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Evaluation of Innovative Approaches to Curve Delineation for Two-Lane Rural Roads

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16. Abstract:

Run-off-road crashes are a major problem for rural roads. These roads tend to be unlit, and drivers may have difficulty seeing or correctly predicting the curvature of horizontal curves. This leads to vehicles entering horizontal curves at speeds that are too high, which can often lead to vehicles running off the roadway. This study was designed to examine the effectiveness of a variety of active and passive curve warning and curve delineation systems on two two-lane rural roads to determine which is the most effective at reducing vehicle speeds and assisting lane-keeping.

The study consisted of a human-factors study, as well as an observational study. There were nine curves examined in the study on two road sections in Southwest Virginia. The human-factors study included participants whose speed and lane position were tracked as they drove through eight curves, both before and after new treatments were installed in each of the eight curves. The observational study examined the speed and lane position of traffic on all the curves before and after the installation of the new treatments. The observational study included a curve on a road near the primary study section.

The results of the study were mixed, with every tested system leading to some reductions in speed or encroachments at some parts of the curve while also leading to increases in the same values at other parts of the curve. No clear difference was discovered between passive and active systems or between delineation and warning systems.

The study recommends that in addition to a safety assessment, specific curve characteristics and budget should be the main considerations in the selection of a treatment for a curve.

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Each contract report is peer reviewed and accepted for publication by staff of the Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

Run-off-road crashes are a major problem for rural roads. These roads tend to be unlit, and drivers may have difficulty seeing or correctly predicting the curvature of horizontal curves. This leads to vehicles entering horizontal curves at speeds that are too high, which can often lead to vehicles running off the roadway. This study was designed to examine the effectiveness of a variety of active and passive curve warning and curve delineation systems on two two-lane rural roads to determine which is the most effective at reducing vehicle speeds and assisting lane-keeping.

The study consisted of a human-factors study, as well as an observational study. There were nine curves examined in the study on two road sections in Southwest Virginia. The human-factors study included participants whose speed and lane position were tracked as they drove through eight curves, both before and after new treatments were installed in each of the eight curves. The observational study examined the speed and lane position of traffic on all the curves before and after the installation of the new treatments. The observational study included a curve on a road near the primary study section.

The results of the study were mixed, with every tested system leading to some reductions in speed or encroachments at some parts of the curve while also leading to increases in the same values at other parts of the curve. No clear difference was discovered between passive and active systems or between delineation and warning systems.

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INTRODUCTION

Run-off-road and head-on crashes accounted for 81% of fatal crashes occurring at horizontal curves, and the average crash rate for horizontal curves is approximately three times that of highway tangents (Srinivasan et al., 2009). It is important to investigate solutions to enhance the safety of horizontal curves.

The Virginia Department of Transportation (VDOT) is focused on identifying areas with critical levels of roadway-departure crashes. These areas are then evaluated to find the most appropriate safety treatment, whether a spot treatment or a complete systematic redesign of the section.

Researchers have suggested a wide range of treatments, from basic traffic signs and markings to advanced curve warning systems. Traditional passive methods of alerting drivers to upcoming curves (including signs, delineators and pavement markings) have been extensively utilized. While research has been conducted that considers the applications of these passive control measures, new technologies (e.g., active delineators and dynamic curve warning signs) are intended to provide additional safety benefits to drivers. Active delineators can be activated automatically by in-ground sensors, motion sensors, pavement loop detectors, radar, or ambient light. These active delineators do not rely on vehicle headlights and are visible regardless of the curvature of the roadway. Currently, VDOT typically implements geometric changes or static traffic control devices.

The effectiveness of a curve delineation treatment is measured by the ability of the treatment to provide the driver with the best possible navigation around curves and to reduce the possibility of crashes. National Cooperative Highway Research Program (NCHRP) Report 500, Volume 7 (Torbic et al., 2004), considers two objectives or strategies. The first strategy is to keep vehicles in their intended travel lanes, eliminating the crash. The second strategy, which is based on the idea that roadway-departure events are impossible to prevent, is to create a roadside that is forgiving of driver errors. Based on these two objectives, the treatments listed in Table 1 are recommended.

