sharpness of the curve and the subjective ratings of the speed at which the curve was driven through in the video. Response times that were greater than the length of the video (typically about 30 seconds) were excluded from the data set and treated as a miss. This could have been due to momentary distraction or inattention on the part of the survey participant or equipment malfunction. Of the 1970 total response, 116 were removed due to extremely long judgment times. Table 6 shows the average response time for participants to press the space bar on the computer indicating that they had judged the sharpness of the curve shown in the video. The standard deviations are shown in Table 7. There were no statistically significant differences between the different conditions (delineation, curve direction, curve deflection angle, or edgeline presence).

Table 6. Average Time (sec) to Make Sharpness Judgments.

	Left Curve				Right Curve			
	45 degree deflection		90 degree deflection		45 degree deflection		90 degree deflection	
	No Edge	Edge	No Edge	Edge	No Edge	Edge	No Edge	Edge
Baseline	11.6	12.0	12.4	12.4	14.2	13.2	12.8	11.7
Chevron	11.2	12.0	12.5	12.2	12.8	13.0	11.1	11.0
Chevron Full	10.5	11.7	12.3	12.0	12.4	11.9	12.2	10.9
Standard PMD	12.3	11.8	13.0	12.5	13.2	13.1	12.2	11.2
Full PMD	11.3	11.8	11.7	12.1	13.1	10.1	10.8	10.8

Table 7. Standard Deviations (sec) for Response Times for Sharpness Judgments.

	Left Curve				Right Curve			
	45 degree deflection		90 degree deflection		45 degree deflection		90 degree deflection	
	No Edge	Edge	No Edge	Edge	No Edge	Edge	No Edge	Edge
Baseline	4.1	4.1	4.2	3.3	6.2	5.1	5.3	3.7
Chevron	4.9	5.0	4.9	3.2	5.1	6.6	3.5	3.4
Chevron Full	4.3	4.7	4.4	5.0	4.9	4.2	4.5	4.1
Standard PMD	5.3	5.2	4.3	3.6	6.0	6.1	5.0	2.8
Full PMD	6.3	6.4	3.8	4.9	4.8	5.9	4.7	3.9

In addition to viewing the videos, participants ranked their preference of the different treatments. The average rankings are shown in Figure 22. The baseline condition was consistently ranked worst, while the four different treatment conditions varied considerably and were not different from each other.

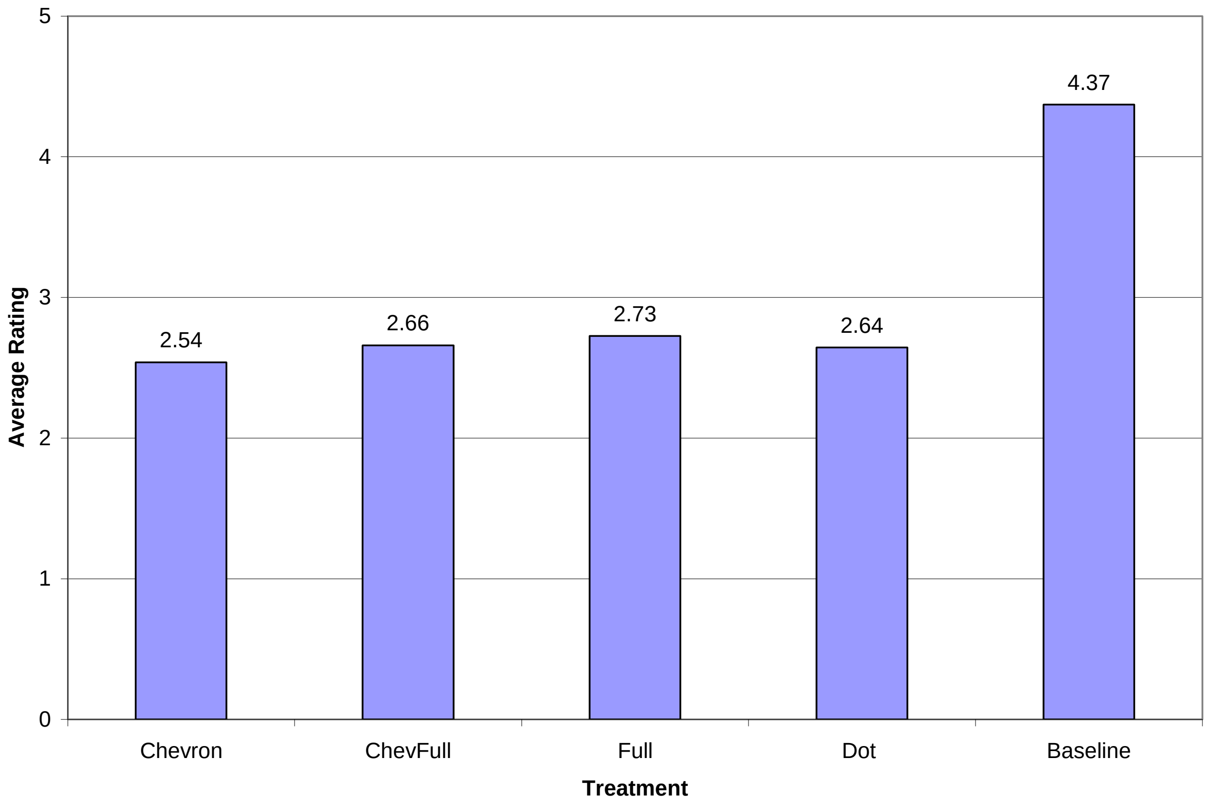

Figure 22. Average Rating of Still Photographs of Treatments (5= worst).

DISCUSSION OF SURVEY TESTING

The researchers had hoped that by filming the test track delineation treatments, data could be gathered from a wider group of drivers in cities throughout Texas. This type of survey has been used successfully for sign comprehension testing using still photos, video clips, and computer animations. Unfortunately, the results showed that the survey presentation method did not produce the same differences among delineation treatments as seen in the actual test track study. There are several reasons why this could have happened. The first is that the depth perception necessary to make curve sharpness judgments is not supported by a two-dimensional video display. Another reason is that the laptop displays were not large enough or did not provide enough contrast ratio or resolution for the participants to judge the relative size and brightness of the delineation treatments. Size and brightness are important depth perception cues and may not have been adequately rendered in the display. Future studies may wish to consider using a larger projection screen and individual response timers for this type of study.

CHAPTER 4: FIELD EVALUATION OF DELINEATION TREATMENTS ON TWO-LANE RURAL ROADS

STUDY APPROACH

The delineation treatments tested in the closed-course and survey studies were evaluated in a before-and-after field experiment at predetermined test sites which met certain criteria. Identified performance measures evaluated the effects of the treatments at the Point of Curvature (PC) and midpoint (MP) of the curve.

Safety Surrogates and Performance Measures

This study used speed and lateral placement as safety surrogates for crashes. Crash data assess the safety roadway geometric design standards, identify the effectiveness of traffic control devices, and assess the performance of vehicle operations. Improvements and enhancements can be directly observed with a reduction or decrease in crash rates or crash severity. Assembling a sufficient data set is a difficult and lengthy process due to low crash rates and vast periods between crash occurrences. Previous research studies have identified recurring crash patterns and have established certain surrogates for crashes. Surrogates are measurements of vehicle performance that have an established relationship with crash rates. They are an accepted intermediate when sufficient crash data are lacking to evaluate the incremental benefit of roadway treatments (*53*).

Measures of effectiveness for the field study were selected based on vehicle movements which are likely to cause either a run-off-the-road or head-on crash in a horizontal curve. Vehicle operations include both longitudinal components (speed) and lateral components (lateral lane position). The following advantageous measures of effectiveness for improving vehicle performance on a horizontal curve are:

- achieving desirable PC and MP lane positions,
- lowering the change in lateral position from the PC to the MP,
- lowering variance in lateral position at observed locations,
- lowering the encroachment rates,
- lowering reduction of speed between the PC and the MP of the curve, and
- lowering variance in vehicle speed.

Before-and-After Field Experiment

Treatment evaluation was determined in a before-and-after experimental design, where any performance modifications or improvements could be identified. Vehicle performance was measured at a specific site "before" the addition of the treatment in the baseline evaluation. The same site was reevaluated in an identical manner to assess the "after" effects attributed to the added treatment. The data, from the before and after analyses, were compared to identify any significant changes or improvements that are a result of the treatment. The Institute of Transportation Engineers (ITE) *Manual of Transportation Engineering Studies* (*54*) has acknowledged that before-and-after experiments are effective and practical for the following reasons:

- site-to-site variation is eliminated,
- fewer sites are necessary to draw useful conclusions, and
- results make intuitive sense and are easily understood by engineers and non-technical readers alike.

SITE SELECTION

Regional Site Selection

Site selection was a critical component to this study and was conducted through a comprehensive and systematic approach to locating ideal sites. The objective of this study was to identify effective horizontal curve delineation treatments that may be implemented throughout the State of Texas. Texas is an immensely vast state and the terrain and driver population vary greatly. If a delineation treatment was to be recommended throughout the State of Texas, then it would be necessary to select sites that differed in environmental and population characteristics. It was determined that sites near Odessa, Bryan, and Lufkin would provide sufficient regional diversity.

A preliminary list of possible horizontal curves was established by seeking the expertise of regional TxDOT and knowledgeable TTI staff about possible horizontal curves. Basic criteria for the preliminary list required the following:

- roadway shall be classified as a high-speed rural highway,
- curves shall exhibit distinctive horizontal deflection,

- curves should warrant a reduction in speed from the posted speed limit,
- curves shall be located on the TxDOT roadway system, and
- curves should yield volumes of approximately 1,000 vehicles per day.

There were 170 curves near Bryan, 70 curves near Lufkin, and 43 near Odessa that were identified as possible candidates. Roadway information was solicited and curves were documented on a regional map. TTI personnel visited each potential site and digitally filmed each curve. Geometric characteristics, traffic control devices, roadway features, and other attributes were documented and compiled into a spreadsheet.

Site Selection Criteria

Based on allocated resources and the project schedule, it was decided that 2 sites near Bryan, 2 sites near Lufkin, and 1 site in Odessa would be selected for the field study. The size of the potential horizontal curve list needed to be reduced to attain the five study curves. Site selection criteria were determined to systematically eliminate any curves that exhibited undesirable traits that would jeopardize or negatively compromise the results of the experiment. The list was generated through comprehensive deliberation and verified through engineering judgment. The site selection criteria were that chosen curves:

- shall have edgeline, centerline, and a total travel width greater than 20 feet,
- shall have Curve Warning (W1-1 or W1-2) and Advisory Speed signs (W13-1),
- shall have identical posted speed limits on both approaches,
- should have minimal interference from intersecting roadways or driveways,
- should all exhibit similar roadway geometry and design characteristics,
- should exhibit a curve length greater than 200 feet from tangent to tangent,
- should have minimal vertical deflection,
- should not be a part of a series of connected curves and have signed with Reverse Curves (W1-3), Reverse Turn (W1-4) ,or Winding Road (W1-5),
- shall be rejected if obstacles, guardrail, construction, railroad crossing, or other objects are deemed likely to influence vehicle performance,
- should be avoided if preexisting delineation devices are presently installed, and
- shall present the ability to safely install and maintain delineation treatment and data collection equipment.

The list of possible curve candidates was reduced to 39 curves near Bryan, 23 curves near Lufkin, and 15 curves near Odessa. The curve film was reviewed and curves that did not meet the site selection criteria were rejected. The remaining curves were located through geographic information system (GIS) software. Distance measuring capabilities were utilized to estimate linear distances between two points. Curve length and deflection angle were approximated by visually identifying the locations of the point of curvature (PC) and the point of tangent (PT). An estimate of the curve radius could then be derived from fundamental circular curve equations.

Curve candidates with comparable curve lengths, radii, and deflection angles were grouped together. The purpose was to select curves with similar or comparable geometry. It was not an objective to isolate curves with exact or identical geometric measurements. Selecting comparable curves was a step to minimize uncertainty and strength the validity of the results by avoiding curves that differed drastically. A site-to-site direct comparison not an objective, but it was desirable to differentiate major differences in treatment between sites. Radius was the most critical geometric parameter used site grouping and selection. Curves were also classified based on similar posted speed limit and the advisory curve speed. The curve film was once more reviewed and examined. The advantages and disadvantages of each curve were identified. After much deliberate and thorough consideration, sites were selected.

Selected Sites

Two sites near Bryan, two sites near Lufkin, and one site near Odessa were selected. Selected curves complied with the site selection criteria and were deemed to exhibit comparable geometric design. The Bryan sites were located on FM 974 and FM 50, and the Lufkin sites both were located on FM 1818. Data collection was attempted twice at the Odessa site, but was abandoned after consultation with the project director due to bad weather and equipment malfunctions.

All selected curves employed centerline, edgeline, and RPM and there was no existing vertical delineation, such as PMD or chevrons. All tangent distances on both curve approaches were deemed sufficient in length for vehicles to approach the curves at or near the posted speed limit. All curves were in the vicinity of intersecting driveways and/or roadways. The nearby driveways and/or roadways were reasoned to produce negligible affects. Pertinent selected curve data are contained in Table 8 and other relevant information is contained in Appendix B.

Table 8. Selected Curve Characteristics.

Selected Sites	Name	Deflection (degrees)	Radius (ft)	Length (ft)	Speed Limit	Advisory Speed	Surrounding Terrain
FM 974	Site 1	37.5	1071	701	70	45	Wooded & Ranchland
FM 50	Site 2	45	1238	972	70	50	Open Farmland
FM 1818 CV1	Site 3	89	642	997	55	40	Dense Woods
FM 1818 CV2	Site 4	88	607	932	55	35	Dense Woods

DELINEATION TREATMENTS AND APPLICATIONS

Evaluating vertical delineation was the main focus of the field study. Centerline, edgeline, and RPMs were already in place at all of the selected curves. Existing longitudinal pavement markings were not changed or modified for this study. The unconventional or experimental component for this study involved modifying or increasing the amount of retroreflective material that is applied to both chevrons and PMD treatments. These enhancements had shown promise in the closed-course study reported in Chapter 2. Standard PMD utilizes retroreflective material at the top of the devices that measures 3 inches in width and 4 inches in length (*55*). The experimental treatment that was evaluated involved applying retroreflective material along the entire length of the PMD from top to bottom and on both sides. The second experimental treatment involved applying supplemental retroreflective material to the sign post of a standard chevron sign. Yellow retroreflective material would encircle the circumference of a circular sign post and extend from the bottom of the chevron sign to the ground.

Treatment Assignment

At all of the selected curves, the before or baseline evaluation measured vehicle performance when there were no modifications or additional delineation added to the site. Delineation treatments were then installed and data were collected in the after evaluation. The PMD treatments were evaluated at the Lufkin curves and the chevron treatments were evaluated at the Bryan curves. The reasoning for the treatment assignments was based on speed reduction, curve geometry, and curve location. The chevron treatments would be employed at the curves with the highest posted speed limit and greatest differential speed reduction, and this occurred at both Bryan sites. Both the corresponding Bryan and Lufkin curves were more comparable in geometry. It was rationalized that the similar delineation treatments should be placed on curves with similar geometry. It was also reasoned that installing one type of delineation treatment on the FM 1818 curves would be prudent since they are in sequential series.

It was feasible to conduct an additional "after-after" evaluation for the chevron treatments at the Bryan curves. Both standard chevrons and the experimental chevrons with fully retroreflective posts were evaluated at Site 1 and Site 2. Employing both types of chevron treatments at each curve site would allow for the direct comparison between treatments. This would minimize uncertainty when comparing the effects of the treatments. The additional after-after evaluation was only conducted at the Bryan curves and not for the Lufkin sites. The chevron treatment after-after evaluation was feasible because of the minimal travel time to the sites, the nominal cost of materials and labor, and availability of the data collection equipment. The PMD with full length retroreflective post were designated as Full PMD and the PMD with the standard retroreflective application were designated as Dot PMD. In a similar fashion, chevrons with fully retroreflective posts were designated as ChevFull. A matrix of the treatment analyses are contained in Table 9.

Table 9. Delineation Treatment Matrix.

Selected Sites	Name	Before	After	After - After
FM 974	Site 1	Baseline	ChevFull	Chevrons
FM 50	Site 2	Baseline	Chevrons	ChevFull
FM 1818 CV1	Site 3	Baseline	Dot PMD	N/A
FM 1818 CV2	Site 4	Baseline	Full PMD	N/A

Treatment Materials and Equipment

All materials and equipment utilized for this evaluation were in accordance and complied with TxDOT and MUTCD standards. All materials and equipment were deemed to be suitable and appropriate by TxDOT staff and TTI researchers before they were implemented in the field. Types, models, and brands of materials and equipment were obtained impartially and reflected what is currently used in the State of Texas.

The standard chevron assembly was comprised of the sign face and the post system. The dimensions of the W1-8 chevrons sign were 24 inches in width by 30 inches in height, which is the required size for a high speed conventional road (*56*). The sign was composed of aluminum construct and diamond grade fluorescent yellow retroreflective sheeting. A wedge anchor assembly was used as the post system. This was specified by the TxDOT district maintenance as their preferred choice. TxDOT district offices would assume responsibilities and upkeep of the signs following the completion of the study and it was necessary that all materials meet their specifications. Chevron signs were mounted back-to-back on one sign post. Signs were attached to the post with square head sign bolts and angled towards the direction of an oncoming vehicle. All chevrons signs had a maximum height of 6.5 feet, which is the regulation height for a wedge anchor post and measured from the top of the sign to the ground.

The retroreflective material for the ChevFull treatment was microprismatic flexible fluorescent yellow sheeting (Texas Type C). The sheeting was applied to a section of PVC pipe that consisted of a 2.5-inch diameter and 4-foot length. The retroreflective PVC pipe was then placed over the 2 ⅜ inch sign post. The retroreflective PVC pipe would then cover the entire sign post from bottom of the sign to the ground. Justification for applying the retroreflective material to PVC pipe and not directly to the sign post was because removing the sheeting would damage the appearance of the post. The retroreflective PVC pipe also proved to be very efficient and economical for changing between chevron treatments.

The PMD treatments were composed of white flexible thermosetting composite material (purchased from Carsonite ™). White high-intensity retroreflective sheeting was used as the applied sheeting. The PMD had a width of 3.75 inches and a length of 6.6 feet. The standard application of retroreflective sheeting, 3 inches in width and 4 inches in length (*55*), was applied to the Dot PMD treatment. The Full PMD treatment sheeting measured 3 inches in width and 4 feet in length. Retroreflective sheeting was applied on both sides of the PMD treatments. An anchor system was attached to all PMD to ensure durability and longevity.

Treatment Placement

All treatments and devices were installed in accordance with TxDOT and MUTCD standards and under the supervision of TxDOT staff. Spacing for the locations of chevrons and PMD were based on the Roadway Delineation section of the Texas MUTCD (*57*). Spacing could be derived from either length of horizontal curve radius or curve advisory speed sign. Spacing for all sites was generated from both radii and advisory speed signs. Calculated values were rounded up to the nearest integer and the more conservative and smaller spacing distance was selected for each site.

Treatment lateral offset from the roadway edge was based on TxDOT and MUTCD standards. The chevrons were located 12 feet from the roadway travel lane to the nearest part of the sign (*57*). PMD were allowed to be located between 2 to 8 feet off the edge of pavement and PMD were installed 4 feet off the edge of pavement at Site 3 and Site 4. Devices were placed to minimize conflicts with driveways, vegetation, and objects. When conflicts arose, devices were placed in the manner that avoided conflict and minimized inconsistencies with overall device spacing. The total number of devices installed was 7 chevrons on Site 1, 9 chevrons on Site 2, 22 PMD on Site 3, 23 PMD on Site 4.

DATA COLLECTION AND ANALYSIS

Collection Locations

Speed and lateral position data were collected at each site so that the delineation treatments could be evaluated based on the measures of effectiveness. It was determined that treatments could be evaluated sufficiently by collecting data at two primary locations and at one secondary location. The tangent speed of a vehicle was measured at the Curve Warning Sign before the vehicle enters the curve. The curve warning sign location was selected because the sign was present on all upstream curve approaches and would provided a fixed object to secure equipment. These sign locations were not hindered or obstructed by objects or access points. The distance from the curve warning sign to the PC varied at all sites. The tangent speed served as a reference in the before-and-after experimental design. The tangent speed assessed if vehicle speeds were drastically altered between collection periods from an outside influence other than the experimental treatment. Questionable or problematic curve data would be referenced and likely clarified by the tangent speed data. The tangent speed is not intended to be used as a control speed where any alternation in speed analyzed and used in the final evaluation. The curve warning sign speed is meant to serve as a reference that may help to explain or clarify any uncertainty in the curve data.

The two primary locations where speed and lateral position were collected were at the PC and the MP of each site. Curve deceleration profiles have shown that vehicles decelerate on the tangent approach and continue slowing after the PC (*58*). While in the curve, a vehicle will usually decelerate to a comfortable or preferred speed. The selected curve speed will then be maintained throughout the curve until the vehicle can accelerate on the exiting tangent (*58*). It has also been identified that the majority of crashes are attributed to differential speed reduction from tangent speed to curve negotiation speed (*59*). The curve entrance, where the reduction in speed is required, is more critical than the approach tangent or exiting half of the curve. The PC and the MP data collection locations were selected because they are points easily referenced, they provide uniform locations at all sites, they have functioned well in past research (*15*), and they were recommended as ideal locations by follow TTI researchers. Data were collected on both curve approaches. A diagram of data collection locations is shown in Figure 23.

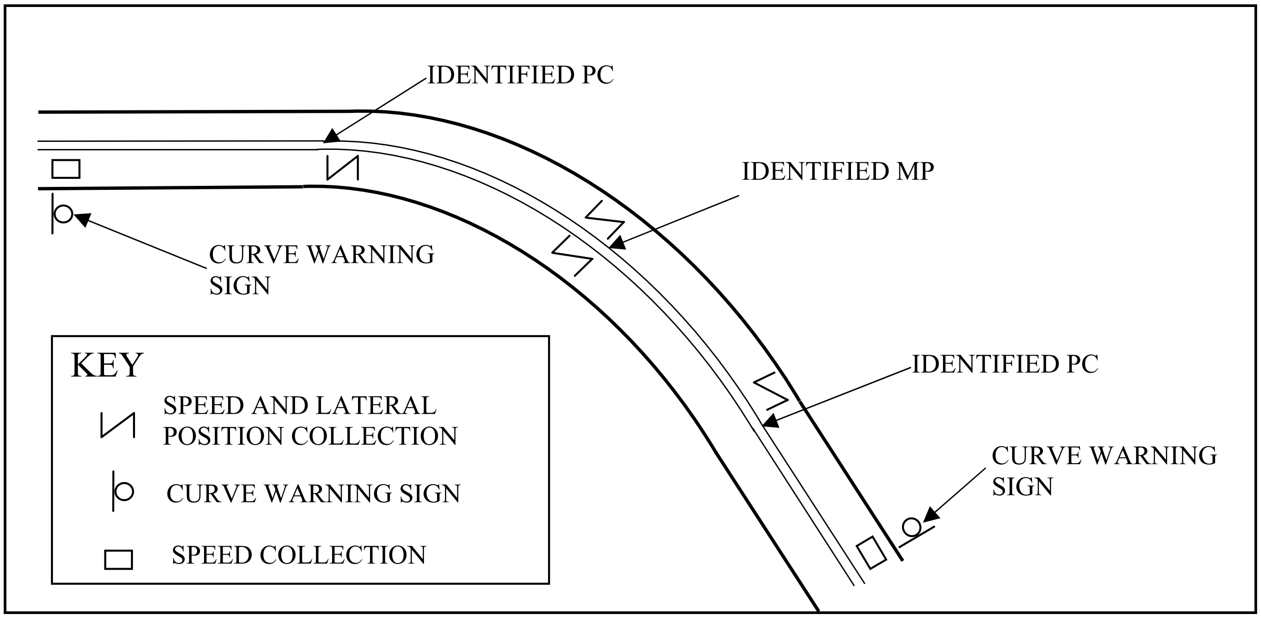

Figure 23. Data Collection Location Diagram.

Data Collection Equipment

Traffic classifiers were utilized for collection of all speed and lateral position data. A traffic classifier detects the presence of a passing vehicle and stores the information with an exact time stamp. The time stamp orders the detected vehicles in a chronological sequence at an accuracy of one-thousandth of a second. At the curve warning sign, two pneumatic tube traffic sensors were attached to one traffic classifier. The traffic classifier detects a passing vehicle when a vehicle's tires compress the tube, which then sends a pulse of air to the traffic classifier where it is registered. The tubes are secured to the roadway surface in a parallel series and are placed precisely eight feet apart. The traffic classifier generates vehicle speed from the time it takes a vehicle to travel across the known distance of both tubes.

The speed and lateral position data collected at the PC and the MP were obtained in a similar manner, but with a different roadway sensor layout. The layout for collecting lateral position data are referred to as the Z-configuration because the layout employs three piezoelectric sensors positioned in a pattern that resembles the letter "Z." Piezoelectric sensors are thin metallic wire sensors that detects the tire pressure of a passing vehicle. The Z-configuration layout is depicted in Figure 24. The piezoelectric sensors are secured to the roadway at precise distances. Vehicle speed is derived from the two parallel sensors. The lateral position of the vehicle is calculated from known geometric proportions of a right triangle, vehicle speed, and sensor time stamps. The longitudinal position, the x-component where a vehicle's right tire touched the diagonal sensor, is determined from the vehicle's speed and the travel time from the first sensor to the diagonal sensor. The latitudinal position, the y-component of the right tire to the diagonal, is derived from known geometric proportions of the Z-configuration.

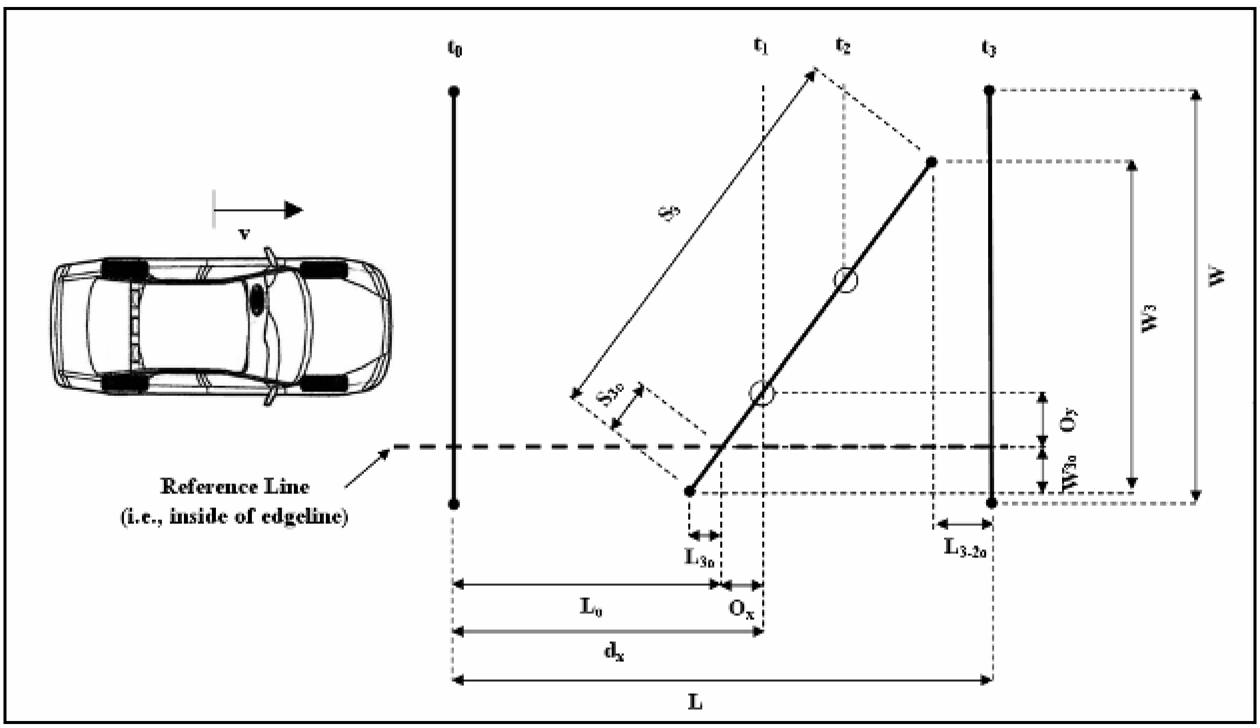

Figure 24. Z-Configuration Layout.

Data Collection Schedule

The data collection schedule was based on the following basic format:

- collect baseline data for the before evaluation,
- install horizontal curve delineation devices,
- allow for a minimum 10-day acclimation period to allow the novelty or surprise affects of the new treatment to subside,
- collect data for the after evaluation in an identical manner as in the before evaluation, and
- switch chevron treatments and repeat the 10-day acclimation period before collecting the after-after evaluation if applicable.

Weather and the availability of the equipment dictated the schedule for the data collection process. The dates when the equipment was placed and retrieved for each evaluation period are contained in Table 10. Equipment was installed for three to six whole days. The minimum collection period of three whole weekdays was expected to provide at least 100 functioning vehicle data points for each evaluation at all sites. The minimum number of 100 data points was deemed an acceptable sample size. Data collection analyses that include weekend dates were a result of TTI staff availability to place equipment late in the work week. Weekend vehicle data remained in the overall data set and was not analyzed separately or removed. Weekend traffic characteristics may vary slightly from the weekday traffic, but researchers are interested in the treatments effects at all times and not just during weekday conditions.

All before data collection periods were conducted in late fall of 2007. The data collection was initiated in the late fall immediately following the completion of the site selection process. The after data collection periods were resumed in early spring because the piezoelectric sensors are problematic and unreliable to install in cold temperatures. The sensors are secured to the roadway with adhesive packet tape. If the temperature is too low, then the glue on the tape will not adhere to the road properly. A loose sensor that did not stick properly could damage equipment or create a roadway hazard. For this reason, it was decided to discontinue the data collection in the fall and resume in the spring.

Table 10. Data Collection Dates.

Analysis Scenario	Before Analysis		After Analysis	After-After Analysis
	First Attempt	Second Attempt	First Attempt	First Attempt
Site 1	10/18/07 - 10/26/07	N/A	5/20/08 - 5/23/08	6/20/08 - 6/25/08
Site 2	10/23/07 - 10/30/07	N/A	5/27/08 - 5/30/08	6/30/08 - 7/3/08
Site 3	11/2/07 - 11/8/07	N/A	6/12/08 - 6/18/08	N/A
Site 4	11/2/07 - 11/8/07	N/A	6/12/08 - 6/18/08	N/A

Equipment in the field was checked and monitored periodically to ensure credible data. Weather, the amount of daylight, and site conditions were recorded at all collection periods.

Data Processing

After the equipment was removed from the roadway, the vehicle data from the traffic classifiers were transferred onto a computer. Specialized software was utilized to download the raw vehicle data. The speed data at the curve warning sign were processed and the software was able to generate the vehicle's speed, classification, number of axles, length, and headway. The software preformed all of the raw data processing. Very little manual modifications needed to be done to obtain usable and working speed data. The data were transferred to a spreadsheet for further screening and formatting.

Obtaining lateral position data are not common in the transportation profession and is almost limited exclusively to research applications. Commercial software had limited capabilities and much of the processing of the raw lateral position data were accomplished by internal means. The basic time stamp data from the three sensors was transferred into a spreadsheet and processed with a customized macro. The macro was able to distinguish a vehicle passing along all three sensors. Lateral position could then be calculated from the vehicle's speed and travel time. At this point the data were still unusable and required further manual processing. Erroneous data which the macro was unable to detect was removed from the spreadsheet. Vehicles with a speed of zero mph, an impossible axle spacing, or a lateral position greater than the length of the sensor are examples of erroneous and removed data.

Preliminary Data Screening

The speed and lateral position data were screened to identify uninhibited passenger vehicles (i.e. excluding agricultural vehicles). The purpose of the screening process was to isolate the effects of the treatments on the passenger vehicles and to eliminate or minimize potential bias and unwanted outside influences.

Minimum Headway

All free-flow vehicles were identified. A driver traveling behind a slower moving vehicle may not be traveling at his or her preferred speed. Their speed selection is determined by the vehicle ahead of them and not from the driver's acceptable risk level derived from the roadway environment. A driver at night may also react differently to a treatment when there are vehicle headlights behind them or vehicle brake lights in front of them. It is necessary to evaluate only free-flowing uninhibited vehicles that are not greatly influenced by a vehicle ahead or behind them.

The screening was achieved by removing any two vehicles that had a headway of 6 seconds or less between them. Headway is the time between two vehicles to sequentially pass over one point. It was identified in a previous study that vehicle speeds in a work zone were significantly different when there was a minimum headway of 4 seconds between vehicles (*60*). A minimum headway of 3 to 5 seconds was deemed acceptable by several highly experienced TTI researchers. A conservative minimum headway of 7 seconds was selected. The 7 seconds of headway was also utilized in a previous study and was judged to be appropriate (*15*).

Vehicle Type

Heavy vehicles were separated from the passenger vehicles and both vehicle types were evaluated independently. The vehicle performance of heavy vehicles and passenger vehicles typically differ. Selected sites also exhibit varying rates of heavy vehicle traffic. Analyzing the treatment effects on passenger vehicles was the main focus of the study and it was critical that the vehicle types were separated and evaluated independently. The separation was achieved by identifying vehicles with more than two axles or vehicles with a single axle spacing greater than 15 feet in length. The criteria were derived from the Scheme "F" Chart (*61*) and the AASTHO Greenbook (*62*).

Time Classification

Data for both passenger vehicles and heavy vehicles were grouped into three different time classifications, which included overall, night, and day. The overall time data were comprised of all vehicle data, which included both night and day volumes. The night data referred to the hours that were devoid of natural sunlight and the day data consisted of hours with ample sunlight. Data were collected at different times of the year that yielded varying durations of sunlight. The times of sunrise and sunset for each data collection period are contained in Table 11. The times in the table are averages while the equipment was implemented in the field. Sunlight hours were obtained from the National Oceanic and Atmospheric Administration's National Weather Service website (*63*). Table 11 displays two different hours for the sunrise and sunset in the before analysis at Site 3 and Site 4. The two values are a result of collecting data at the end of the daylight savings period, where clocks were set back one hour. The time change was recorded and remembered when formatting the data at Site 3 and Site 4.

Table 11. Average Times of Sunrise and Sunset.

Site	Before Analysis		After Analysis		After-After Analysis	
	Sunrise	Sunset	Sunrise	Sunset	Sunrise	Sunset
Site 1	7:32 AM	6:47 PM	6:27 AM	8:17 PM	6:24 AM	8:31 PM
Site 2	7:35 AM	6:42 PM	6:24 AM	8:21 PM	6:27 AM	8:32 PM
Site 3	7:35 AM / 6:36 AM	6:29 PM / 5:26 PM	6:14 AM	8:24 PM	N/A	N/A
Site 4	7:35 AM / 6:36 AM	6:29 PM / 5:26 PM	6:14 AM	8:24 PM	N/A	N/A

Uniform analysis periods were established for the night data. A uniform night period would ensure that the data in the before analysis, which was collected during early sunrise and early sunset, does not contain work commuters or peak hour volumes. Work commuters are typical of the day period and results may be fouled if the before night data includes work commuters and the after night data does not include them. A regular and uniform night period was established between the hours of 9:00 PM to 6:00 AM for all night data evaluations. The night hours were based on the earliest sunrise and latest sunset. The times were then rounded to the nearest half an hour, up for sunset and down for sunrise, to minimize vehicles counted during twilight.

Uniform analysis hours were not established for the day period. For the day analysis, the before evaluation in the fall had a much earlier sunset than the spring data collection. Uniform hours for the day period would limit vehicle data between the hours of 8:00 AM to 5:00 PM. Uniform hours would eliminate a great deal of valuable vehicle data in the spring analyses. It was reasoned to be needless and imprudent to ignore important peak hour volumes between the hours of 5:00 PM to 8:00 PM during the spring. A small sample of vehicle data also proved that vehicle performance between the hours of 5:00 PM to 8:00 PM was not statistically different from the values obtained from 8:00 AM to 5:00 PM. The daylight hours for each individual analysis were set by their corresponding sunrise and sunset times. Times were rounded to the nearest half an hour, up for sunrise and down for sunset, to minimize vehicles counted during twilight.

Functional Data Formatting

Vehicle data were arranged in working lists according to category and analysis method. The compiled and formatted speed and lateral position data lists allowed vital and functioning information to be extracted for final evaluation. Lists include categories for vehicle type and time period. Basic descriptive statistics of means and standard deviations were generated from each list. Data were assembled into comparative histograms and working tables. .

Encroachments

Encroachment percentages of passenger vehicles were obtained for the overall, night, and day periods. Encroachments occurred when the outside edge of a vehicle's tire intruded upon a regulatory pavement marking such as a white edgeline or a yellow centerline. The encroachment data were expressed as a percentage of encroachments out of the total number of observed vehicles.

Edgeline encroachments were easily established since lateral position measures were collected from the outside edge of a vehicle's right tire. Edgeline encroachments were obtained from the lateral position of a vehicle and the measured lane lengths. The centerline encroachments were not as straightforward since individual spacing between the tires, or the track width, was unknown. Centerline encroachments were approximated by assigning an 80 and 61-inch track width to all vehicles and determining the possible number of encroachments based on those two track widths.

The 80-inch track width was the maximum value from a list of 45 common large commercial passenger vehicles, such as a SUV, van, or truck. The data were obtained in 2006 from the manufactures' website. It was reasoned that a larger and more conservative track width would account for the majority of the possible centerline encroachments. Any beneficial reduction in centerline encroachments, attributed to the treatments, would not be missed or overlooked due to the larger track width. If the treatments decrease encroachment rates for a wider vehicle, then it will decrease the rates for vehicles with a narrower track width.

The 61-inch vehicle width was derived as the average track width of 14 common and top selling mid-size passenger vehicles, such as a Toyota Camry, Honda Accord, and Ford Taurus. All vehicles were 2008 models and data were acquired from the manufactures' website. The average 61-inch track width portrays the possible centerline encroachments of the average mid-size passenger vehicle. Maximum and average track widths provide a sufficient representation of possible centerline encroachments.

Vehicle Tracking

Individual vehicles were tracked from the PC to the MP. The vehicle tracking was performed for all sites, analysis time periods, and vehicle types. The data provide an exact account of how a single vehicle changes their performance from the PC to the MP. This is a more accurate method for assessing change in speed and lateral position than by simply comparing the means from the PC and the MP locations.

Individual vehicle tracking data were generated by matching vehicle characteristics from the PC and MP data lists. All pertinent information was assembled into one spreadsheet. The time stamps of vehicles were aligned as close as possible. The traffic classifiers were plagued with clock drift and some of the internal clocks passed at different rates. This was not a concern with the accuracy of speed or lateral position data, but it was a factor in the vehicle tracking. Time stamps from different traffic classifiers could differ by approximately 10 to 25 seconds by the end of the data collection period. Individual vehicles were tracked through the curve by matching vehicle characteristics from the PC and the MP. The characteristics included axle spacing, the number of axles, and vehicle classification. Corresponding vehicle data were then validated by checking the headway between sequential vehicles and travel time from the PC to the MP. Vehicle data that were not found at the PC and the MP was removed from the spreadsheet. Vehicle data with partially matching or questionable data were also removed. The means and standard deviations were generated from the final vehicle tracking lists. The overall vehicle change in speed and lateral position was obtained with the following equation:

$$\Delta = X_{MP} - X_{PC}$$

Where:

X_{MP} = single speed or lateral position data point from the MP and

X_{PC} = single speed or lateral position data point from the PC.

Analysis Methods

The vehicle performance data were statistically analyzed following the comprehensive screening and formatting process. Statistically analysis techniques were used to determine if the delineation treatments produced a significantly difference in vehicle performance. The statistical methods utilized in the study helped to provide legitimacy and validity to the findings.

Analysis of Variance (ANOVA)

The Univariate ANOVA test was used to test for significant differences in speed and lateral position data. The multifactor ANOVA tests for the differences between mean values of multiple populations as a function of independent variables and interactions between the independent variables (*64*). The dependent variables were speed and lateral position and the independent variables were:

- site (Site 1, Site 2, Site 3, or Site 4),
- location (PC or MP),
- curve direction (right-handed curve (inside) or left-handed curve (outside))
- time (night or day)
- vehicle type (passenger vehicle or heavy vehicle), and
- treatments (baseline, chevrons, ChevFull, Dot PMD, or Full PMD).

A confidence interval of 95 percent was used to test for significance. If the test produced a P-value less than 0.05 or 5 percent, then the main effects of the independent variables or variable interactions were considered significant. The P-value indicates the probability of concluding significance.

Models were developed from the main effects of the independent variables and interaction between variables. The variable interactions were selected based on relevance to the objective of the study. Variables or interactions that were perceived as unrelated or not having a meaningful relationship were excluded. All model inputs were deemed pertinent and each variable or interaction can be rationalized.