Table 1. Recommended treatments for improving safety at horizontal curve (NCHRP Report 500, Volume 7, Torbic et al., 2004)

Strategy	Treatment
Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve	• Provide advance warning of unexpected changes • Enhance delineation along the curve • Provide adequate sight distance • Install shoulder rumble strips • Install centerline rumble strips • Prevent edge drop-offs • Provide skid-resistant pavement surfaces • Provide grooved pavement • Provide lighting of the curve • Provide dynamic curve warning system • Widen the roadway • Improve or restore superelevation • Modify horizontal alignment • Install automated anti-icing systems • Prohibit/restrict trucks
Minimize the adverse consequences of leaving the roadway at a horizontal curve	• Design safer slopes and ditches to prevent rollovers • Remove/relocate objects in hazardous locations • Delineate roadside objects • Add or improve roadside hardware • Improve design and application of barrier and attenuation systems

Some of the suggested treatments can be prohibitively expensive, or even impossible in some places, such as widening the roadway. Typically, the treatments which are the easiest and cheapest to implement are providing advance warning of unexpected changes (e.g., a curve warning sign), and enhancing the delineation along the curve (e.g., chevrons). These types of treatments can be classified as either passive or active. Most current forms of warning and delineation systems are passive, meaning they are dependent on external light sources (e.g., daylight or vehicle headlights) for illumination. This results in the following limitations:

- Car headlights have a limited range around corners.
- The presence of moisture reduces visibility.
- Overhead illumination reduces the effectiveness of the delineation.

Active delineators and warning systems include internally lit lighting elements, typically light-emitting diodes (LEDs), and therefore do not rely on an external light source for visibility. This allows the system to be seen in situations where a passive system may not be visible, such as when an approaching vehicle's headlamps are aimed away from the system due to the curvature of the roadway. However, active delineation and warning systems are typically more expensive than passive systems, and cost more to maintain. Therefore, they may not be appropriate in all scenarios.

PURPOSE AND SCOPE

The purpose of this study was to assess the effectiveness of active and passive curve warning and delineation systems on a two-lane rural road, with respect to driver speed and lane keeping. A total of six treatments (3 passive and 3 active) were installed across nine curves, and a before-and-after analysis was performed.

The results of an extensive literature review and survey were documented in an interim report. The focus of this report is on the field testing phase of this study.

METHODS

This study consisted of two different data collection efforts. The first was a human-factors study in which participants drove experimental vehicles on a test route while their speed and lane position was tracked through each curve. The second data collection effort was an observational study which utilized pneumatic road tubes arranged in a Z configuration to measure the speed and lane position of traffic at three points along each curve. Data were collected before and after new treatments were installed at each of the curves of interest.

The baseline (i.e., "before") data for the observational study was collected between November 2014 and February 2015. The installation of the new treatments occurred over the summer of 2016 and was completed in July 2016. The "after" data were collected in November and December 2016, allowing a period of time for traffic to acclimate to the new treatments.

The baseline data for the human-factors study were collected in March and April 2016, with a total of 36 participants. The “after” data were collected in October and November 2016 with 28 of the original 36 participants. However, one of these participant’s data had to be omitted due to the loss of their “before” data.

Experimental Design

The human-factors study used a 2 Age Group x 2 Treatment (i.e., “before” and “after”) full-factorial design. A participant’s data were included in the analysis only if they completed both the before and after data collection sessions (n = 27). Treatment was the only factor in the observational study.

Independent Variables

Between-Subjects Variables (Human-Factors Study)

Gender

Gender had two levels: female and male. The gender independent variable was chosen in order to generalize the results of this study to a broad user population. This factor was used for balance only; it was not used in the data analysis.

Age

Age had two levels: younger (18–34) and older (60+). The younger and older age groups were chosen to investigate changes in vision and perception that occur with age. For example, older drivers benefit from experience, but their age-related visual and physiological characteristics might cause them to perceive the roadway differently. On the other hand, younger drivers may react to the roadway environment differently because they have less driving experience but may have better vision.

Within-Subjects Variables (Human-Factors Study)

Treatment

Treatment had two levels: before and after. This variable was chosen in order to examine how driver behavior changed when a new treatment was introduced to a curve. The particular type of treatment varied between curves, so each curve was analyzed separately.

Observational Study Variables

Treatment

Treatment had two levels: before and after. This variable was chosen in order to examine how driver behavior changed when a new treatment was introduced to a curve. The particular type of treatment varied between curves, so each curve was analyzed separately.

Categorical Analysis Variables

Lane

Lane had two levels: Inner and Outer. Because each curve is experienced differently depending on which lane/direction of travel a driver is in, the analyses were divided between the inner and outer lanes.

Segment

In the human-factors study, curves were conceptually divided into four segments in order to examine driver behavior in different parts of the curve. Figure 1 illustrates the four segments which are similar to those described in NCHRP Report 600C (Campbell et al., 2010). Segment 1 includes the area between the tangent and the first point of curvature (PC), and is analogous to the “curve discovery” segment. Segments 2 include the area from the first point of curvature to the middle point (MP). Segment 3 includes the area from the middle point to the second point of curvature. These two segments combined are analogous to the “entry and negotiation” segment as described in NCHRP Report 600C (Campbell et al., 2010). Finally, segment 4 includes the area from the second point of curvature to the second tangent, and is analogous to the “exit” segment. Each segment of each curve was analyzed separately for each lane of travel.