Two-Sample T-test

The independent two-sample T-test compared the means for both speed and lateral position to assess the effects of the treatments. A confidence interval of 95 percent and a value of ± 1.96 were used to test for significance in a two-tailed test.

Z-test of Proportions

The Z-test was utilized to test for significant differences in proportions (percentages or rates) of two samples. The test determined if there was a significant difference in the percentages of encroachments when the treatments were implemented. A confidence interval of 95 percent and a value of ± 1.96 were used to test for significance in a two-tailed test.

F-test

The F-test was used to test for significant differences in the variance of two samples. The F-test assessed if the standard deviations of the speed and lateral position were significantly different. A confidence interval of 95 percent was used to test for significance. The test value of 1.25 was used to determine significance. It was determined that the test value of 1.25 was appropriate and conservative. Two standard deviations were considered significantly different if the F-test results were greater than 1.25 or less than 0.8 (the reciprocal of 1.25).

Normality of Data

All tests utilized in this study are prescribed for normally distributed data. The normal distribution occurs when the frequency of the data follows a symmetric bell shaped curve (*6564*). The speed and lateral position data were assessed to determine if the data were normally distributed. Analysis of data normality was tested with the One-Sample Kolmogorov-Smirnov (K-S) Test. Data were also visually inspected through Histograms and Q-Q Plots. The normality analysis initially started with the entire set of 62,348 data points. This analysis was then narrowed to assess each site and specific curve location. The results showed that the speed and lateral data were not normally distributed. Histograms of the entire data set are shown in Figure 25. The figures show the frequency of each data point value. The Q-Q plots are contained in Figure 26 and compare the observed values to the normal distributed expected values.

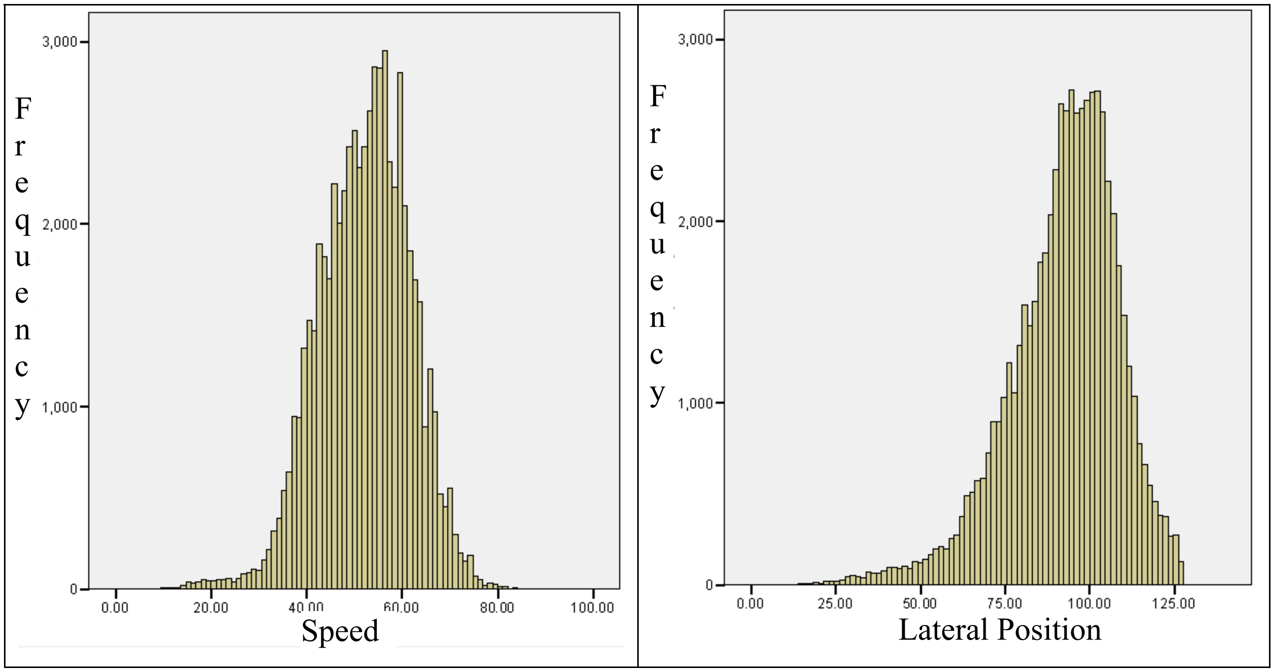

Figure 25. Histograms of All Speed and Lateral Position Data.

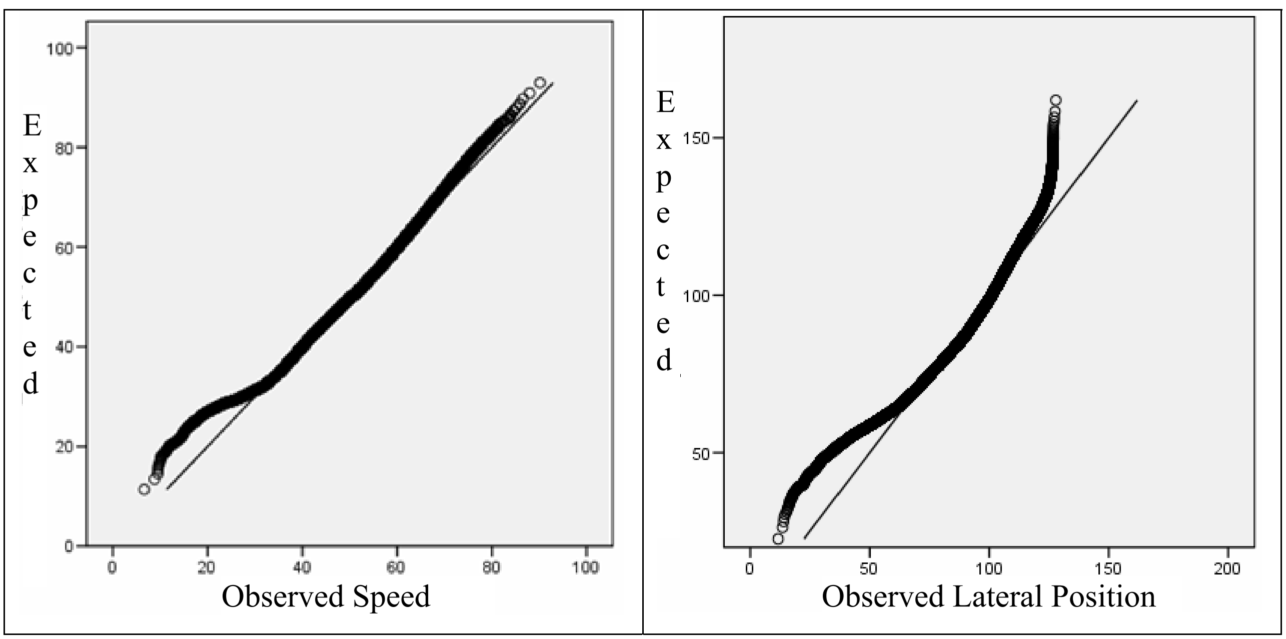

Figure 26. Q-Q Plots of Entire Speed and Lateral Position Data Set.

The speed data in the histogram resembles a normal distribution, but the K-S test confirmed that the data were not normally distributed. A closer examination at the speed Q-Q plot reveals that the data deviates from the normal distribution around the speeds of 10 to 30 mph. The speed data has a long-tail or greater frequency to the left of the mean in the extreme cases. The speed data may also exhibit kurtosis traits or extreme peaks that are uncharacteristic of normally distributed data.

The K-S test also verified that the lateral position data were not normally distributed. The histogram depicts that the lateral position data has a long-tail to the left of the mean. Also, the data abruptly stops around 125 inches in Figure 25 instead of continuously decreasing. The characteristics of lateral position distribution were not surprising. The end of pavement on the shoulder and length of the sensor explains the abrupt termination of data around 125 inches. The long-tail to the left is a result of vehicles encroaching onto the centerline and into opposing lane.

Non-normal distributed data could be remedied in two possible methods. The first method involves manipulation of the data to transform it into a normal distribution. An example of data manipulation would entail using the natural logarithmic or exponential functions to alter the data. The results and figures would then also need to be expressed in terms of the functions used for transformation, which is not desirable. The second method would be segmenting the data in groups that exhibit normal distribution characteristics. Separating the curve location data into many different sub-groups would be a tedious and laborious process. The segmenting method was performed on lateral position data in a previous study (*66*). The results in that study determined that the T-test produced approximately the same values for the segmented data as there were for the unaltered non-normal distribution data. The study concluded that "the independent sampled T-test is robust enough to accurately draw statistical conclusions from the data, even with the departure from the normal distribution ."

Therefore, the collected non-normally distributed speed and lateral position data will remain unaltered for the statistical analysis. The tests employed were robust and the sample size is sufficient to achieve acceptable results without manipulating or further segmenting the data to obtain a normal distribution.

Sample Size

Sample size varied between site and data collection periods. Table 12 contains the number of passenger vehicles for the overall period in each data collection period. The variation in sample size is due to the differing traffic volumes at each site, duration of data collection periods, and rejection rate of invalid data attributed to traffic classifier error. It was a study objective to obtain a sample size of 100 or more working data points for each evaluation. The sample size goal was achieved during all data collection periods. Overall samples were deemed sufficient in size to produce reliable and accurate non-normally distributed results.

Table 12. Overall Sample Size Summary.

Curve Location	Inside		Outside		Inside		Outside	
	PC	MP	PC	MP	PC	MP	PC	MP
Sites	**Site 1**				**Site 2**			
Baseline	2673	2948	3155	3063	2590	2401	2570	2389
Chevrons	1848	1769	1831	1790	1016	1061	1058	1051
ChevFull	1193	1151	1005	1134	913	908	944	928
Sites	**Site 3**				**Site 4**			
Baseline	1160	1006	1048	946	312	982	1030	857
PMD	1038	988	999	949	896	907	965	891

RESULTS FOR CHEVRON TREATMENTS

This section describes the statistically findings from the baseline and treatment evaluations. The chevron treatment findings will be introduced first and then followed by the PMD treatments findings. Results of lateral position, encroachment, and speed analysis will be presented in sequential order. The findings from each category will initially start broad and then the focus of the evaluation will narrow to describe treatment impacts on curve direction and individual curve location. Chevron and the ChevFull treatments results will be directly compared since both treatments were implemented at the same sites. The findings of the PMD treatments will be assessed independently since Dot PMD and Full PMD were not installed at the same site.

Lateral Position at PC and MP

In general, both the chevrons and the ChevFull treatment produced beneficial results and promoted ideal vehicle operations when measured in aggregate comparing all PC data to all MP data. Individual vehicle lane tracking is presented in the next section. The findings from both chevron treatments were very similar and one treatment was not significantly advantageous compared to the other treatment.

This section examines two types of lateral position data. The first type is directional curve data, where vehicle movement within the lane from the PC to the MP for inside and outside curve directions will be analyzed. The second type of data involves the individual curve locations such as the PC and MP. This section will initially start broad with the curve directions and then the focus will narrow to the individual curve locations.

The curve direction analysis provides insight into driver behavior on a curve and the effects of the chevrons treatments. Figure 27 depicts the mean lateral position of the outside edge of the right tire from the centerline at both the PC and MP locations. The mean lateral position in the figure is a weighted average of values from Site 1 and Site 2 in the corresponding curve direction. The lines in the figure represent vehicles movement within their lane while traveling longitudinally from the PC to the MP of the curve. The baseline evaluation confirms the curve cutting strategy identified in the literature review. Vehicles traveling on an inside curve (right-hand) are shifting closer to the edgeline. Vehicles traveling on an outside curve (left-hand) are shifting towards the centerline. The shift in lateral position verifies that vehicles in the baseline evaluation are adopting a curve flattening path that maximizes their travel radius. The shift is pronounced and apparent in both baseline directions. Both baseline PC lateral position means are alarmingly close to the centerline and a heavy vehicle at the outside MP would be encroaching onto the centerline. The shift in lateral position from the PC to the MP still persists in the chevron and ChevFull evaluations, but to a lesser extent. Figure 27 depicts that the slope of the lines for chevrons and the ChevFull treatments are not as pronounced as the slope of the baseline evaluations. This is clearly apparent in the outside curve direction. The rate of change in lateral position between the PC and MP will be expanded upon further in the vehicle tracking summary.

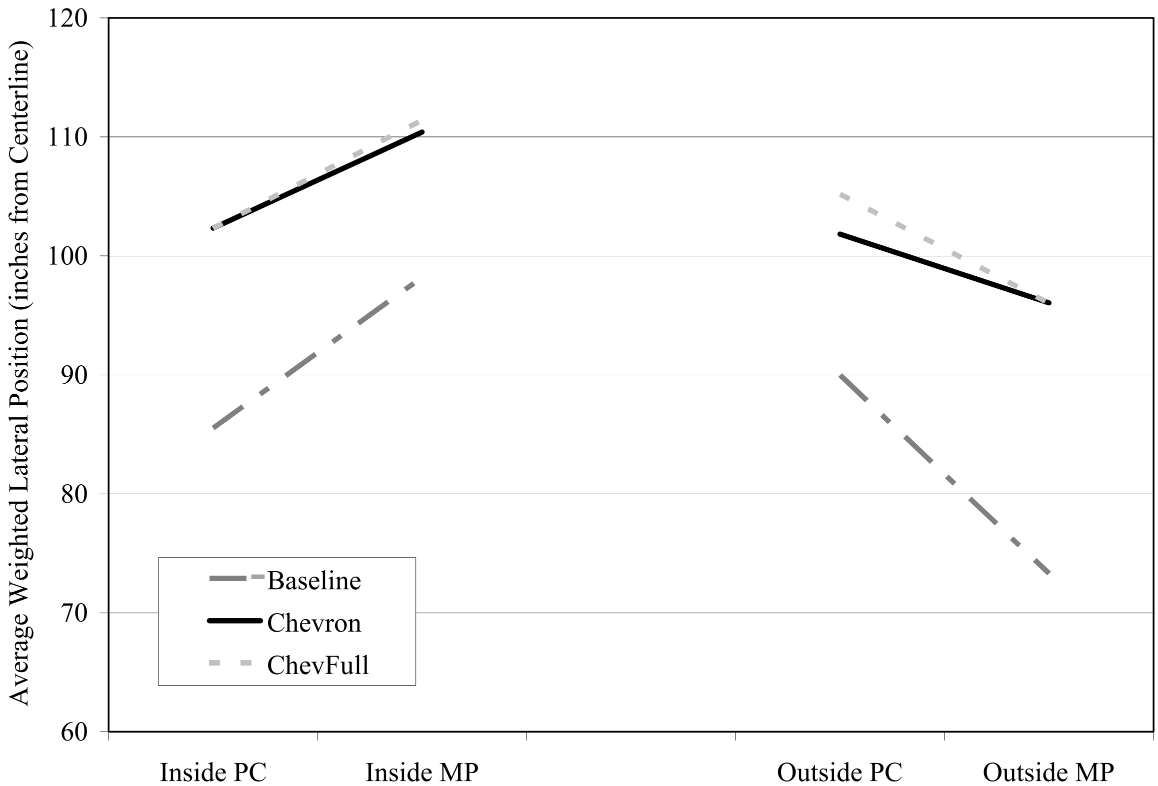

Figure 27. Directional Lateral Position Shift in Curve.

There is a clear distinction in the mean lateral position when chevrons and ChevFull treatments are implemented for both curve directions. The PC lateral position in both curve directions is more uniform and at an ideal location in the travel lane. Vehicles are entering the curve closer to the edgeline and not precariously close to the centerline. It is reasoned that vehicles in the baseline evaluation straddled the centerline at the PC because it was the main source of roadway guidance. The findings suggest that both chevron treatments provide additional guidance to allow drivers to enter the curve at a more advantageous lateral position. The MP lateral position of the chevron treatments has also improved from the baseline evaluation. Similar to the PC assessment, vehicle lateral position at the MP is now closer to the edgeline in the chevron treatment evaluations than in the baseline evaluation. The mean lateral positions at all MP locations are deemed acceptable and a heavy vehicle at the outside MP of the curve would no longer be encroaching onto the centerline.

Figure 28 depicts the change in the lateral position from the PC to the MP on an outside curve for a baseline and chevron comparison. The wheelbase in the figure has a track width of

61 inches. The measurements reference the outside edge of the right tire from the centerline. The centerline at the PC and the MP locations are aligned at a datum of zero but other pavement markings, lane width, and shoulder may vary because of different dimensions at the two roadway locations. The figure shows that the baseline mean lateral position at the PC is near the centerline and mean at the MP is much closer to the centerline. The chevron mean lateral positions at the PC and the MP are both at ideal locations and are more uniform than the baseline mean. The figure clearly depicts that chevrons produced a considerable effect in curtailing curve flattening.

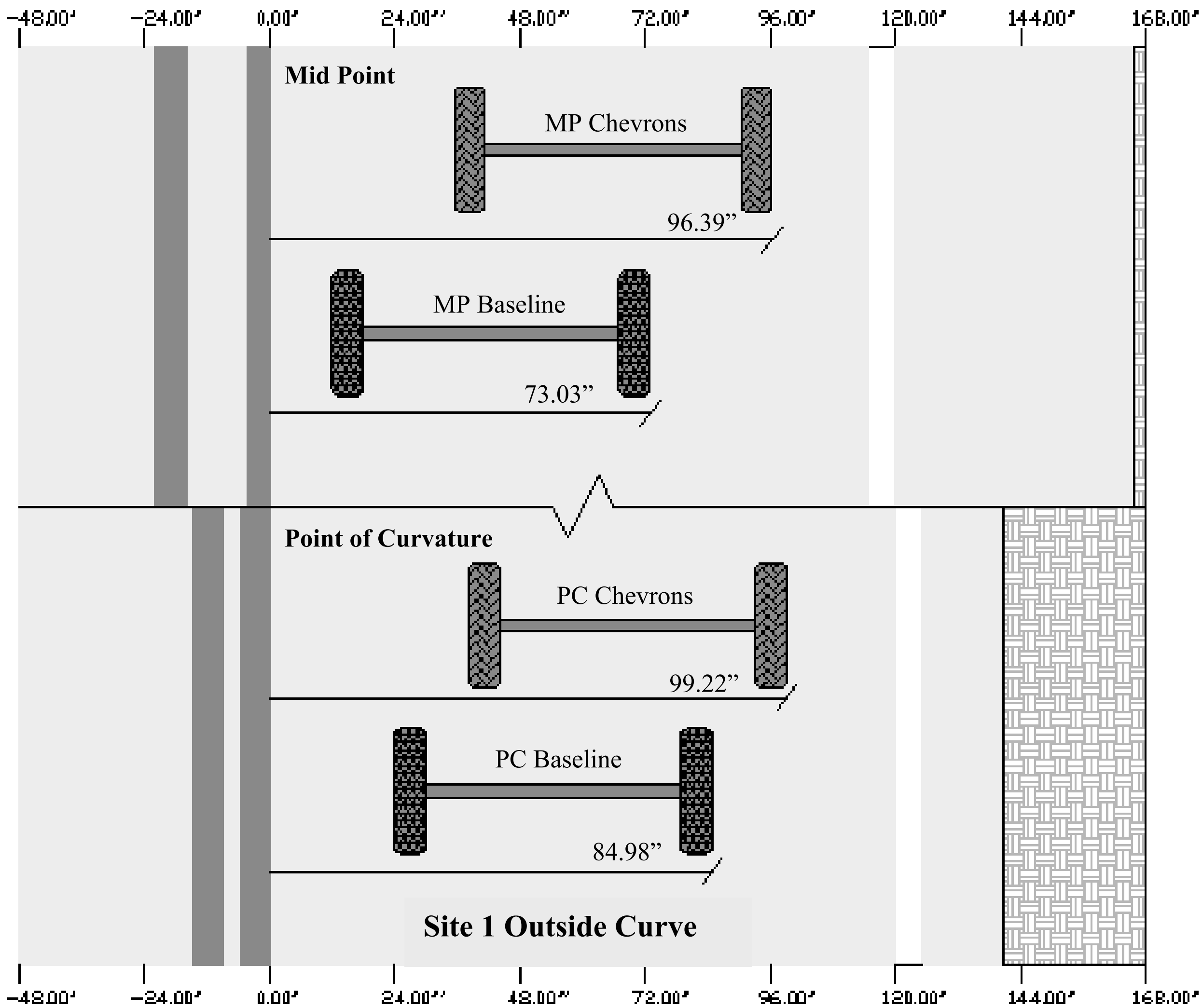

Figure 28. Baseline and Chevron Lateral Position Diagram

The T-test was performed on the individual curve location data to assess if lateral position means were statistically different between two evaluations. A confidence level of 95 percent was used at the eight locations. The mean lateral position data is contained in Table 13. The mean lateral positions from chevrons and the ChevFull treatment evaluations were proven to be statistically significant from all baseline means. The T-test confirmed that chevrons and the ChevFull treatment achieved beneficial results at all PC and MP locations. The T-test was performed to determine if there was a statistical difference in means between the two types of chevron treatments. The results determined that four of the eight tests were statistically significant.

Table 13. Mean Lateral Position from Centerline.

Curve Location		PC (inches)			MP (inches)		
		Baseline	Chevrons	ChevFull	Baseline	Chevrons	ChevFull
Site 1	Inside	91.13	104.88	102.34	106.89	114.30	114.82
	Outside	84.98	99.22	103.45	73.03	96.39	96.36
Site 2	Inside	79.72	97.66	102.27	87.52	103.90	107.09
	Outside	96.12	106.34	107.02	73.61	95.47	95.57

In summary, the directional curve analysis determined that there was a beneficial modification in vehicle lateral position when chevrons or ChevFull delineation treatments were implemented. Lateral position improved at the PC and the MP in both curve directions. Chevrons and ChevFull produced results similar to each other. There was no additional benefit to full reflectorizing the chevron post.

A Univariate ANOVA test was conducted to assess the differences in means of the lateral position data. The objective of the test was to determine if each model variable significantly affected lateral position differently. ANOVA test models were created from variable main effects and variable interactions. Main effects were location, curve direction, time, vehicle type, and treatment. Two-way interactions were comprised of the model main effects and were selected based on relevance to the objective of the study.

The results showed that the treatment main effect was significantly different. Overall, chevrons and the ChevFull treatment influenced vehicle lateral position differently than in the baseline evaluation and the effects of the treatments were similar for passenger and heavy vehicles.

The Univariate ANOVA test was performed on the lateral position data at all individual curve locations. A total of eight tests were conducted and the results are contained in Table 14.

Test results showed that the treatment achieved significant results for all tests. The main effects of time and vehicle type were significant for all tests, except in one test for each main effect. The vehicle type and treatment interaction was not significant for four of the eight tests and one other test was close to being not significant. The time and treatment interaction was not significant for three of the eight tests. Findings may suggest treatments are achieving a significant difference in lateral position and the change was not affected by time of day or vehicle type.

Table 14. P-values for Lateral Position ANOVA Test at Curve Locations.

Model Variable		Site 1				Site 2			
		Inside		Outside		Inside		Outside	
		PC	MP	PC	MP	PC	MP	PC	MP
Main Effect	Time	**0.259**							
Main Effect	Vehicle Type						**0.770**		
Main Effect	Treatment								
2-way	Vehicle Type * Treatment		**0.555**	**0.060**	**0.108**		**0.448**	**0.040**	**0.016**
2-way	Time * Treatment	**0.018**		**0.310**	**0.010**	**0.089**	**0.533**		

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

Individual Vehicle Lane Tracking

In addition to the aggregate analysis presented in the previous section, individual vehicles were tracked from the PC to the MP and the change in lateral position is contained in Table 15. A positive value indicates that a vehicle is shifting toward the edgeline between the PC at the MP and a negative value indicates a shift towards the centerline. The mean change in lateral position was derived from the passenger vehicle data in the overall time period.

Table 15 contains the mean tracking data. The baseline mean lateral change for an inside curve was noticeably larger than for an outside curve meaning drivers shifted their position towards the edgeline more in right-hand curves than in left-hand curves. Both chevrons and the ChevFull treatment reduced the mean lateral change from baseline mean in all but one direction. The ChevFull treatment increased the mean change by 0.14 inch for the outside curve of Site 1. Chevrons achieved the greatest reduction in mean lateral change in all cases except for the outside curve of Site 2 where the ChevFull treatment further lowered the mean by 1.54 inches. Apart from the one exception, the findings determined that chevrons reduced the baseline mean lateral change by almost half. Chevrons were most effective in lowering the mean on an inside curve direction. The ChevFull treatment was also effective in reducing the mean in three of the four cases. The T-test statistically confirmed that chevrons significantly reduced the mean lateral change in all tests. The ChevFull treatment significantly reduced the mean lateral change in all cases except for the outside curve direction of Site 1, where the change was slightly raised.

Table 15. Lateral Position Tracking Difference Between PC and MP.

Curve Location		Mean (inches)		
		Baseline	**Chevrons**	**ChevFull**
Site 1	Inside	17.25	9.50	12.61
	Outside	-12.36	-6.15	-12.50
Site 2	Inside	-23.89	-10.94	-11.74
	Outside	8.89	6.37	4.83

Overall, both chevrons and ChevFull treatments achieved a significant reduction in mean lateral change from the baseline evaluation in all but one comparison. Chevrons achieved the most consistent results and their benefits were most substantial in the inside curve direction. The ChevFull treatment produced consistent results in the inside curve direction. There was little to no difference in treatment when the findings from both the chevrons and ChevFull treatment were compared.

An Univariate ANOVA test was performed on the lateral position tracking data and the same model described above was employed to assess significance differences in means. A total of four tests were conducted and the results are contained in Table 16. The vehicle tracking tests produced differing results from the individual location ANOVA tests. There were more main effects that were not significant in the tracking testing. Vehicle type was not significant in three of the four tests and time was not significant in two tests. The treatment main effect was not significant in one test and it occurred on the inside direction of Site 2. Both two-way interactions were not significant for three tests. The findings from these tests could suggest that both time and vehicle type did not significantly impact the lateral change of a vehicle from the PC to the MP. In summary, the main effect of the treatment was significant, but the effects of the treatment were the same regardless of time or vehicle type.

Table 16. P-values for Lateral Position ANOVA Test of Tracking Data.

Model Variables		Site 1 Inside	Site 1 Outside	Site 2 Inside	Site 2 Outside
Main Effect	Time		0.510	0.409	
	Vehicle Type	0.764	0.317	0.720	
	Treatment			0.183	
2-way	Vehicle Type * Treatment	0.518	0.749		0.584
	Time * Treatment		0.433	0.680	0.135

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

Variance of Lateral Position at PC and MP

Variance in lateral position was assessed by the standard deviation of passenger vehicles in the overall time period. The standard deviation values are contained in Table 17. The standard deviation determined the fluctuation in the lateral position and indicated how uniform vehicles were in their lateral placement at the two Z-configurations. The MP standard deviation for the baseline evaluation was consistently higher than the PC value. The baseline standard deviation for the outside curve direction was also higher than the value for the inside curve direction.

Table 17 shows that the standard deviations for both chevrons and the ChevFull treatment were considerably lower than the baseline value. This reduction signifies that both treatments are obtaining more uniform and consistent lateral position at both the PC and the MP locations. At the PC, chevrons achieved an average percentage reduction of 46 percent and the ChevFull obtained an average of 40 percent. At the MP, both chevron treatments achieved an average of approximately 43 percent. Chevrons produced a lower standard deviation at the PC than the ChevFull treatment in three out of the four tests. The ChevFull treatment produced a lower standard deviation at the MP in three out of the four tests. There was only one notable difference in standard deviations and that occurred when the chevrons produced a much lower value at the inside curve direction of Site 1. Similar to the baseline values, the highest standard deviation for both chevrons treatments was observed at the MP of an outside curve.

Table 17. Lateral Position Standard Deviations.

Curve Location		PC (inches)			MP (inches)		
		Baseline	Chevrons	ChevFull	Baseline	Chevrons	ChevFull
Site 1	Inside	12.27	5.56	7.82	13.95	8.41	8.80
	Outside	11.26	6.19	6.29	14.49	7.57	7.45
Site 2	Inside	12.62	7.38	7.20	14.91	7.08	7.07
	Outside	12.99	7.53	7.98	15.88	10.40	10.28

The F-test proved that chevrons and the ChevFull treatment statistically reduced the standard deviation and produced more uniform lateral position at both the PC and the MP locations. The F-test determined that there was only one test where chevrons and ChevFull treatments had statistically different standard deviations. The exception occurred at the inside curve direction on Site 1 where chevrons obtained a lower value. Despite this single occurrence, the differences in standard deviation between chevrons and ChevFull treatment evaluations were considered negligible and both treatments were significantly effective in reducing the variances in lateral position.

Variance of the individual vehicle tracking data reconfirmed the previous variance findings. The standard deviation measures the fluctuation in lateral position change from the PC to the MP. Table 18 contains all standard deviations from the vehicle tracking data. The standard deviation was derived from all passenger vehicle data in the overall time period. The table shows that chevrons and the ChevFull treatment considerably reduced the standard deviation from the baseline. The reduction indicates that the treatments are achieving less variances and more uniform lane position.

Table 18. Vehicle Tracking Standard Deviation.

Curve Location		Total Change (inches)		
		Baseline	Chevrons	ChevFull
Site 1	Inside	14.94	9.16	11.03
	Outside	14.76	7.78	7.75
Site 2	Inside	16.74	10.28	10.29
	Outside	18.50	8.28	9.03

The F-test proved that all standard deviations obtained by the treatments are significantly different from the values found in the baseline evaluation. There was one statistical difference in standard deviations between chevrons and the ChevFull treatment and this occurred at the inside curve direction on Site 1. This difference in standard deviation at the inside curve direction on Site 1 coincides with the one exception from the previous variance analysis. Overall, chevrons and the ChevFull treatment produced a significant reduction in the variance and the treatments achieved very similar results despite the one exception.

Edgeline and Centerline Encroachments

Encroachment data are contained in Table 19 and values are expressed as the percentage of encroachment occurrences out of the total number of passenger vehicles. The edgeline encroachment rates are accurate observations. The centerline encroachment rates are an estimate of possible encroachments based on a conservative track width of 80 inches and an average track width of 61 inches.

Table 19. Encroachment Data.

Curve Location			Centerline 80 in Track			Centerline 61 in Track			Edgeline		
			Base.	**Chev.**	**C.Full**	**Base.**	**Chev.**	**C.Full**	**Base.**	**Chev.**	**C.Full**
Site 1	Inside	PC	9.3%	0.6%	4.4%	2.4%	0.0%	0.0%	0.5%	0.6%	0.7%
		MP	4.1%	0.2%	0.2%	1.2%	0.0%	0.0%	19.7%	31.2%	35.7%
	Outside	PC	29.2%	0.8%	1.0%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%
		MP	69.1%	6.5%	7.6%	14.4%	0.0%	0.0%	0.0%	0.2%	0.1%
Site 2	Inside	PC	51.5%	2.2%	1.0%	4.8%	0.1%	0.1%	0.3%	0.2%	0.5%
		MP	20.6%	0.8%	0.9%	7.9%	0.0%	0.1%	0.1%	1.3%	0.9%
	Outside	PC	10.0%	1.1%	1.1%	1.5%	0.0%	0.1%	1.1%	1.3%	1.9%
		MP	67.2%	8.8%	8.7%	18.6%	0.4%	0.3%	0.3%	0.2%	0.3%

Note: Base. = Baseline, Chev. = Chevrons, and C.Full = ChevFull treatment.

In the baseline evaluation, the highest possible centerline encroachment percentages occurred at the MP locations on the outside curve direction. The MP location on the inside curve direction exhibited a low rate of centerline encroachments, but had the highest rates of edgeline encroachments. The encroachment data from the baseline evaluation are characteristic of curve flattening path. Locations with high encroachments rates were also associated with high standard deviations. There was one instance of high edgeline encroachments in the baseline evaluation, which occurred at the MP on the inside curve direction of Site 1.

Chevrons and the ChevFull treatment considerably reduced the centerline encroachment rates for both the 80 and 61-inch vehicle track width. The reductions achieved by the treatments were most pronounced at the MP on an outside curve, which were decreased by approximately 90 percent. The outside curve MP location was plagued with high encroachment rates in the baseline evaluation and treatments produced a substantial improvement. In general, chevrons reduced the centerline 80-inch encroachment rate by approximately 93 percent and the ChevFull treatment reduced it by 88 percent. The treatments also reduced the centerline encroachments for a 61-inch track vehicle to approximately zero at many of the locations.

All edgeline encroachments were lowered or remained approximately unchanged except for the MP location on the inside curve of Site 1. The edgeline encroachment rates increased for both the chevron treatments. It has been identified that chevrons and the ChevFull treatment move vehicles away from the centerline at the inside MP location. At this site location, there is a wide, 4-foot paved shoulder. The inside MP location of Site 2 had a 1.2-foot shoulder and did not exhibit the same increase in edgeline encroachments. The combination of wide paved shoulder and delineation treatment may encourage edgeline encroachments at the MP of an inside curve.

The Z-test was performed to determine if the encroachment rates were statistically different. The results determined that all centerline encroachment rates achieved by both chevrons and the ChevFull treatment were statistically different from the baseline rates. Both chevron treatments statistically reduced the baseline centerline encroachment percentages at all PC and MP locations regardless of curve direction. The centerline encroachment rates from chevrons and the ChevFull treatment were compared and tested for significance. The results showed that there were only two tests where the centerline encroachment rates significantly differed between both treatments. The Z-test confirmed that chevrons and the ChevFull treatment statistically reduced possible centerline encroachments and there was negligible difference between the results of the two chevron treatments.

The Z-test was also performed on the edgeline encroachment rates. Chevrons and the ChevFull treatment statistically increased the percentage of edgeline encroachments at the inside MP location of Site 1. This was the only noteworthy or significant difference in edgeline encroachment rates. The ChevFull treatment also produced a statistically higher encroachment rate than chevrons at that location. Apart from this one location, there were no other substantial or significant differences in edgeline encroachments.

Speed

The mean speed data at individual curve locations are contained in Table 20. The mean speed values were derived from passenger vehicle data from the overall time period. Chevrons and the ChevFull treatment achieved mean speeds that were constantly lower than all baseline speeds. The chevron treatments produced a reduction in mean speed at all individual curve locations and in both curve directions.

Table 20. Speed Data.

Curve Location		PC Mean Speed (mph)			MP Mean Speed (mph)		
		Baseline	Chevrons	ChevFull	Baseline	Chevrons	ChevFull
Site 1	Inside	57.27	56.39	56.03	57.66	56.29	55.76
	Outside	60.33	59.12	58.95	57.83	56.82	57.43
Site 2	Inside	57.21	54.51	53.16	54.83	53.18	51.26
	Outside	56.61	55.43	53.75	55.68	54.51	53.56

The differences in mean vehicle speed between evaluations are shown in Table 21. A positive value in Table 21 signifies a reduction in speed caused by one of the treatments and a negative value indicates a speed increase. The decrease in mean speed at all locations indicates that both chevron treatments achieved beneficial results. The ChevFull treatments consistently produced a larger reduction in speed than chevrons. On average, chevrons achieved approximately a 2.5 percent reduction in vehicle speed and the ChevFull treatment obtained approximately a 4.0 percent reduction. When chevrons and the ChevFull treatments were compared, chevrons had a greater speed reduction in only one of the eight comparisons.

Table 21. Mean Speed Differential (mph).

Curve Location		PC Δ in Mean Speed (mph)			MP Δ in Mean Speed (mph)		
		B-Ch	B-CF	Ch-CF	B-Ch	B-CF	Ch-CF
Site 1	Inside	0.88	1.24	0.36	1.38	1.90	0.53
	Outside	1.21	1.38	0.17	1.01	0.40	-0.61
Site 2	Inside	2.70	4.05	1.35	1.65	3.57	1.92
	Outside	1.18	2.86	1.68	1.17	2.12	0.95

Note: B-Ch = Baseline speed minus the Chevron speed, B-CF = Baseline speed minus the ChevFull speed, and Ch-CF = Chevron speed minus the ChevFull speed.

The T-test was conducted to determine if the reductions were significant. Both chevron treatments achieved a significant reduction in speed at all individual curve locations from the baseline evaluation. The T-test was also used to compare the mean speeds of both chevron treatments. The ChevFull treatment produced a mean speed that was statistically lower than the mean speed from chevrons in five of the eight total tests. Chevrons achieved a significant reduction in speed in one test and there were two tests where the means were not significantly different.

In summary, chevrons and the ChevFull treatment statistically reduced the mean speed from the baseline evaluation in all tests. The findings suggest that the ChevFull treatment could have a more substantial effect on lowering travel speed through a horizontal curve than standard chevrons.

A Univariate ANOVA test was conducted to assess the differences in means of the speed data. The results showed that all main effects were significant. Treatment interaction with curve direction and location were also significant. The two-way interaction between treatment and time was not significant, which could suggest that treatments affected vehicle speed in the same manner regardless of time of day.

The Univariate ANOVA test was performed on the speed at individual curve locations. A total of eight tests were conducted and the results are contained in Table 22. The results showed that the main effect of the treatment was significant for all trials except for one test, which occurred at the inside PC location of Site 1. The main effect of time was not significant in two tests and both occurred at the inside MP and outside MP locations of Site 2. The analysis of two-way interaction determined that vehicle type and treatment were not significant in four of the eight tests. The two-way interaction between time and treatment was not significant in five of the eight tests.

Table 22. Speed ANOVA Test at Curve Locations.

Model Variables		Site 1				Site 2			
		Inside		Outside		Inside		Outside	
		PC	MP	PC	MP	PC	MP	PC	MP
Main Effect	Time					**0.044**	**0.099**		**0.078**
Main Effect	Vehicle Type								
Main Effect	Treatment	**0.092**							**0.013**
2-way	Vehicle Type * Treatment	**0.297**	**0.121**					**0.257**	**0.202**
2-way	Time * Treatment	**0.658**	**0.216**	**0.024**	**0.024**	**0.995**	**0.927**		**0.137**

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

Individual Vehicle Speed Change

The tracking data were utilized to assess the change in speed from the PC to the MP. It was identified in the literature review that there is a relationship between differential speed reduction and crash rates (*59*). It is a measure of effectiveness to lessen the differential speed change between the PC and the MP or bring the change in speed closer to zero. A smaller differential speed reduction will indicate that vehicles are decelerating prior to entering and maintaining a more advantageous speed through the critical sections of the curve.

Table 23 contains the mean change in speed from the PC to the MP for passenger vehicles for the overall period. A negative value indicates a decrease in speed from the PC to the MP and a positive value indicates an increase. The findings from the chevrons and the ChevFull treatments are not as apparent and straightforward as in the previous sections. Chevrons appear to have a very negligible effect on reducing the speed differential between curve locations. Chevrons lowered the change in speed at the outside curve of Site 1 and the inside curve of Site 2, but the reductions were quite small. At the other two curve directions, the baseline and chevron values were nearly identical. The ChevFull treatment achieved a more noticeable impact on the change in speed between locations. In three of the four curve directions, the ChevFull treatment attained a speed differential that was closer to zero than in the baseline evaluation. At the inside curve of Site 1, the ChevFull treatment produced a reduction in speed that was greater than the baseline speed differential.

Table 23. Tracking Speed Data.

Curve location		Mean Speed Δ (mph)		
		Baseline	**Chevrons**	**ChevFull**
Site 1	Inside	0.09	-0.02	-0.47
	Outside	-2.41	-2.23	-1.81
Site 2	Inside	-2.66	-2.07	-1.65
	Outside	-0.52	-0.51	0.09

The T-test proved that chevrons produced a change in speed that was statistically different for the outside curve of Site 1 and the inside curve of Site 2. The results from the ChevFull treatment were statistically different from both the baseline and chevron evaluations in all tests. In summary, chevrons produced mixed or negligible results and the ChevFull treatment achieved significantly more uniform and constant vehicle speeds between curve locations.

The Univariate ANOVA test was performed on the speed tracking data. A total of four tests were conducted and the results contained in Table 24. The main effects of the time and treatments were significant for all tests except in one test for each main effect. The main effects that were not significant in the ANOVA test of tracking data were also not significant in the ANOVA test of individual curve locations in Table 22. Unlike the previous analysis, the main effect of the vehicle type was not significant in three of the four tests. Both two-way interaction variables were not significant in two tests. In general, the main effect of the treatments were significant and in some cases the treatment effects on the change in speed were the same regardless of vehicle type or time of day.

Table 24. Speed ANOVA Test of Tracking Data.

Model Variables		Site 1		Site 2	
		Inside	**Outside**	**Inside**	**Outside**
Main Effect	Time			**0.349**	
	Vehicle Type	**0.254**	**0.294**		**0.288**
	Treatment	**0.424**			
2-way	Vehicle Type * Treatment	**0.578**	**0.205**		
	Time * Treatment	**0.040**	**0.502**	**0.204**	

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

Variance in Speed

The standard deviations of the speed data are contained in Table 25. The table shows that the standard deviations produced by both chevron treatments generally increased from the baseline evaluation. All treatment standard deviations increased except for the outside PC at Site 1. Neither treatment achieved a reduction in curve speed variance. The standard deviations produced by chevrons and the ChevFull treatments were similar.