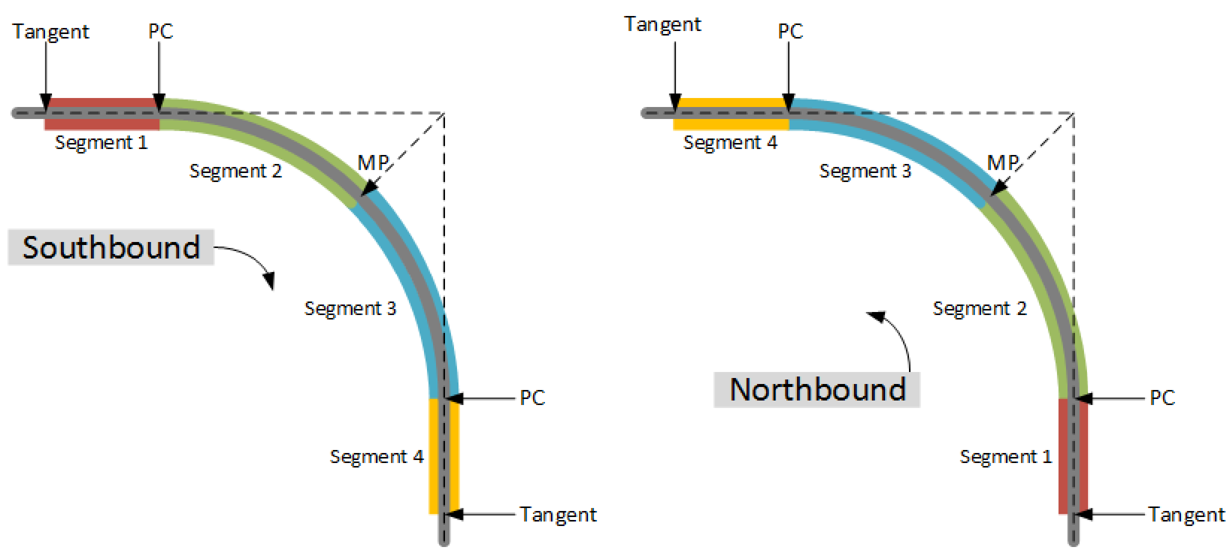

Figure 1. Curve segments (human-factors study)

Point

In the observational study, data were collected at three points in each curve. These included the two points of curvature, and the middle point. The points were numbered sequentially based on the direction the vehicle was travelling (Figure 2). Data was collected at these three points in order to examine driver behavior in different parts of the curve. Each point of each curve was analyzed separately for each lane of travel.

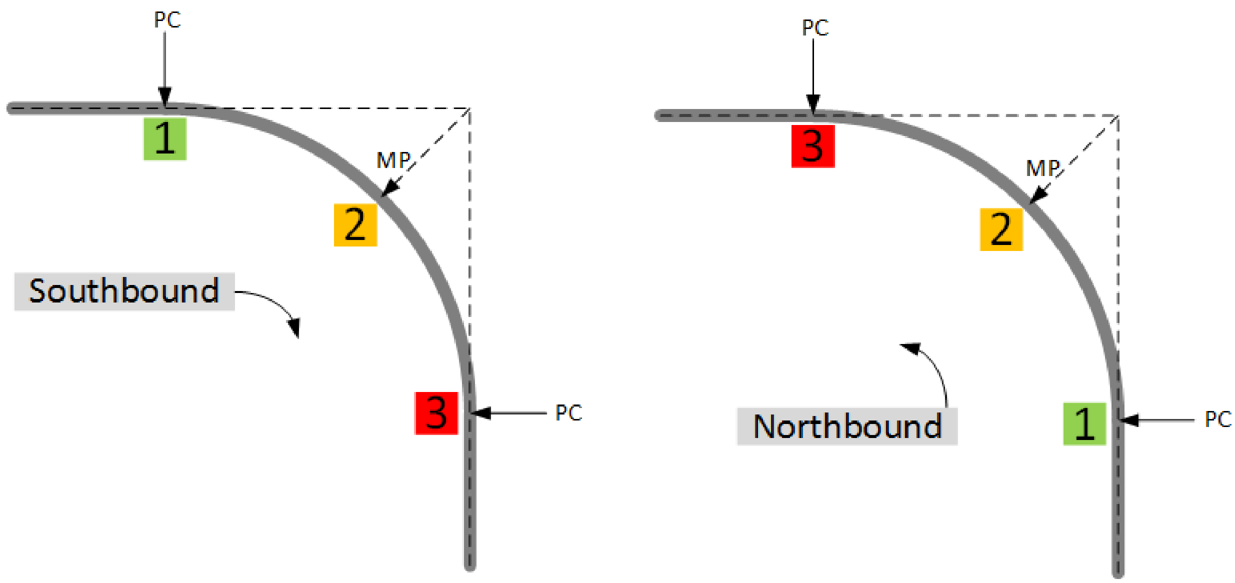

Figure 2. Curve points (observational study)