Table 25. Speed Standard Deviation.

Curve Location		PC Standard Deviation (mph)			MP Standard Deviation (mph)		
		Baseline	**Chevrons**	**ChevFull**	**Baseline**	**Chevrons**	**ChevFull**
Site 1	Inside	6.91	7.21	7.40	6.86	6.95	7.16
	Outside	7.63	7.59	7.22	6.98	7.13	7.02
Site 2	Inside	9.35	10.41	10.69	7.71	8.65	9.07
	Outside	8.73	9.15	9.34	8.20	8.87	8.95

The F-test was conducted to test if the standard deviations were statistically different. The tests concluded that the majority of the standard deviations produced by both chevron treatments were not significantly different from the baseline standard deviation. In total, there were three tests out of sixteen that proved to be significantly different. The lack of statistical difference suggests that the chevron treatments do not have a significant impact the speed variance in a horizontal curve.

RESULTS FOR POST-MOUNTED DELINATOR TREATMENTS

Recall that for the PMD evaluations, a simple before-after design was used where one site got Dot PMD and one site got Full PMD treatments. In general, both the Dot PMD and the Full PMD treatments produced beneficial results and promoted ideal vehicle performance as identified by the measures of effectiveness. The Full PMD treatment was able to achieve more uniform vehicle position in the tracking data. The curve flattening was less apparent at Site 4 after implementing the Full PMD treatment. The findings suggest that neither PMD treatment was effective in reducing vehicle speed at the PC or MP locations.

Lateral Position at PC and MP

The lateral positions of vehicles at the PC and MP for the three treatments are shown in Figure 29. The figure depicts the lateral position of the outside edge of the right tire from the centerline at both the PC and MP locations. The data from both Site 3 and Site 4 are shown individually and directional data are not averaged as in Figure 27. It was decided not to average the curve direction data since the treatments were not implemented at both sites as in the chevron treatment evaluations.

In the baseline evaluation, three of the four curve directions exhibit a considerable shift in lateral position between curve locations. Vehicles are flattening their curve path at the three directions by either moving closer to or encroaching onto the lane lines. The one exception is on the inside direction of Site 3 where there is a very moderate and acceptable change in lateral position. Besides the one acceptable curve direction, the baseline mean values are not ideal. Heavy vehicles on the inside direction of Site 4 would be encroaching onto the centerline as they enter the PC. On the outside curve at both sites, heavy vehicles would be inches away from the centerline at the PC and then encroach over the centerline at the MP. At the outside MP of Site 3, the average passenger vehicle would be encroaching onto the centerline. The majority of the baseline lateral position data are alarming. In general, there is considerable change in lateral position between curve locations and a high percentage of vehicles could be precariously close or encroaching onto the centerline.

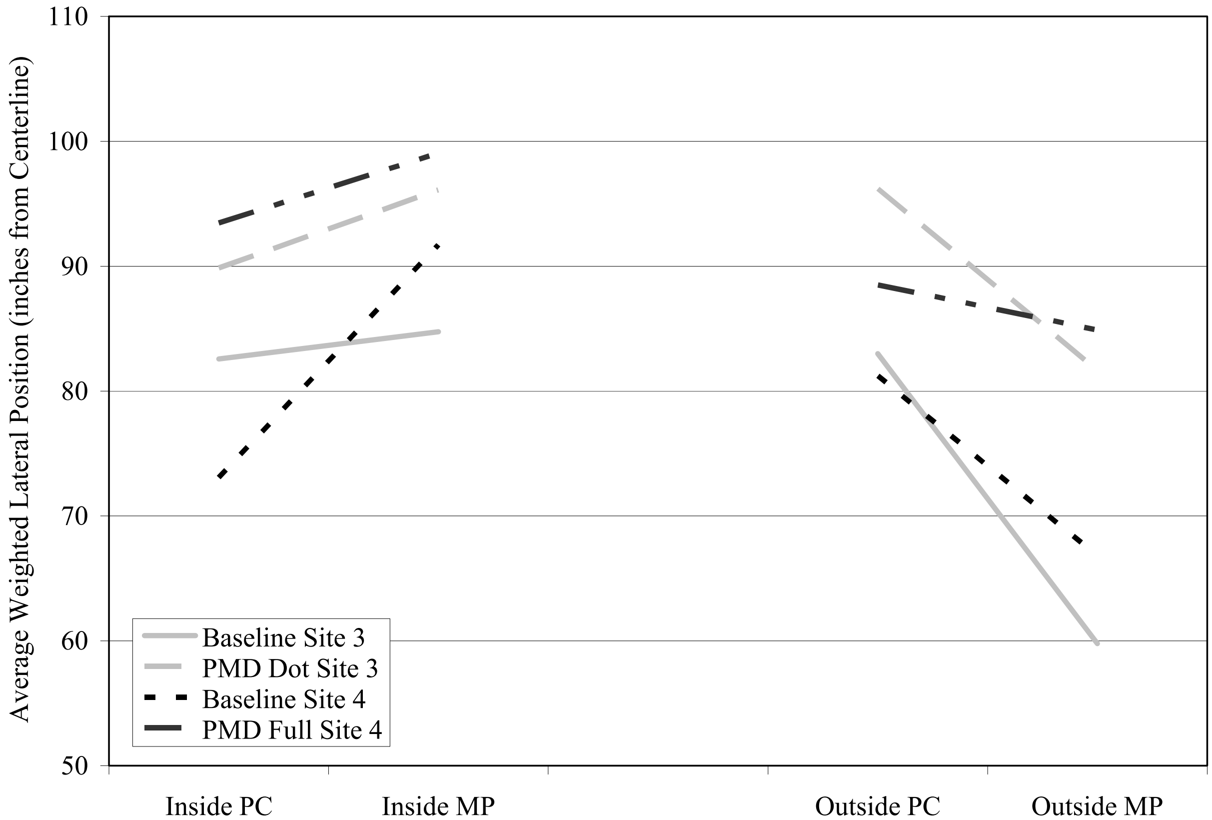

Figure 29. Directional Lateral Position Shift in Curve.

Figure 29 indicates that both the Dot PMD and the Full PMD treatments achieved a more uniform curve path and allowed vehicles to select a more advantageous lateral position. On the inside curve direction, vehicles entered the PC at an appropriate distance from the centerline and then moderately shifted towards the edgeline at the MP. Results were similar, but the variation in lateral position between the Dot PMD and Full PMD on the inside direction may be attributed to different lane dimensions.

The treatments also produced beneficial results on the outside curve direction at both sites. Vehicles were entering the PC at an acceptable location further from the centerline. Vehicles continued to shift towards the centerline at the MP, but it was still a vast improvement from the baseline values. The PMD treatments minimized the lateral shift between curve locations and results on the outside curve direction were deemed beneficial. Examples of the uniform lane positions achieved by the treatments are depicted in Figure 30 and Figure 31.

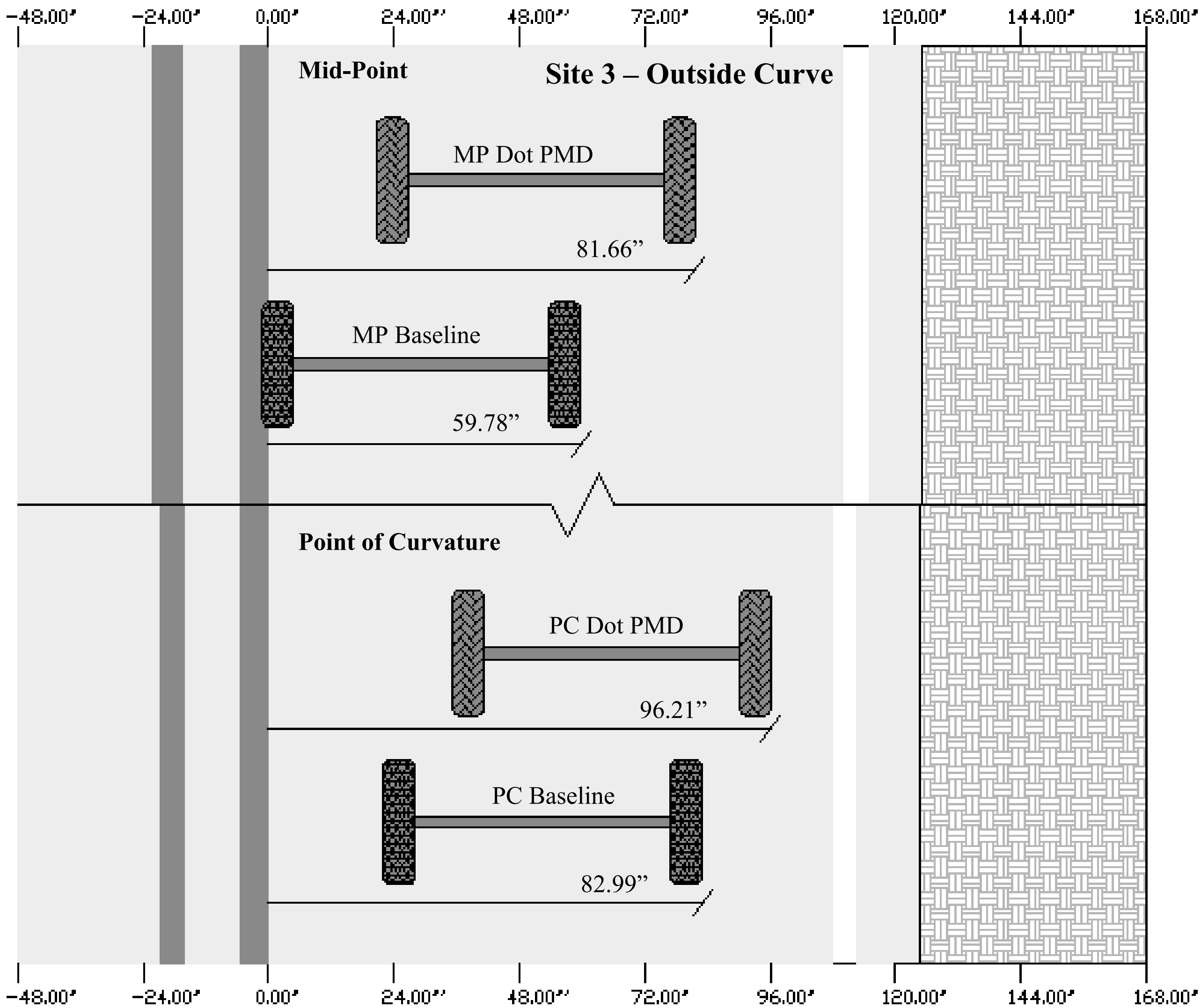

Figure 30. Baseline and Dot PMD Lateral Position Diagram.

The wheelbases in both figures have a track width of 61 inches. Figure 30 shows the change in lateral position at the outside curve direction of Site 3 for a baseline and Dot PMD comparison. It should be noted that in Figure 30 the baseline wheelbase at the MP is encroaching onto the centerline. The Dot PMD treatment moved the vehicle away from the centerline by approximately 20 inches at the MP. Figure 31 depicts the shift in lateral position at the inside curve direction of Site 4 for a baseline and Full PMD comparison. The obvious difference is at the PC. The Full PMD treatment moved vehicles away from the centerline and lateral position deviated very little between the curve locations.

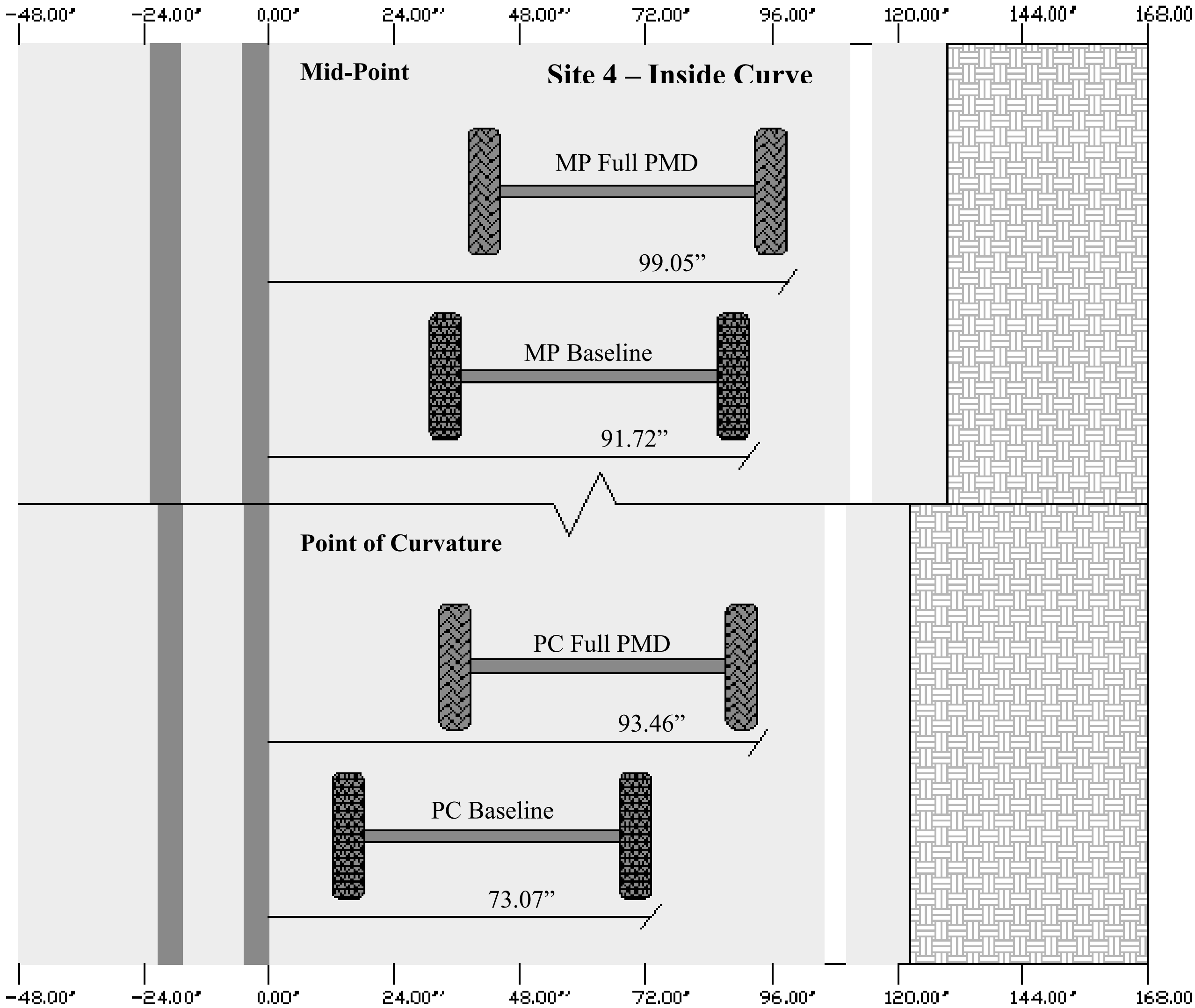

Figure 31. Baseline and Full PMD Lateral Position Diagram.

The T-test was performed to assess if the PMD findings were statistically different. There were a total of eight tests conducted at a confidence interval of 95 percent. The mean lateral position values that were tested are contained in Table 26. All tests confirmed that the mean lateral positions produced by the PMD treatments were statistically different from the baseline means. The T-test proved that the Dot PMD and Full PMD treatments were significantly affecting the lateral position selection of vehicles and curtailing the curve flattening path. The T-test was not used to compare the means of the Dot PMD and Full PMD treatments as in the chevron treatment comparison. The PMD treatments were not employed at the same curves and a site-to-site treatment evaluation may provide misleading results.

Table 26. Mean Lateral Position from Centerline.

Curve Location		PC (inches)		MP (inches)	
		Baseline	PMD	Baseline	PMD
Site 3 (Dot PMD)	Inside	82.57	89.86	84.74	96.10
	Outside	82.99	96.21	59.78	81.66
Site 4 (Full PMD)	Inside	73.07	93.46	91.72	99.05
	Outside	81.22	88.51	66.79	84.89

A Univariate ANOVA test was conducted to assess the differences in means of the lateral position data. Model main effects were location, curve direction, time, vehicle type, and treatment. All main effects were statistically significant except for vehicle type. The data indicates that passenger vehicles and heavy vehicles select a curve path with similar lateral positions at the two sites. The main effect of curve direction produced the highest F-value and indicates that lateral position for an inside curve significantly differs from an outside curve. This considerable difference may suggest that the curves are plagued by high encroachment rates from vehicles flattening their curve path. The main effect of treatment produced the second highest F-value, which strongly indicates that the treatments are influencing vehicles to select a lateral position that differs from the baseline values.

All two-way interactions were significantly different except for the interaction between time and treatment. The exception suggests that the treatments are achieving the same affect in the night period as in the day period. The interaction between treatment and vehicle type was significant, but the F-value was low and may not have been significant if there was an alteration in the model or a reduction in sample size. Overall, the findings suggest the treatments are influencing a driver's vehicle path and the treatment effect is similar regardless of vehicle type or time.

The Univariate ANOVA test was performed on the data at individual curve locations. A total of eight tests were conducted and the results are contained in Table 27. Time, vehicle type, and treatment were the main effects and two-way interaction between treatments and both vehicle type and time were modeled.

The tests determined that the main effect of the treatment was significantly different at all curve locations. The main effect of time was significant in all but one test. The vehicle type was not significant for four of the eight tests, which compiles the results from the previous ANOVA test. The two-way interaction results were also similar. The interaction between the treatment and both vehicle type and time were not significant in many of the tests. Treatment and vehicle type were not significant in three tests and three other tests were close to being not significant. Treatment and time were not significant in four tests and three other tests were close to being not significant. The closest tests could easily have been not significant if there was an alternation in the sample size and if the model was changed. Time and vehicle type were not significantly different at the outside PC of both curves. Again, the treatments were significantly affecting the vehicles' lateral position and findings suggest that the treatment has the same effect regardless of vehicle type or time.

Table 27. Lateral Position ANOVA Test at Curve Locations.

Model Variable		Site 3				Site 4			
		Inside		Outside		Inside		Outside	
		PC	MP	PC	MP	PC	MP	PC	MP
Main Effect	Time						**0.26**		
	Vehicle Type	**0.248**		**0.241**	**0.444**	**0.427**	**0.010**		
	Treatments								
2-way	Vehicle Type * Treatment	**0.016**		**0.725**	**0.011**	**0.020**		**0.311**	**0.361**
	Time * Treatment	**0.635**	**0.476**	**0.924**	**0.026**	**0.041**	**0.028**	**0.710**	**0.011**

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

The Univariate ANOVA test was performed on the lateral position tracking data. The same model described above was employed to assess the change in lateral position between curve locations. A total of four tests were conducted and the results are contained in Table 28. Again, the tracking data tests confirm the results from the previous two ANOVA analyses. The main effects of the treatment were significant for three of the four tests. Time was not significant in three tests and vehicle type was not significant in two tests. The interaction between treatment and both vehicle type and time were not significant in two tests and one other test was close to being not significant.

Table 28. Lateral Position ANOVA Test of Tracking Data.

Model Variables		Site 3		Site 3	
		Inside	Outside	Inside	Outside
Main Effect	Time	**0.123**		**0.177**	**0.200**
	Vehicle Type	**0.210**	**0.014**	**0.518**	
	Treatments		**0.479**		
2-way	Vehicle Type * Treatment	**0.026**	**0.966**	**0.076**	
	Time * Treatment	**0.606**	**0.028**	**0.523**	

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

Individual Vehicle Lane Tracking

The mean lateral position change of individual vehicles is contained in Table 29. The change in lateral position was considerable for three of the four baseline curve directions. At these curves, vehicles were moving approximately a foot closer to the edgeline on the inside curve of Site 4 and a foot towards the centerline on an outside curve of Site 3 and Site 4. There was a slight vehicle shift at the inside curve of Site 3 and the lateral position change was acceptable.

The Dot PMD treatment did not produce much of a change from the baseline values. The inside curve direction of Site 3 was originally quite acceptable in the baseline evaluation. The Dot PMD increased the mean change to 6.21 inches. The mean change of 6.21 inches was still an acceptable value and is similar to the results obtained from the Full PMD treatment on the inside curve direction of Site 4. The value from the outside curve of Site 3 increased by approximately ¾ of an inch and was considered minimum. Nevertheless, the Dot PMD treatment failed to achieve any beneficial results in the tracking data.

The Full PMD treatment produced substantial reductions in both curve directions at Site 4. There was approximately a 50 percent decrease in mean lateral position change on the inside direction and approximately a 75 percent reduction on the outside direction. The Full PMD treatment achieved more uniform lateral position in both curve directions.