Time

Time had two levels: Day and Night. For the observational study, data were collected over a full 24-hour period at each curve point. Due to the differences that exist in the visibility of the roadway, and the visibility of the treatments in daytime vs. nighttime conditions, the data were divided by the time of day. Additionally, the times were restricted to off-peak hours. Daytime data were restricted to 9:00 am to 4:00 pm. Nighttime data were restricted to 8:00 pm to 6:00 am. Data collected during each time frame were analyzed separately.

Dependent Variables

Speed

In the human-factors study, participants' speed was tracked through each curve segment. In the observational study, the instantaneous speed of a vehicle was recorded at each of the three points.

Offset

Offset was defined as the distance from the center line of the vehicle to the center of the lane, with negative values representing distances that were to the left of center, and positive values representing distances to the right of center.

Encroachment

In the human-factors study, encroachment was defined as occurring when the left side of the vehicle was at least 200 mm (0.2 m) (0.66 ft) over the inside edge of the center line, or when the right side of the vehicle was at least 200 mm (0.2 m) over the inside edge of the right edge line. In the observational study, encroachment was defined as occurring when the left tire was at least 200 mm (0.2 m) over the middle of the center line, or when the right tire was at least 200 mm (0.2 m) over the middle of the right edge line.

Curves

A total of 9 curves were selected for inclusion in this study. In collaboration with VDOT personnel, it was decided that the Route 615 corridor would be the main focus of the study due to the large number of problematic curves. One additional curve located on Route 8 was also included, but only in the observational data collection. The curves are shown in Figure 3. Curve 8 was an S curve that was subdivided into two separate curves (8.1 and 8.2). Curve 8.1 was not included in the human-factors study due to a malfunction in the new treatment. Curve 8.2 was not included in the observational study due to its proximity to a gas station which would have affected the flow of traffic through the curve. Characteristics of each of the curves are shown in Table 2.

Table 2. Curve characteristics

Location	Route No.	Latitude	Longitude	Posted Speed Limit (mph)	Advisory Speed (mph)	AADT (2015)	Radius (ft)	Length (ft)	Lane width (ft)
Curve 1	615	37.1119	-80.3788	45	35	2909	406	465	10.5
Curve 2	615	37.1087	-80.3782	45	30	2909	580	343	10.1
Curve 3	615	37.0913	-80.3902	45	30	3169	400	466	10.5
Curve 4	615	37.0881	-80.3911	45	30	3169	392	504	11
Curve 5	615	37.0651	-80.3749	45	25	3303	207	232	10.2
Curve 6	615	37.0641	-80.3744	45	25	3303	230	320	10.3
Curve 7	615	37.0629	-80.3717	45	15	3303	84	252	10.3
Curve 8	615	37.0591	-80.3737	45	30/25	3303	274	254	10
							337	302	
Curve 9	8	37.05368	-80.43945	55	45	8,900	605	699	10.3

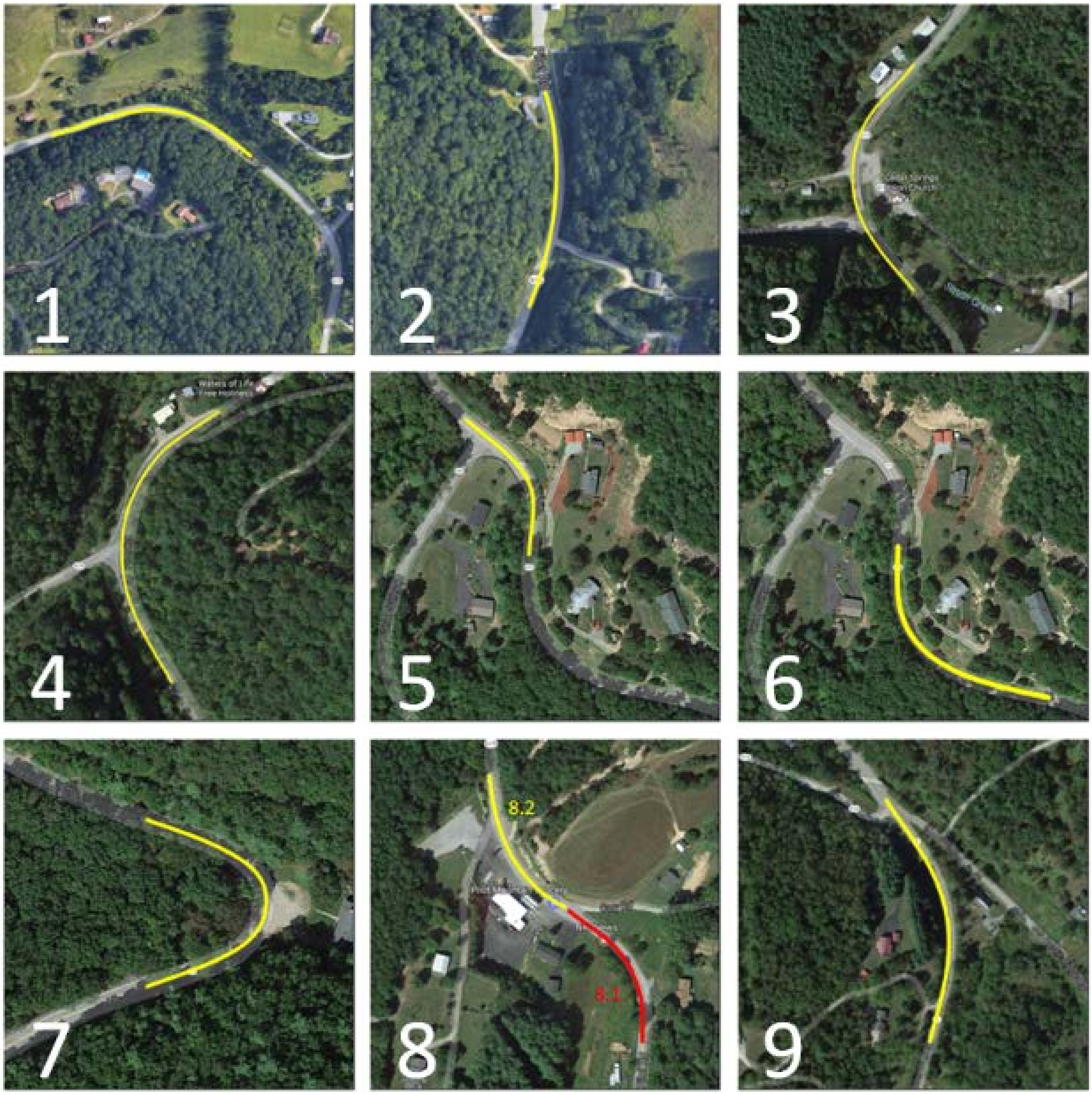

Figure 3. Selected curves on Route 615 (#1-8), and Route 8 (#9)

Curve Treatments

The research team provided VDOT with a list of recommended treatments for each curve based on existing treatments, and the curve characteristics. VDOT made the final decision on the selected treatments and then coordinated the purchase and installation of each of the treatments. Table 3 lists the existing treatments for each curve (before), and the additional treatment that was installed for the study (after).

Table 3. Curve treatments

	Measurement Phases	
Location	**Before (Existing)**	**After (Additional)**
Curve 1	Curve Warning Sign + Chevrons	Retroreflective Posts
Curve 2	Winding Road Sign	Sequentially Flashing Chevrons
Curve 3	Winding Road Sign	Blinking Curve Warning Sign
Curve 4	Winding Road Sign	On-pavement Signage
Curve 5	Winding Road Sign	Dynamic Curve Warning Sign
Curve 6	None	Continuous Guardrail Reflectors
Curve 7	Curve Warning Sign	On-pavement Signage
Curve 8	Winding Road Sign	Dynamic Curve Warning Sign
Curve 9	Chevrons	Retroreflective Posts

Active Treatments

Sequentially flashing chevrons were added to curve 2. This was a BlinkerChevron dynamic curve warning and guidance system purchased from Traffic & Parking Control Company (TAPCO). This solar powered system used radar to detect oncoming vehicles, which then activated the LEDs embedded in each sign in sequence using wireless communication (Figure 4). The sign used 3M diamond grade cubed (DG3) sheeting.

Figure 4. Promotional image of BlinkerChevron system

A blinking curve warning sign was added to curve 3. This was a BlinkerSign curve warning sign purchased from TAPCO. This solar powered system used radar to detect oncoming vehicles, which then activated the LEDs embedded in the sign (Figure 5). The sign used 3M diamond grade cubed (DG3) sheeting.

Figure 5. Promotional image of a BlinkerSign

A dynamic curve warning sign (DCWS) was added to curves 5 and 8. This was a vehicle activated traffic calming system (VATCS) purchased from Unipart Dorman. This solar-powered system used radar to measure the speeds of oncoming vehicles. When a vehicle was detected exceeding the advisory speed, a curve sign and a "SLOW DOWN" message appeared on the sign, as well as four flashing circles in each corner of the sign (Figure 6).