Table 29. Lateral Position Tracking Data.

Curve location		Mean (inches)	
		Baseline	PMD
Site 3 (Dot PMD)	Inside	2.27	6.21
	Outside	-14.03	-14.81
Site 4 (Full PMD)	Inside	12.98	5.76
	Outside	-14.75	-3.91

The T-test confirmed the tracking data observations. The Dot PMD produced a significant increase in mean lateral position change at the inside curve direction of Site 3. The means of the outside direction of Site 3 were not significantly different. The Full PMD treatments achieved a significant reduction in lateral position change in both curve directions.

Variance of Lateral Position at PC and MP

Lateral position variance was determined by assessing the standard deviations. These values are contained in Table 30. As in the chevron findings, all the standard deviations at the MP were greater than the PC values. The outside curve direction in the baseline evaluation exhibited greater variance than the inside direction.

The Dot PMD and Full PMD treatments achieved a reduction in standard deviation at all curve locations. The average decrease in standard deviation obtained by both PMD treatments was approximately 38 percent. There were substantial reductions at the outside direction of Site 3 and inside direction of Site 4, which were lowered by approximately 50 percent. The F-test statistically proved that all Dot PMD and Full PMD standard deviations were significantly lower than the baseline values.

Table 30. Lateral Postion Standard Deviations.

Curve Location		PC (inches)		MP (inches)	
		Base	PMD	Base	PMD
Site 3 (Dot PMD)	Inside	11.23	7.12	14.73	10.44
	Outside	12.75	6.28	16.13	9.88
Site 4 (Full PMD)	Inside	12.42	5.49	12.58	7.74
	Outside	10.14	7.58	14.93	9.94

The standard deviations for the vehicle tracking data are contained in Table 31. The standard deviations in the tracking data remained relatively the same between the baseline and PMD treatment evaluation. There was a reduction in standard deviation in three of the four cases, but neither reduction was considered substantial. The F-test confirmed this observation.

Three of the four tests were not significant. The exception occurred at the outside curve direction of Site 4, where there was a significant increase in standard deviation. Overall the PMD treatments did not have a substantial effect in lowering the variance in the change in lateral position between curve locations.

Table 31. Tracking Standard Deviation.

Curve location		Total Change (inches)	
		Base	PMD
Site 3 (Dot PMD)	Inside	11.26	11.11
	Outside	10.31	9.47
Site 4 (Full PMD)	Inside	9.08	8.25
	Outside	9.31	11.01

Edgeline and Centerline Encroachment

The PMD encroachment rates are contained in Table 32. Both sites experienced high centerline encroachments rates at the PC location when PMD treatments were not in place. In the baseline evaluation, PC centerline encroachment rate for an 80-inch track width ranged from 37 percent to 73 percent and the MP rates ranged from 16 percent to 93 percent. The baseline findings at Site 3 and Site 4 coincide with the baseline findings at Site 1 and Site 2 where the highest rates occurred at the MP of an outside curve. The highest baseline edgeline encroachment rate occurred at the inside MP of Site 4, which exhibited a rate of 2.44 percent. This edgeline rate is not distressingly high but nonetheless could be problematic.

Table 32. Encroachment Data.

Curve Location			Centerline 80 in		Centerline 61 in		Edgeline	
			Base	PMD	Base	PMD	Base	PMD
Site 3 (Dot PMD)	Inside	PC	37.24%	5.78%	3.88%	0.29%	0.78%	0.10%
		MP	31.41%	9.41%	5.57%	0.20%	0.80%	0.71%
	Outside	PC	34.73%	1.80%	5.15%	0.20%	1.05%	1.30%
		MP	93.13%	36.56%	47.25%	4.11%	0.00%	0.11%
Site 4 (Dot PMD)	Inside	PC	73.40%	1.90%	10.58%	0.11%	0.32%	0.45%
		MP	15.89%	4.74%	2.65%	0.11%	2.44%	0.44%
	Outside	PC	42.04%	10.67%	2.62%	1.66%	0.19%	0.31%
		MP	82.85%	27.16%	31.86%	1.57%	0.23%	0.11%

The Dot PMD and the Full PMD treatments dramatically reduced centerline encroachment rates. On average, the Dot PMD treatment achieved a centerline encroachment rate reduction of approximately 78 percent for the 80-inch track width and 94 percent for the 61-

inch track width. The Full PMD produced a rate reduction of approximately 77 percent for the 80-inch and 82 percent for the 61-inch track width. There were considerable decreases in rates at both PC and MP locations. The MP centerline encroachment reductions were substantial and beneficial as identified by the safety surrogates. Most of the edgeline encroachments remained relatively the same when compared to the baseline evaluation. The only noteworthy change occurred at the inside MP of Site 4, where the previous rate was reduced by approximately 80 percent.

The Z-test proved that all reductions in centerline encroachment rates were statistically significant. The treatments were able to lower the rates of centerline encroachments at all curve locations for both 80 and 61-inch track width vehicles. The Z-test verified that the decrease in edgeline encroachments at the inside MP of Site 4 was also insignificant.

Speed at PC and MP

All of the mean speed data are contained in Table 33. The table displays the vehicle speed from the baseline and PMD treatment evaluation and also the differences in speed between the two evaluations. A negative difference value indicates that the treatment achieved a lower speed than the baseline evaluation and a positive value signifies an increase in speed when the treatment was installed. Table 33 shows that there were no prevalent speed reduction trends and results were varied. The inside curve direction of Site 3 was the only direction that experienced a moderate and consistent reduction in mean speed. The speed remained relatively the same in most curve locations. There was a sizeable increase in mean speed at the inside PC of Site 4 when the Full PMD treatment was installed.

Table 33. Speed Data.

Curve Location		PC			MP		
		Base	PMD	Diff.	Base	PMD	Diff.
Site 3 (Dot PMD)	Inside	46.22	44.15	-2.07	44.72	43.02	-1.70
	Outside	46.46	46.36	-0.10	43.33	42.86	-0.47
Site 4 (Full PMD)	Inside	43.57	46.11	2.54	42.69	42.64	-0.05
	Outside	48.43	47.59	-0.84	42.76	42.77	0.01

Note: the Diff. is the difference in mean speed.

The T-test was conducted to determine if the differences in mean speed were significant. Both locations on the inside direction of Site 3 achieved a significant reduction in speed, but the outside curve locations values were not significant. Site 4 also produced mixed results. The increase in speed at the inside PC and the decrease in speed at the outside PC were both significant. Both MP locations at Site 4 were not significant. The PMD treatment effects on speed were mixed and a consistent relationship between speed and treatment was not identified. Overall, the findings suggest that the treatments did not improve or lower curve speed, but neither did they significantly raise speeds.

A Univariate ANOVA test was conducted to assess the differences in means of the vehicle speed data. The main effects of location, curve direction, time, vehicle type, and treatment were modeled as independent variables. The results showed that all main effects were significant. The interaction between treatment and vehicle type was not significant which could suggest that the PMD treatments affected all vehicle types in the same manner.

The Univariate ANOVA test was performed on the speed data at individual curve locations. A total of eight tests were conducted and the results are contained in Table 34. The main effect of time was not significant in all of the tests, which clearly indicates that vehicles are negotiating the curves at a similar speed during both night and day periods. Vehicle type was significant in all tests and the treatment was significant in all tests except for three. The three tests that were not significant occurred at Site 4 and two tests took place on the outside curve direction. The two-way interaction of vehicle type and treatment were significant in all of the tests except for one test. There were three tests between the vehicle type and treatment that were close to being not significant. The two-way interaction between treatment and time was not significantly different in seven of the eight tests and this strongly indicates that the treatments are influencing vehicle speed in a similar manner during the night and day periods.

Table 34. Speed ANOVA Test at Curve Locations.

<table>
<tr><th colspan="2" rowspan="3">Model Variable</th><th colspan="4">Site 3</th><th colspan="4">Site 4</th></tr>
<tr><th colspan="2">EB - Outside</th><th colspan="2">WB - Inside</th><th colspan="2">EB - Inside</th><th colspan="2">WB -Outside</th></tr>
<tr><th>PC</th><th>MP</th><th>PC</th><th>MP</th><th>PC</th><th>MP</th><th>PC</th><th>MP</th></tr>
<tr><td rowspan="3">Main Effect</td><td>Time</td><td>0.123</td><td>0.103</td><td>0.103</td><td>0.819</td><td>0.101</td><td>0.107</td><td>0.906</td><td>0.111</td></tr>
<tr><td>Vehicle Type</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Treatment</td><td>0.029</td><td></td><td></td><td></td><td>0.052</td><td></td><td>0.300</td><td>0.199</td></tr>
<tr><td rowspan="2">2-way</td><td>Vehicle Type * Treatment</td><td>0.027</td><td>0.048</td><td></td><td>0.089</td><td>0.020</td><td></td><td></td><td></td></tr>
<tr><td>Time * Treatment</td><td>0.847</td><td>0.530</td><td></td><td>0.055</td><td>0.972</td><td>0.221</td><td>0.067</td><td>0.327</td></tr>
</table>

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

Individual Vehicle Speed Change

The individual vehicle tracking speed data are contained in Table 35. The total change in speed obtained from the PMD treatments increased for all directions except for the outside direction of Site 4. The T-test proved that all differences between the baseline and PMD treatment evaluations were significantly different except for the inside direction of Site 3. The PMD treatments significantly increased the total change in speed at two of the curve direction and significantly reduced it at one direction. Again, the speed results were varied and inconsistent

In summary, there was no strong or clear indication that the Dot PMD or Full PMD treatments significantly reduced vehicle speed at either Site 3 or Site 4. Contrarily, it was deemed that the PMD treatment did not significantly increase speed. The speed findings were mixed and inconsistent and the findings suggest that the PMD treatments may have a negligible effect on a vehicle speed in a horizontal curve.

Table 35. Tracking Speed Data.

Curve location		Mean Speed Δ (mph)	
		Baseline	**PMD**
Site 3 (Dot PMD)	Inside	-2.17	-2.39
	Outside	-2.94	-3.55
Site 4 (Full PMD)	Inside	-1.14	-3.45
	Outside	-5.51	-5.00

The Univariate ANOVA test was conducted to evaluate the means of the tracking data. A total of four tests were performed and the results are contained in Table 36. The vehicle type was not significant in two of the four tests and both tests occurred on the inside curve direction. The main effects of the treatments were significant in all but one test, which took place on the outside curve direction of Site 4. This is similar to the previous ANOVA analysis where in Table 34 the PC and the MP locations on the outside direction of Site 4 were also not significant. The two-way interaction between treatment and time was not significant for all tests and the interaction between treatment and vehicle type was not significant for all but one test. In general, the treatment effects are the same regardless of vehicle type or time period.

Table 36. Speed ANOVA Test of Tracking Data.

<table>
<tr><th colspan="2" rowspan="2">Model Variables</th><th colspan="2">Site 3</th><th colspan="2">Site 4</th></tr>
<tr><th>Inside</th><th>Outside</th><th>Inside</th><th>Outside</th></tr>
<tr><td rowspan="3">Main Effect</td><td>Time</td><td>0.742</td><td>0.311</td><td></td><td>0.899</td></tr>
<tr><td>Vehicle Type</td><td>0.493</td><td></td><td>0.708</td><td></td></tr>
<tr><td>Treatment</td><td></td><td></td><td></td><td>0.395</td></tr>
<tr><td rowspan="2">2-way</td><td>Vehicle Type * Treatment</td><td>0.304</td><td></td><td>0.090</td><td>0.188</td></tr>
<tr><td>Time * Treatment</td><td>0.062</td><td>0.690</td><td>0.135</td><td>0.584</td></tr>
</table>

Note: Shaded squares signify statistical significances model variables and values above 0.01 were placed on the table.

Variance in Speed

The speed data standard deviations are contained in Table 37. The PMD treatments seemed to have a very minimal or negligible effect on the variance of speed at all of the curve locations. The greatest difference in standard deviations between evaluations was less than 0.5 mph. The F-test proved that all of the standard deviations are not significantly different. The Dot PMD and Full PMD treatments did not have a significant impact on the speed variance at all curve locations.

Table 37. Speed Standard Deviation.

Curve Location		**PC**		**MP**	
		Base	**PMD**	**Base**	**PMD**
Site 3	Inside	6.93	6.87	5.85	5.72
	Outside	6.65	6.17	5.76	5.32
Site 4	Inside	7.01	6.63	5.50	5.12
	Outside	6.19	6.43	5.03	5.38

SUMMARY AND RECOMMENDATIONS

Chevrons

Both the chevrons and the ChevFull treatment significantly improved vehicle lateral lane position. Improvements to lateral position were similar for both heavy and passenger vehicles and during night and day time periods. The benefits of chevrons and ChevFull treatments were effective and relevant in all test situations and treatments were not limited to selective applications such as only influencing passenger vehicles at night. This is somewhat surprising because the retroreflective material is highly visible at night and often the most prominent feature in the roadway scene. These findings of the significant daytime benefits of vertical delineation are a new contribution to the literature.

Chevrons and the ChevFull treatment significantly improved vehicle lateral position at both the PC and the MP locations. Both treatments induced drivers to move closer to the edgeline and away from vehicles traveling in the opposing direction. The curve flattening path was less apparent when chevron treatments were implemented. The variance in lateral lane position was significantly reduced at all curve locations. The treatments produced a lane position that was more uniform and consistent between curve locations. The lateral position findings for both chevrons and the ChevFull treatment were found to be similar. Both treatments achieved desirable lateral position results and neither treatment was deemed more beneficial or superior over the other.

The encroachment rates significantly improved when both chevron treatments were installed. Chevrons reduced the centerline 80-inch encroachment rate by approximately 93 percent and the ChevFull treatment reduced it by 88 percent. Also, both chevron treatments reduced the centerline encroachments for a 61-inch track vehicle to approximately zero at many of the locations. The centerline encroachment rate reduction was significant in all tests. Edgeline encroachments did significantly increase on an inside curve with a wide paved shoulder. Apart from that specific situation there were no other substantial or significant differences in edgeline encroachments.

The speed results were comparable to the lateral position findings in that both treatments were effective in reducing vehicle curve speed regardless of vehicle type or time period. Both chevron treatments significantly reduced speed at all curve locations. Chevrons achieved an average of 2.5 percent reduction in mean vehicle speed and the ChevFull treatment obtained an average of 4.0 percent reduction. In a direct comparison between both chevron treatments, the ChevFull treatment produced a statistically lower mean vehicle speed in five of the eight total tests. The variance in speed was not significantly reduced by either chevron treatment.

Chevrons and the ChevFull treatments both achieved advantageous and beneficial vehicle performance. The lateral position, vehicle tracking, and encroachment findings were similar and neither treatment was significantly more superior over the other. The ChevFull treatments did achieve a more substantial reduction in curve speed and should be implemented with the intent to curtail excessive vehicle curve speed. Therefore, it is recommended that both chevrons and the ChevFull treatments should continued to be implemented on horizontal curves and the ChevFull treatment should be considered as a viable option for reducing vehicle curve speed.

Post-Mounted Delineators

The Dot PMD and Full PMD treatments influenced drivers in a way that lead to more beneficial lateral lane position. The effects of both PMD treatments were similar to the findings from the chevrons and the ChevFull analysis where the PMD treatments achieved significant overall results regardless of vehicle type or time period. The evaluation determined that the Dot PMD and Full PMD treatments have broad applications and provide effective guidance to passenger and heavy vehicles during various periods of the day.

Dot PMD and Full PMD treatments significantly improved vehicle lateral position at both the PC and the MP locations. On average, both PMD treatments moved drivers away from the centerline and toward the edgeline by approximately a foot. This was a substantial roadway performance improvement from the baseline evaluation where vehicles were precariously close to the centerline at both the PC and MP locations. The Full PMD treatment proved to be effective in reducing the change in lateral position between curve locations and achieved approximately a 50 percent reduction on the inside direction and approximately a 75 percent reduction on the outside direction. The Dot PMD treatment did not significantly reduce or impact the change in lateral position between curve locations. Both PMD treatments were able to reduce the variance in lateral position by approximately 38 percent. In general, the Dot PMD and Full PMD treatments achieved a more uniform and consistent lane position at both the PC and MP.

The Dot PMD and Full PMD treatments significantly reduced the centerline encroachment rates. The baseline centerline encroachment rates were found to be alarmingly high. On average, the Dot PMD treatment achieved a 78 percent reduction for a vehicle with an 80-inch track width and 94 percent reduction for a 61-inch track width. The Full PMD treatment achieved a 77 percent reduction for an 80-inch track width and 88 percent reduction for a 61-inch track width. All reductions in rates were statistically significant and both treatments were considered extremely effective and beneficial. The edgeline encroachment rates either remained the same or were reduced slightly when the treatments were implemented. All changes in edgeline encroachments were considered acceptable.

The results from the speed data were inconsistent and it is determined that in this study the PMD treatments did not significantly lower or impact vehicle curve speed. Statistical tests of the mean vehicle speed provided inconclusive results and a majority of the tests were not significantly different. The standard deviation results were also similar and nearly all of the tests were not significantly different. It was concluded that the PMD treatments produced a negligible effect on vehicle curve speed.

In summary, the Dot PMD and Full PMD treatments achieved more uniform lane position, minimized vehicle tracking, and greatly reduced the centerline encroachment rates. Neither treatment was effective in lowering vehicle curve speed. Both treatments produced similar results, but the Full PMD treatment achieved a more substantial reduction in the curve flattening strategy. It is recommended that both Dot PMD and Full PMD treatments should be continued to be implemented on horizontal curves and the Full PMD treatment should be considered when a large number of vehicles are exhibiting a curve flattening path.

CHAPTER 5: COMPREHENSIVE GUIDELINE FOR DELINEATION FOR HORIZONTAL CURVES

This research project used a closed-course study and driver survey to identify promising new delineation treatments which were then tested in the field in the Bryan and Lufkin districts. The findings from the field study showed that when curves are marked with centerline, edgelines, and raised pavement markers (the baseline condition in this project) many vehicles enter the curve very close to the centerline and often encroach into the other lane or onto the shoulder. The use of any vertical delineation system greatly improved the lane position of vehicles day and night. It is therefore recommended that TxDOT districts increase their use of vertical delineation for horizontal curves on rural two-lane roads.

Post-mounted delineators with retroreflective sheeting the full length of the post did not have a significant effect on vehicle speed in curves, but did improve their lane position both at the entry to the curve and at its midpoint. It is therefore recommended that TxDOT consider changing its specifications for post-mounted delineators to call for a fully reflective post.

Chevrons had a large effect on both speed and lateral placement in the curve. Adding reflective sheeting to the post of a chevron did not produce any larger improvements than a standard chevron. It is therefore recommended that TxDOT maintain its current standards for chevron design.

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APPENDIX A: COMPILATION OF CURRENT TXDOT DELINEATION STANDARDS

Table A-1. Summary of Delineation Standards.

	Paved Urban Arterials and Collectors Width 20' ADT 6,000+	Paved Urban Arterials and Collectors Width 20' ADT 4,000+	Rural Arterials and Collectors Width 20' ADT 3,000+	Rural Arterials and Collectors Width 18' ADT 3,000	Traveled Ways Width 16' ADT N/A	Paved 2-way Traveled ways Width < 16' ADT N/A
Centerline	Standard	Guidance	Guidance	Guidance	Guidance	Option
No Passing Zone Markings	Standard*	Guidance	Guidance	Guidance	Guidance	Option
No Passing Zone Signs	Option	Option	Option	Option	Option	Option
Edgelines	Standard	Guidance	Guidance	Option	Option	Option
RPMs	Option	Option	Option	Option	Option	Option
Delineators	Option	Option	Option	Option	Option	Option
Barrier Reflectors	Option	Option	Option	Option	Option	Option
Chevrons	Option	Option	Option	Option	Option	Option

			Specific to Curves		
	All paved 2-way streets or highways with 3 or more lanes	Where Engineering Study Indicates a Need	Advisory Speed at Curve 0-14 MPH < Posted Speed	Advisory Speed at Curve 15-24 MPH < Posted Speed	Advisory Speed at Curve 25 MPH > Posted Speed
Centerline	Standard	Guidance			
No Passing Zone Markings	Standard*	Guidance			
No Passing Zone Signs	Option	Option			
Edgelines	Option	Guidance			
RPMs	Option	Option	Guidance	Guidance	Guidance
Delineators	Option	Option		Guidance	
Barrier Reflectors	Option	Option			
Chevrons	Option	Option			Guidance

*** See Combinations Table**

Table A-2. Summary of Guidance Concerning Combinations of Treatments.