Figure 6. Promotional image of a dynamic curve warning sign

Passive Treatments

The passive treatments used materials commonly used by VDOT. For curves 1 and 9, 2 in x 48 in yellow diamond grade sheeting was applied to the posts of each existing chevron. For curves 4 and 7, preformed thermoplastic was used to create on-pavement signage which consisted of two white bars, a curved arrow, and the word "SLOW." For curve 6, reflectors were added to the guardrail along the outside of the curve. These consisted of 1.5 in x 36 in 3M linear delineation panels with white diamond grade sheeting, each spaced approximately 36 in apart. The reflectors were adhered to the guardrail using double-sided 3M VHB tape.

Equipment

Traffic Data Recorder

The traffic data recorder used to measure the speed and lane position of traffic in the observational study was a TRAX Apollyon from JAMAR Technologies, Inc. Three pneumatic tubes were connected to one recorder, and configured in a Z pattern. The distances and angles shown in Figure 7 were measured at the time of installation. Three recorders and nine tubes were used to collect data at all three points for a single curve for approximately 24 hours and were then moved to the next curve. This was repeated until 24 hours of data were collected for all curves.

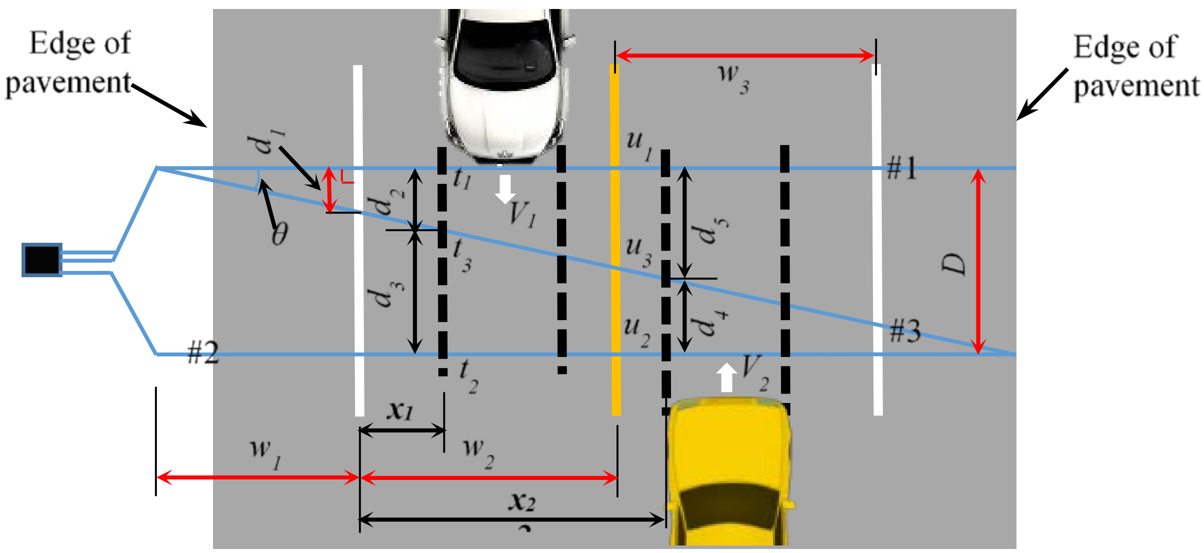

Figure 7. Pneumatic tube Z configuration for measuring vehicle speed and lane position

The before and after data were collected for each of the 3 points of the curve during weekdays, and in clear weather. To assure the validity of each data collection point, the data for each location was analyzed shortly after collection. Due to unforeseen circumstances such as rain, very low temperature, or equipment malfunctions, the data collection was repeated for some locations. Each data collection point provided enough data to disaggregate the sample for separate daytime and nighttime analyses.

Experimental Vehicles

The experimental vehicles used in the human-factors study included a 2005 Infiniti FX35 SUV, and a 2002 Cadillac STS sedan. In order to increase the amount of data, each participant drove the test route twice; once in each vehicle. By having participants switch vehicles between laps, the research team tried to prevent participants from becoming too comfortable with the route for their second lap.

Each vehicle was equipped with a data acquisition system (DAS). The DAS recorded camera views inside and outside the vehicle, as well as speed, GPS location, and other variables. Each vehicle was also equipped with a Road Scout system which used computer vision to track lane markings to determine lane position, lane width, and line type among other variables.

Participants

A total of 36 participants took part in the human-factors study. All 36 participants completed the "before" data collection, and 28 of those participants completed the "after" data collection. Eight participants did not complete the "after" data collection because they were not available or chose not to return. Participants were required to have a minimum visual acuity of 20/40, and a valid driver's license, as well as meet the following criteria:

1. Must drive at night at least 2 times per week.
2. Must be comfortable driving on an unlit, curvy rural road at night.
3. Must be a U.S. citizen or hold a green card and be willing to complete a W9 tax form which includes providing their SSN.
4. Must not have more than two moving violations in the past three years.
5. Must have normal (or corrected to normal) hearing and vision.
6. Must be able to drive an automatic transmission vehicle without assistive devices.
7. Must not have caused an injurious accident in the past three years.
8. Cannot have lingering effects of heart condition, brain damage from stroke, tumor, head injury, recent concussion, or infection.
9. Cannot have had epileptic seizures within 12 months, uncontrolled current respiratory disorders or require oxygen, motion sickness, inner ear problems, dizziness, vertigo, balance problems, uncontrolled diabetes for which insulin is required, chronic migraine or tension headaches.
10. Cannot currently be taking any substances that may interfere with driving ability, cause drowsiness or impair motor abilities.
11. Must be at least 18 years old.
12. Must not have a history of eye injury or eye surgery.

Experimental Procedure

An experimenter drove the participants from VTTI to a parking lot in Christiansburg, VA located near the test route. Participants were then escorted to one of the two experimental vehicles, and in-vehicle experimenters oriented each participant to the vehicle controls. The experimenters then reviewed the instructions for the task.

The in-vehicle experimenter gave the participant directions, monitored the DAS, and offered to answer questions or provide assistance if needed, but otherwise did not interact with the participant during the drive. Participants were instructed to obey all traffic laws, and to drive in a responsible manner.

In order to prevent the two participants from interfering with each other during the drive, one participant started the drive, while the other waited approximately 2 minutes before starting. Participants first drove a short route around downtown Christiansburg in order to acclimate to the vehicle, before being instructed to drive the test route. Participants then drove approximately 8 miles down Route 615, which included curves 1 through 8. Participants then stopped in the parking lot of a post office. The first participant waited for the second to reach the post office before beginning the return trip in order to avoid having participants drive past each other in opposite directions. The second vehicle again waited approximately 2 minutes to keep a safe distance between the vehicles.

Once both participants completed the first lap, driving the route in both the southbound and northbound directions, they switched cars in the starting parking lot, and performed the same task again. Once the second lap was complete, the participants were shuttled back to VTTI where they were compensated for the session. Participants were paid at a rate of $30 per hour, prorated for the amount of time they participated.

Data Analysis

Human-Factors Study

Two analyses of variance (ANOVAs) with confidence intervals of 95% ($\alpha = 0.05$) were conducted for each segment of each lane for each curve; one for speed, and one for offset. This resulted in up to 16 analyses for each curve. Data for participants that did not complete the "after" session were not included in the analysis. One other participant's "before" data were lost, and so their data were also excluded from the analysis. The data for the 27 participants (13 younger, and 14 older) that completed both data collection sessions were analyzed. In some instances, the Road Scout system had difficulty tracking the lane lines, which affected the offset measurement. For the analysis, the offset was only calculated when the Road Scout system was able to precisely track the right lane line. Of the 228,386 data points collected, 160,817 data points had valid offset data.

Observational Study

Two ANOVAs with confidence intervals of 95% ($\alpha = 0.05$) were conducted for each point of each lane of each curve in each time frame; one for speed, and one for offset. This resulted in up to 24 analyses for each curve. Data in which the speed of a vehicle was measured as more than 20 mph over the regulatory speed limit, or the offset was more than 3m were removed from the data prior to analysis as these were likely errors or extreme behavior that did not represent typical driving behavior. Additionally, only free flow vehicles were included in the analyses. To this end, data in which the headway between a vehicle and the vehicle in front of it was less than 5 seconds was removed prior to analysis as that vehicle's speed would likely be affected by the vehicle in front of it. Table 4 shows approximate number of vehicles with usable data for each curve and lane. The number is approximate because the vehicle count was not always exactly the same at each of the three curve points.

Table 4. Approximate number of vehicles for each curve

Curve	Lane	DAY		NIGHT	
		Before	After	Before	After
1	Inner	411	462	265	249
	Outer	525	546	88	94
2	Inner	348	357	195	234
	Outer	398	436	83	70
3	Inner	438	334	122	220
4	Inner	472	503	114	88
	Outer	352	361	245	247
5	Outer	429	355	159	307
6	Inner	468	576	168	126
	Outer	403	390	214	267
7	Inner	384	426	239	305
	Outer	518	521	130	113
8.1	Outer	513	552	155	100
9	Inner	741	930	426	403
	Outer	629	562	207	271

RESULTS

Retroreflective Posts on Existing Chevrons

Curve 1

The existing treatments for curve 1 consisted of a curve warning sign (CWS), and several chevrons. The new treatment consisted of adding retroreflective material to the posts of the existing chevrons (Figure 8). This was a bidirectional treatment (two chevrons per post). The distance from the point of curvature to the first chevron was approximately 42ft in the inner lane, and 23ft in the outer lane. The ANOVA results of the human-factors study are shown in Table 5. Due to the large number of analyses, only the P values are shown. Values in boldface indicate significant results ($p < 0.05$).