Centerline Markings			
Combined With:	Centerline Markings	*no standards or guidance*	
	No Passing Zone Markings	Standard	Lane Reduction Transitions
		Standard	Approaches to Obstructions that Must Be Passed on the Right
		Standard	On Approaches to HRGC
		Standard	At Vertical and Horizontal Curves and Other Locations Based on Engineering Study (Inadequate Sight Distance at 85th Percentile Speed or Posted or Statutory Speed or Special Conditions); on 3-lane Roadways with Center Lane Transitions
	No Passing Zone Signs	Option	To Emphasize Existence and Extent of NPZ
	Edgelines	Option	May be Used With or Without CL
	RPMs	Guidance	To Supplement or Substitute Longitudinal Markings
		Option	Positioning Guides w/Longitudinal Markings (Spacing = 2N)
		Option	On Curves, Spacing May Be Reduced to N
	Delineators	Option	Long Continuous Sections with Changes in Horizontal Alignment
	Barrier Reflectors	*no standards or guidance*	
	Chevrons	*no standards or guidance*	
No Passing Zone Markings			
Combined With:	Centerline Markings	*no standards or guidance*	
	No Passing Zone Markings	*no standards or guidance*	
	No Passing Zone Signs	Option	To Emphasize Existence and Extent of NPZ
	Edgelines	*no standards or guidance*	
	RPMs	Guidance	To Supplement or Substitute Longitudinal Markings
	Delineators	Option	Long Continuous Sections with Changes in Horizontal Alignment
	Barrier Reflectors		
	Chevrons		

No Passing Zone Signs			
Combined With:	Centerline Markings	*no standards or guidance*	
	No Passing Zone Markings	*no standards or guidance*	
	No Passing Zone Signs	*no standards or guidance*	
	Edgelines	*no standards or guidance*	
	RPMs	Guidance	To Supplement or Substitute Longitudinal Markings
	Delineators	*no standards or guidance*	
	Barrier Reflectors	*no standards or guidance*	
	Chevrons	*no standards or guidance*	
Edgelines			
Combined With:	Centerline Markings	Option	May Be Used with or without CL
	No Passing Zone Markings	*no standards or guidance*	
	No Passing Zone Signs	*no standards or guidance*	
	Edgelines	*no standards or guidance*	
	RPMs	*no standards or guidance*	
	Delineators	Option	Long Continuous Sections with Changes in Horizontal Alignment
		Standard	When Used, Shall Conform to EL Color
	Barrier Reflectors	*no standards or guidance*	
	Chevrons	*no standards or guidance*	
RPMs			
Combined With:	Centerline Markings	Option	May Be Used to Substitute for CLs
	No Passing Zone Markings	*no standards or guidance*	
	No Passing Zone Signs	*no standards or guidance*	
	Edgelines	*no standards or guidance*	
	RPMs	*no standards or guidance*	
	Delineators	Option	Long Continuous Sections with Changes in Horizontal Alignment
	Barrier Reflectors	*no standards or guidance*	
	Chevrons	*no standards or guidance*	
Delineators			
m bi ne d Wi	Centerline Markings	*no standards or guidance*	

	No Passing Zone Markings	*no standards or guidance*	
	No Passing Zone Signs	*no standards or guidance*	
	Edgelines	*no standards or guidance*	
	RPMs	*no standards or guidance*	
	Delineators	*no standards or guidance*	
	Barrier Reflectors	Option	May Supplement Required Delineation; May Replace Optional Delineation
	Chevrons	Option	To Supplement Standard Delineators on Curves
Barrier Reflectors			
Combined With:	Centerline Markings	*no standards or guidance*	
	No Passing Zone Markings	*no standards or guidance*	
	No Passing Zone Signs	*no standards or guidance*	
	Edgelines	*no standards or guidance*	
	RPMs	*no standards or guidance*	
	Delineators	Option	May Supplement or Replace Optional Delineation
	Barrier Reflectors	*no standards or guidance*	
	Chevrons	*no standards or guidance*	
Chevrons	*no standards or guidance for any combination*		

Table A-3. Summary Guidance Concerning Yellow Centerline Pavement Markings.

Document	Yellow Centerline Pavement Markings / No-Passing Zone Pavement Markings				
	Section	*Requirement*	*Terms*	*Combination*	*Features*
Texas Manual on Uniform Traffic Control Devices	3B.01	Standard	CL markings shall be used to delineate separation of traffic lanes that have opposite directions of travel; shall be yellow		
		Standard	On 2-lane, 2-way roadways: for 2-direction passing zones - normal broken yellow line; for 1-direction no-passing zone - normal broken yellow line and solid yellow line; for 2-direction no-passing zones - two normal solid yellow lines (Figure 3B-1)		
		Standard	On undivided 2-way roadways with 4 or more lanes; use 2-direction no-passing zone markings of 2 solid yellow lines (Figure 3B-2).		
		Standard	CL shall be on paved urban arterials and collectors that have 20' or more in width and ADT of 6000 or greater.		
		Guidance	On 2-lane roadways with 3 or more through lanes, no passing zone markings for left-most lane (Figure 3B-3).		
		Guidance	CL markings should be placed on rural arterials and collectors with traveled way of 18 ft or more in width and an ADT of 3000 vpd or greater; on others with engineering studies indicating a need - especially those less than 16 ft wide		
		Option	May be placed at a location that is not the geometric center of the roadway.		
		Option	On roadways without continuous CL markings, short sections may be marked to control traffic position, such as around curves, over hills, etc.		
		Option	CL markings may be placed on other paved two-way traveled ways 16 ft or more in width		
	3B.02	Standard	NPZ shall be marked either 1-direction or 2-direction (Figures 3B-1 and 3B-3).		

		Standard	When CL used on two-way roadways, NPZ markings shall be used at lane reduction transitions and on approaches to obstructions that must be passed on the right	Y	NPZ w/CL
		Standard	When CL markings are used, NPZ markings shall be used on approaches to HRGC	Y	NPZ w/CL
		Standard	When CL markings are used on 2-way 2- or 3-lane roads, NPZ shall be established at vertical and horizontal curves and other locations where engineering studies indicate a need	Y	NPZ w/CL
		Standard	When CL markings are used, NPZ markings shall be used at vertical and horizontal curves where passing sight distance is less than the minimum necessary at 85^{th} percentile speed	Y	NPZ w/CL
		Standard	Table 3B-1 - Minimum Passing Sight Distances		
		Option	Should connect no-passing zones that are spaced less than 400 ft apart		
		Option	NPZ signs may be used to emphasize NPZ pavement markings	Y	NPZ signs w/NPZ
Manual on Uniform Traffic Control Devices	3B.1	Same as TMUTCD			
	3B.2	Same as TMUTCD			
TxDOT Traffic Engineering Standard Sheets	PM (1) - 03	Same as TMUTCD			

Table A-4. Guidance Concerning Edgeline Pavement Markings.

Document	Edgeline Pavement Markings				
	Section	*Requirement*	*Terms*	*Combination with Other Feature*	*Features*
Texas Manual on Uniform Traffic Control Devices	3B.06	Standard	EL markings shall delineate right or left edges of roadway		
		Standard	Except for dotted edge line extensions, EL markings shall not be continued through intersections or major driveways.		
		Standard	Right EL markings shall be a normal solid white line		
		Guidance	EL markings should not be broken for minor driveways		
		Option	Wide solid edge line markings may be used for greater emphasis		
		Support	EL markings have unique value as visual references to guide road users during adverse weather and visibility conditions		
	3B.07	Standard	EL markings shall be placed on rural arterials 20 ft wide or more with an ADT of 6,000 vpd or greater		
		Guidance	EL markings should be placed on rural arterials/highways 20 ft wide or more and ADT of 3,000 vpd or greater and at other facilities where engineering study indicates need		
		Guidance	EL markings should not be placed where engineering study/judgment indicates they will decrease safety		
		Option	EL markings may be placed on streets/highways with/without CL markings	Y	EL w/CL
		Option	EL markings may be excluded based on engineering judgment for reasons where edges are delineated by other treatments (curbs, parking, etc.)		
		Option	EL markings may be used to minimize unnecessary driving on paved shoulders/refuge areas with lesser structural strength		

Manual on Uniform Traffic Control Devices	3B.06	Same as TMUTCD			
	3B.07	Same as TMUTCD			
TxDOT Traffic Engineering Standard Sheets	PM (1) - 03	Same as TMUTCD			
TxDOT Signs and Markings Volume of Traffic Operations Manual	Chapter 10, Section 7	Standard	***ELs required on all undivided highways with traveled ways that are 20 feet wide or wider (<u>This is in conflict with the TMUTCD</u>).***		

Table A-5. Guidance Concerning Raised Pavement Markers.

Document	RPMs				
	Section	*Requirement*	*Terms*	*Combination with Other Feature*	*Features*
Texas Manual on Uniform Traffic Control Devices	3B.11	Standard	RPMs shall be intended to be used as a positioning guide or to supplement or substitute for pavement markings	Y	RPMs w/pvmt mkgs
		Standard	RPMs shall conform to color of marking for which they serve as a positioning guide, or for which they supplement or substitute		
		Standard	N for spacing of RPMs for a broken/dotted line shall equal the length of one line segment plus one gap; for a solid line shall equal the N for the broken/dotted lines that might be adjacent to or might extend the solid lines	Y	RPMs w/broken/ dotted line
		Guidance	Nonretroreflective(NRR) RPMs should not be used alone, without supplemental retroreflective (RR) or internally illuminated (II) markers, as a substitute for other types of pavement markings	Y	RPMs w/pvmt mkgs
		Guidance	Directional configurations should be used to maximize correct information and to minimize confusing information provided to the road user.		
		Guidance	Spacing of RPMs used to supplement or substitute for other types of longitudinal markings should correspond with the pattern of broken lines for which they supplement or substitute	Y	RPMs w/long mkgs

Texas Manual on Uniform Traffic Control Devices	3B.12	Option	RPMs may be used as positioning guides with longitudinal line markings; may be positioned between 2 lines of 1-way or 2-way NPZ marking or positioned in line with or immediately adjacent to single solid or broken centerline or lane line markings	Y	RPMs w/CL and NPZ markings
		Option	Where it is desired to alert the road user to changes in the travel path, such as on sharp curves . . . the spacing may be reduced to N or less.	Y	RPMs w/long mkgs
		Support	Typical spacing is 2N where N = length of one line segment plus one gap	Y	RPMs w/long mkgs
	3B.13	Guidance	Lateral Positioning: when supplementing double line markings, pairs of RPMs placed laterally in line with or immediately outside 2 lines to be used; when supplementing wide line markings, pairs of RPMs placed laterally adjacent to each other should be used	Y	RPMs w/double line markings
		Guidance	Longitudinal Positioning: when supplementing solid line markings, RPMs at a spacing no greater than N should be used, except when supplementing left ELs, a spacing of no greater than N/2 should be used; RPMs should not supplement right ELs; when supplementing dotted line markings, a spacing appropriate for the application should be used	Y	RPMs w/solid line markings
		Option	RPMs may be used to supplement other markings for channelizing islands or approaches to obstructions	Y	RPMs w/long mkgs
	3B.14	Option	RR or II RPMs, or NRR RPMs supplemented by retro or II RPMs, may be substituted for markings of other types		
		Guidance	Pattern/color of RPMs should simulate patter/color of markings they substitute; normal spacing of RPMs when substituting should be determined in terms of the standard length of the broken line segment		

		Option	Side of an RPM visible to opposing traffic may be red		
		Standard	If RPMs are used to substitute for broken line markings, a group of 3-5 markers equally spaced at a distance no greater than N/8 shall be used. If N is other than 40 ft, markers shall be equally spaced over the line segment length. At least 1 RR or II marker per group shall be used or a RR or II marker shall be installed midway in each gap between successive groups of NRR markers. When RPMs substitute for solid lane line markings, the markers shall be equally spaced at no greater than N/4 with RR or II units at a spacing no greater than N/2.		
		Guidance	RPMs should not substitute for right EL markings.		
		Standard	When RPMs substitute for dotted lines, shall be spaced at no greater than N/4 with not less than one RPM per dotted line. At least one RPM every N shall be RR or II.		
		Option	When substituting for wide lines, RPMs may be placed laterally adjacent to each other to simulate the width of a line.		

Manual on Uniform Traffic Control Devices	3B.11	Same as TMUTCD
	3B.12	Same as TMUTCD
	3B.13	Same as TMUTCD
	3B.14	Same as TMUTCD

TxDOT Traffic Engineering Standard Sheets	PM (2) - 00A	Position Guidance
	PM (3) - 00A	Supplemental Markings
	PM (4) - 03	2-Way Left-Turn Lanes Divided Highways and Rural Left-Turn Bays

TxDOT Signs and Markings Volume of Traffic Operations Manual	Chapter 10, Section 4	Guidance	RPMs should not be used in place of pavement markings for pavement marking arrows, symbols or words, except for wrong way arrows.
		Guidance	RR RPMs used to provide retroreflectivity, delineation and guidance, and enhance reflectivity of pavement markings
		Option	NRR RPMs (traffic buttons) may be used for shoulder texturing, to simulate striping patterns during construction.
	Chapter 10, Section 5	Standard	RPMs must be installed using position guidance spacing at a minimum.
		Option	RPMs may be used to supplement standard pavement markings to address safety concerns. Should not be used on a blanket, district-wide basis.

Table A-6. Guidance Concerning Delineator Posts.

Delineators

Document	*Section*	*Requirement*	*Terms*	*Combination with Other Feature*	*Features*
Texas Manual on Uniform Traffic Control Devices	3D.01	Option	Ds may be used on long continuous sections of highway or through short stretches where there are changes in horizontal alignment	Y	Ds w/CL & EL
		Support	Delineators (Ds) are RR devices used when changes in horizontal alignment or pavement width transitions exist. Ds are effective guidance devices at night and during adverse weather. An advantage in certain location is that they remain visible when roadway is wet or covered in snow.		
	3D.02	Standard	Ds shall be RR devices mounted above the roadway surface and along the side of the roadway in a series to indicate the alignment of the roadway. Ds shall consist of RR units that are capable of clearly retroreflecting light under normal conditions from a distance of 1,000 ft when illuminated by the high beams of standard auto lights. RR elements for Ds shall have a minimum dimension of 2-3/4".		

	3D.03	Standard	Color of Ds shall conform to color of EL in 3B.06; shall be provided on the right side of freeways and expressways and on at least one side of interchange ramps, except here: (a) on tangent sections of FWYs and EXPWs when all of the following conditions are met: -1- RPMs are used continuously on lane throughout all curves and on all tangents to supplement pavement markings; -2- where whole routes or substantial portions of routes have large sections of tangent alignment; -3- roadside Ds are used to lead into all curves. (b) on sections of roadways where continuous lighting is in operation between interchanges.	Y	Ds w/RPMs
		Option	Ds may be provided on other classes of roads. If used, see Table 3D-1		
		Option	Straight - D-SW may be used on right or left side; D-SY cannot be used on left side of 2-way roads; spacing of 200-500 ft		
		Option	Curve - D-SW may be used on right or left side; D-SY cannot be used on left side of 2-way roads; spacing varies based on horizontal curve radius - known or unknown - and advisory speeds.		
		Support	Ds uses are summarized in Table 3D-1.		
		Guidance	Red Ds should be placed on both sides of truck escape ramps. Should be spaced at 50' intervals for distance sufficient to identify the ramp entrance. Spacing beyond ramp entrance should be adequate for guidance according to the length and design of the escape ramp.		

		Guidance	Ds should be mounted on suitable support so that bottom of lowest RR is 4' above the near roadway edge. Should be placed 2-8' outside the outer edge of the shoulder, or if appropriate, in line with the roadside barrier that is 8' or less outside the outer edge of the shoulder. Should be placed at a constant distance from edge of roadway, except where an obstruction intrudes into the space between the pavement edge and the extension of the line of the Ds, they should be transitioned to be in line with or inside the innermost edge of the obstruction. If the obstruction is a guardrail, Ds should be transitioned to be either just behind, directly above (in line with), or on the innermost edge of guardrail.		
	3D.04	Guidance	Should be spaced 100' apart on ramp tangent sections. Height should be 4-5 feet above the edge of the travel line.		
		Option	When uniform spacing is interrupted by such features as driveways and intersections, Ds which would ordinarily be located within the features may be relocated in either direction for a distance not exceeding one quarter of the uniform spacing. Ds still falling within such features may be eliminated. Ds may be transitioned in advance of a lane transition of obstruction as a guide for oncoming traffic.		
		Guidance	Spacing of Ds should be adjusted on approaches to and throughout horizontal curves so that several Ds are always simultaneously visible to the road user. Approx. spacing is shown in Table 3D-1 and Figure 3D-2. Additional guidance in Table 3D-3.		
	5E.04	Option	Ds may be used on low-volume roads based on engineering judgment, such as for curves. In addition, they may be used to mark the location of driveways or other minor roads entering the low-volume road.		

Manual on Uniform Traffic Control Devices	3D.01	Same as TMUTCD			
	3D.02	Option	Elongated RR units of appropriate size may be used in place of 2 RR mounted as a unit.		
	3D.03	Same as TMUTCD			
	3D.04	Same as TMUTCD			
	5E.04				
TxDOT Traffic Engineering Standard Sheets	D & OM (2) - 04	Same as TMUTCD			
	D & OM (3) - 04	Spacing & Placement Information			
TxDOT Signs and Markings Volume of Traffic Operations Manual	Chapter 10, Section 6	Option	Use of Ds on conventional highways is optional.		

Table A-7. Guidance Concerning Barrier Reflectors.

Document	Barrier Reflectors				
	Section	*Requirement*	*Terms*	*Combination with Other Feature*	*Feature*
Texas Manual on Uniform Traffic Control Devices	3D.05	Option	If used, should not be used to replace required delineation, but may be used in place of optional delineation. For narrow bridged, BRs or delineation may be used on left side approach rail. When adequate lighting is provided, BRs may not be needed.	Y	w/Ds
		Support	BRs are RR devices used to inform motorists of the present of guardrail, bridge rail, or concrete barrier adjacent to roadway.		
Manual on Uniform Traffic Control Devices	Not in MUTCD.				
TxDOT Traffic Engineering Standard Sheets	D & OM (2) - 04	Same as TMUTCD			
	D & OM (3) - 04	Spacing & Placement Information			

Table A-8. Guidance Concerning Chevron Warning Signs.

Document	Chevrons				
	Section	*Requirement*	*Terms*	*Combination with Other Feature*	*Feature*
Texas Manual on Uniform Traffic Control Devices	3D-06	Option	Chevron Alignment (CA) (W1-8) sign may be used to provide additional emphasis and guidance for a change in horizontal alignment. CA sign may be used as an alternate or supplement to standard Ds on curves or to the One-Direction Large Arrow sign.	Y	CA w/Ds
		Standard	CA sign shall be vertical rectangle with no border. If used, signs shall be installed on the outside of a turn or curve, in line with and at approx. a right angle to approaching traffic.		
		Guidance	Spacing of CA signs should be such that the road user always has at least 2 in view, until the change in alignment eliminates the need for the signs. CA signs should be visible for a sufficient distance to provide the road user with adequate time to react to the change in alignment.		
		Support	Tables 3D-2, Figure 3D-3, and 3D-3 for more guidance.		
	5C.02	Option	Horizontal Alignment signs (Figure 5C-1 / Sign W1-8) may be used where engineering judgment indicates a need to inform the road user of a change in the horizontal alignment of the roadway.		
Manual on Uniform Traffic Control Devices	Not in MUTCD.				
TxDOT Traffic Engineering Standard Sheets	D & OM (2) - 04	Same as TMUTCD			

APPENDIX B: FIELD STUDY INFORMATION

CURVE MAPS

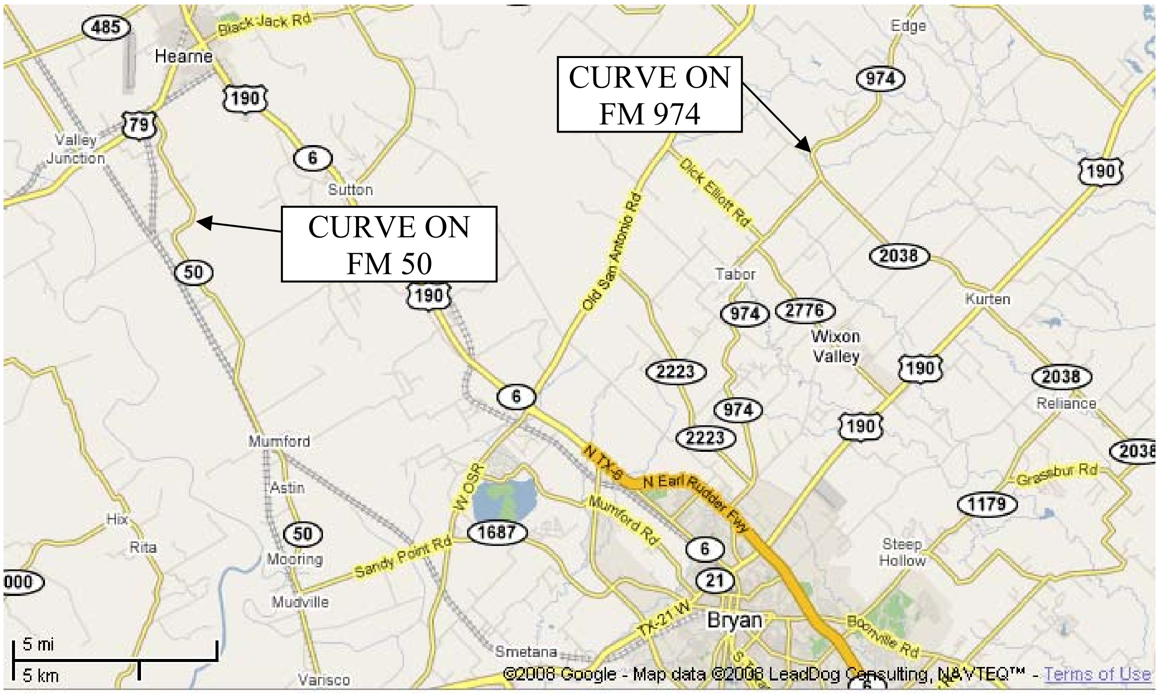

Figure B-1. Map of Bryan Curves.

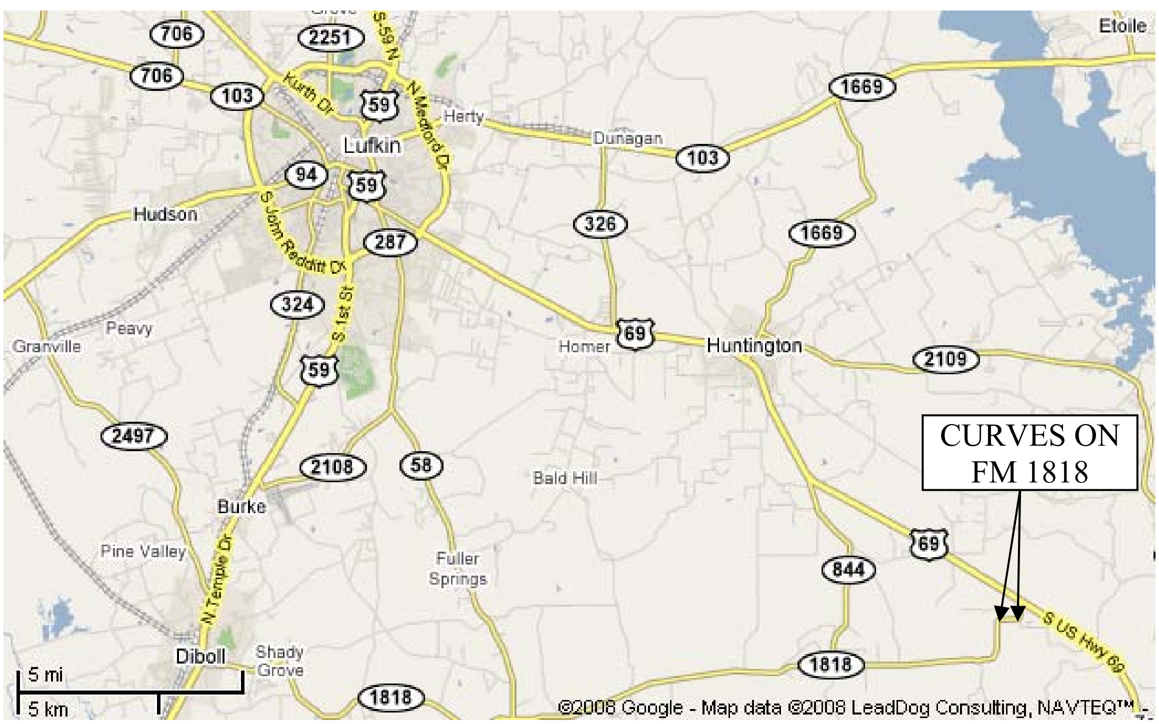

Figure B-2. Map of Lufkin Curves.

CURVE SCHEMATICS

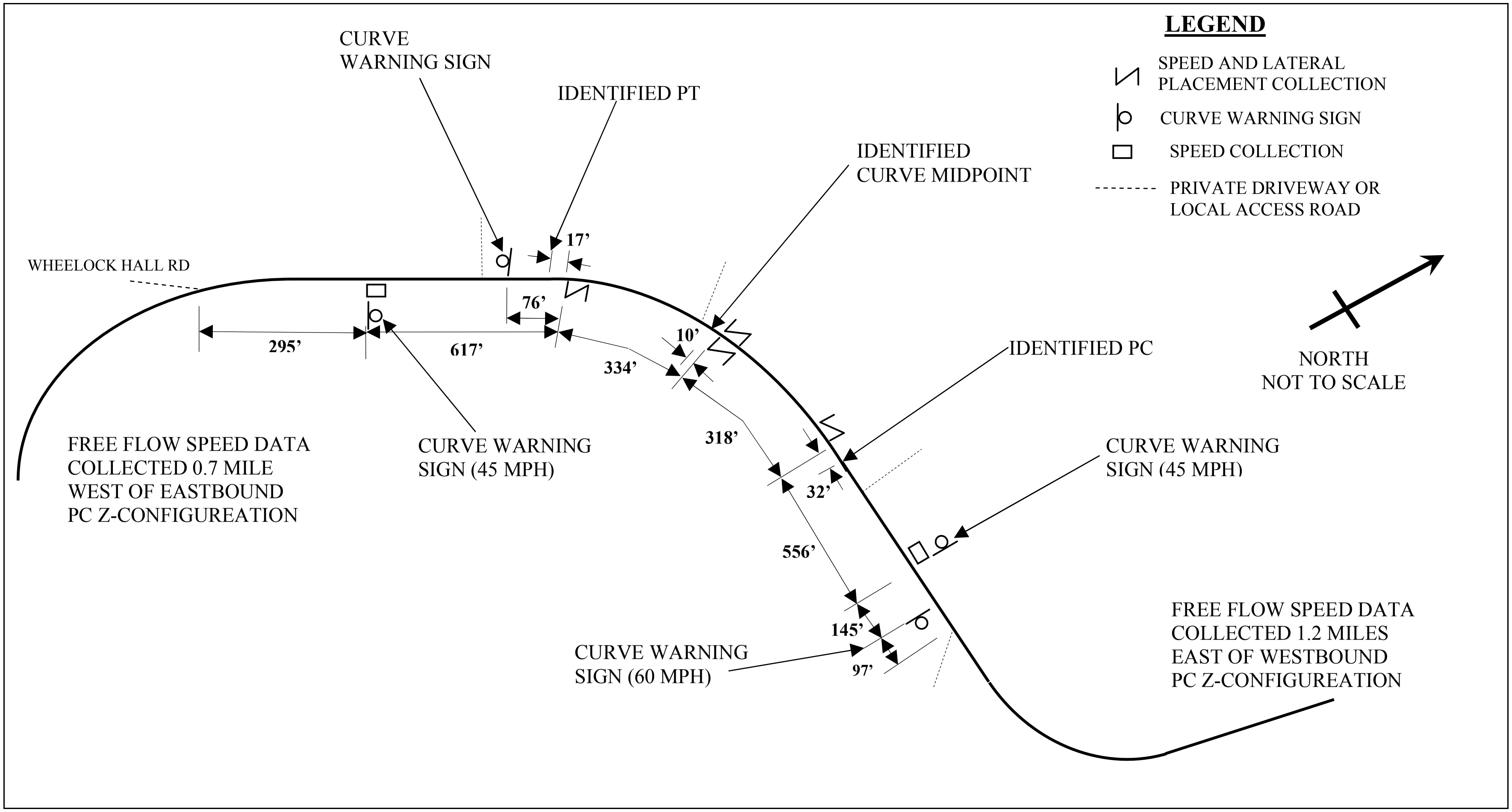

Figure B-3. FM 974 Curve Schematic.

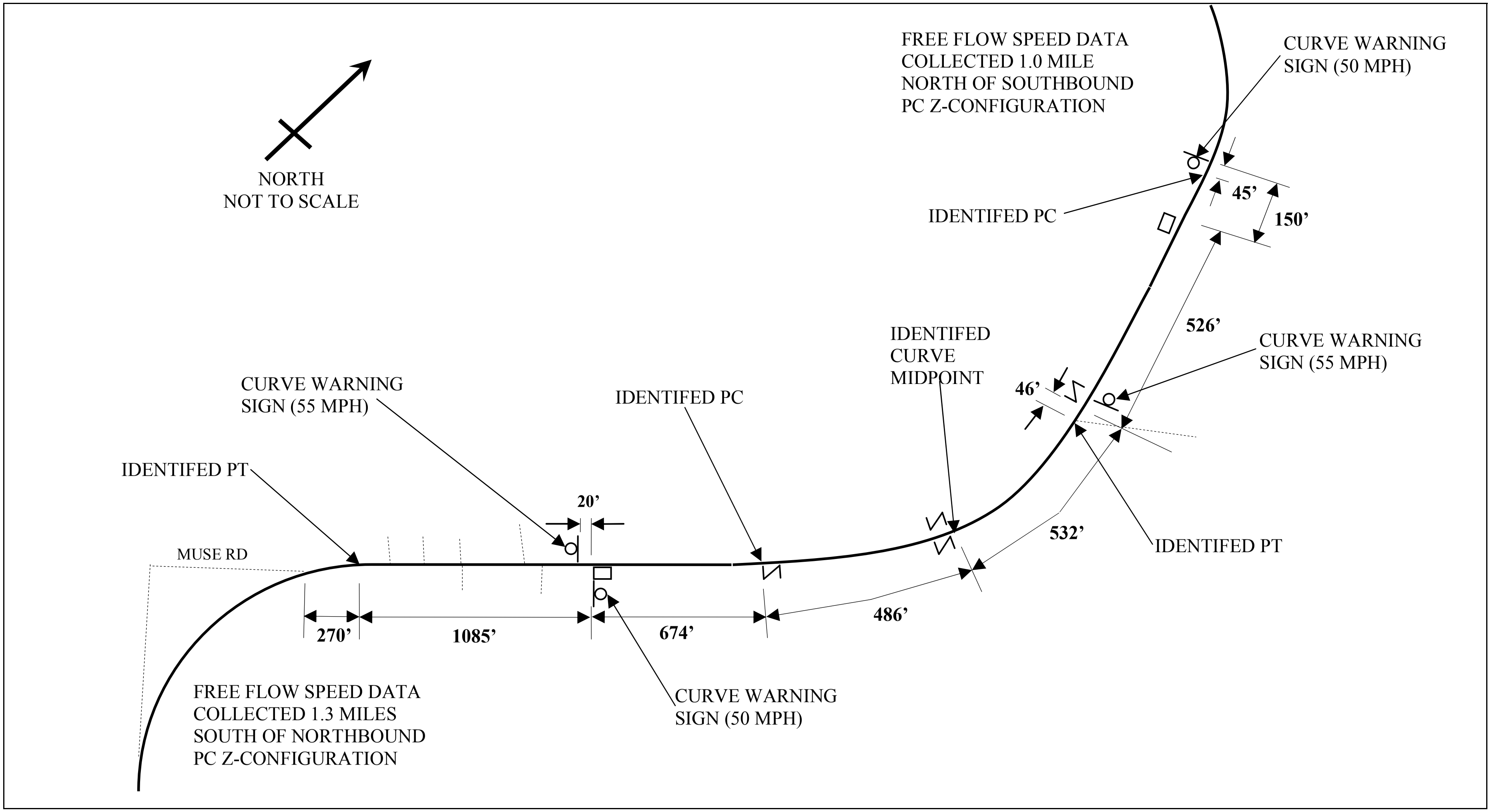

Figure B-4. FM 50 Schematic.

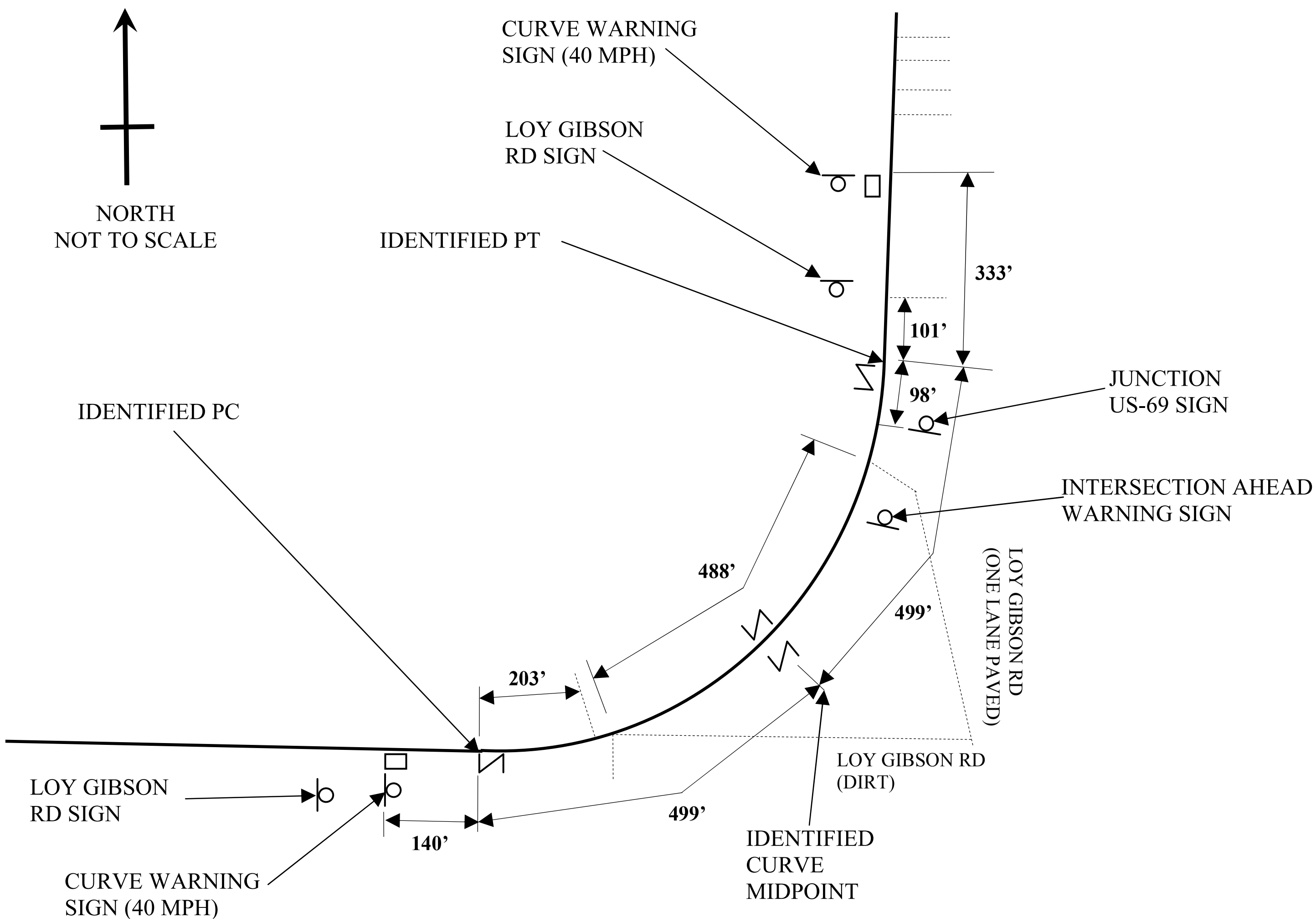

Figure B-5. FM 1818 CV1 Schematic.

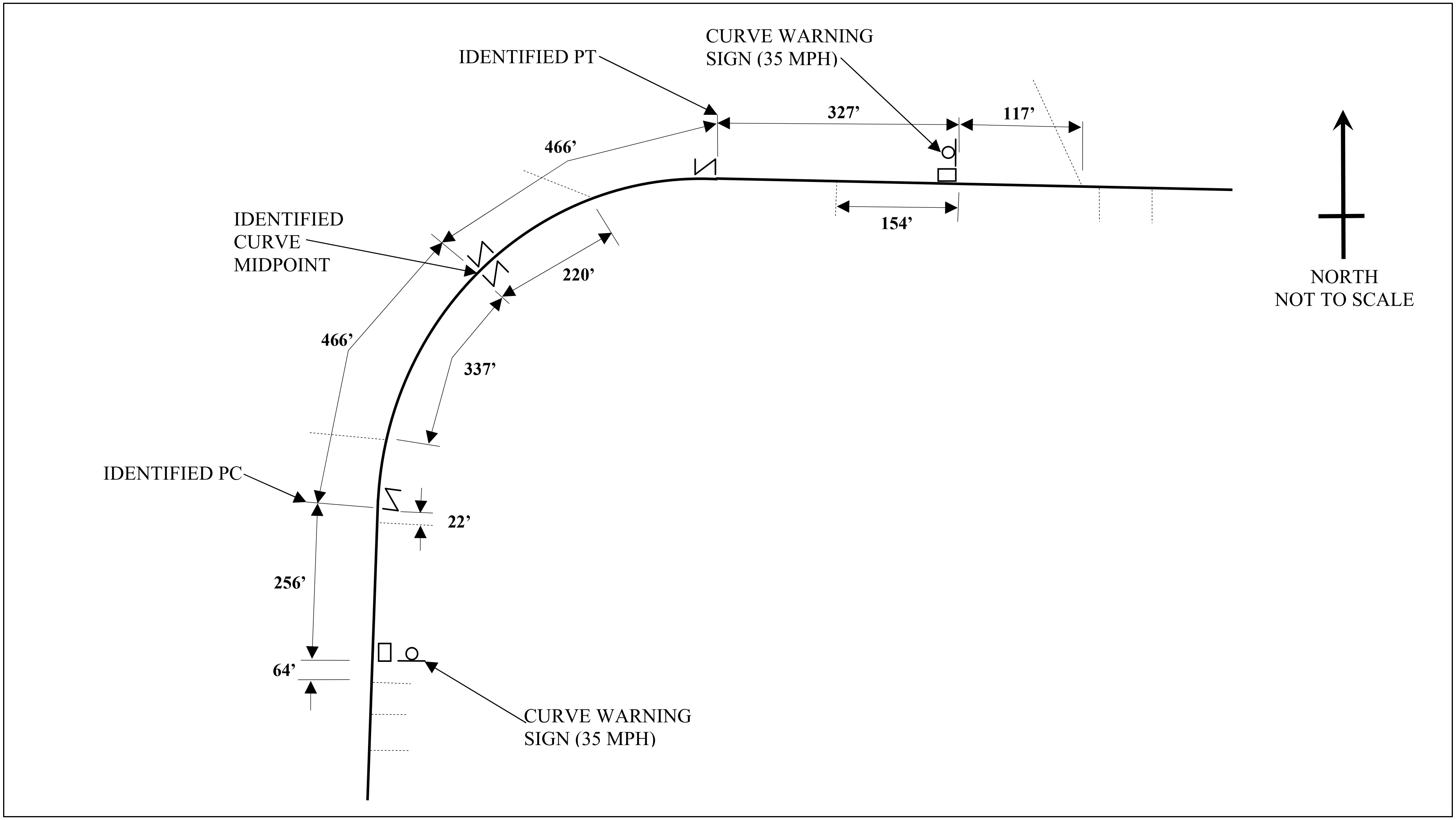

Figure B-6. FM 1818 CV2 Schematic.

UNIVARIATE ANOVA DATA

Table B-1. Overall Bryan Chevron ANOVA.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3307616.125(a)	13	254432.010	1367.770	.000
Intercept	121692664.547	1	121692664.547	654192.890	.000
Site	95657.761	1	95657.761	514.235	.000
Location	37024.142	1	37024.142	199.034	.000
Curve_Direction	445658.117	1	445658.117	2395.760	.000
Time	17339.735	1	17339.735	93.215	.000
Vehicle_Type	1285.632	1	1285.632	6.911	.009
Treatment	1135393.909	2	567696.954	3051.813	.000
Time * Treatment	6267.665	2	3133.832	16.847	.000
Curve_Direction * Treatment	16884.098	2	8442.049	45.383	.000
Location * Treatment	6446.792	2	3223.396	17.328	.000
Error	8177977.310	43963	186.020		
Total	409579607.248	43977			
Corrected Total	11485593.436	43976			