Figure 8. Curve 1 treatment – retroreflective material on chevron posts

Table 5. ANOVA results for Curve 1 (human-factors study)

Curve 1 (Retroreflective Posts) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Inner	Age	0.9146	0.8785	0.6595	0.5571	**0.0404**	0.2631	0.2470	0.0532
	Treatment	**0.0188**	**0.0038**	**0.0269**	**0.0122**	0.1129	**0.0293**	**0.0027**	0.1403
	Age*Treatment	0.4373	0.5878	0.5008	0.6420	0.9717	0.1182	0.3963	0.5128
Outer	Age	0.7598	0.5629	0.6404	0.7149	0.4611	0.2198	0.7162	0.9616
	Treatment	0.4509	0.5757	0.9646	0.7035	**0.0274**	**0.0002**	**0.0481**	0.2383
	Age*Treatment	0.4106	0.2141	0.3541	0.4443	0.2406	0.2729	0.6302	0.3543

Values in boldface indicate significant results.

The treatment had a significant effect on participant speed in all segments of the inner lane, but had no effect for the outer lane. This may be because the speed for outer lane was already much lower due to an adjacent curve, so there was not much room for further reduction (Figure 9). The mean speed of the inner lane was decreased by 1.7 mph, bringing the mean speed to a similar level for both lanes.

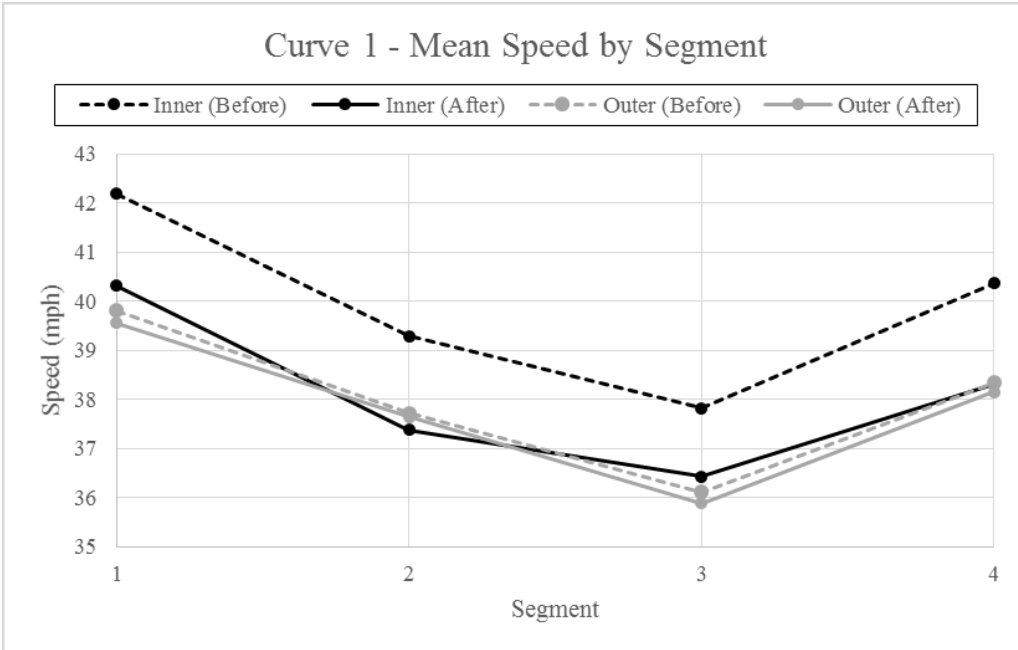

Figure 9. Curve 1 – Mean speed by segment

Figure 10 shows the mean offset for participants in each lane both before and after the installation of the retroreflective posts. The figure is formatted to represent the participants' driving lane, with the upper edge representing the center lane line, and the height of the figure approximating the lane width. The center of the lane is represented by a white line. Negative offset values (top half of the figure) represent distances to the left of center, and positive values (bottom half of the figure) represent distances to the right of center.

The treatment caused a slight shift in offset toward the outside of the curve for both lanes; the offset for the inner lane shifted slightly to the left in all but one segment, while it shifted slightly to the right for the outer lane in all segments. The changes were small, however, with the largest difference (127 mm) occurring in segment 2 for the outer lane.

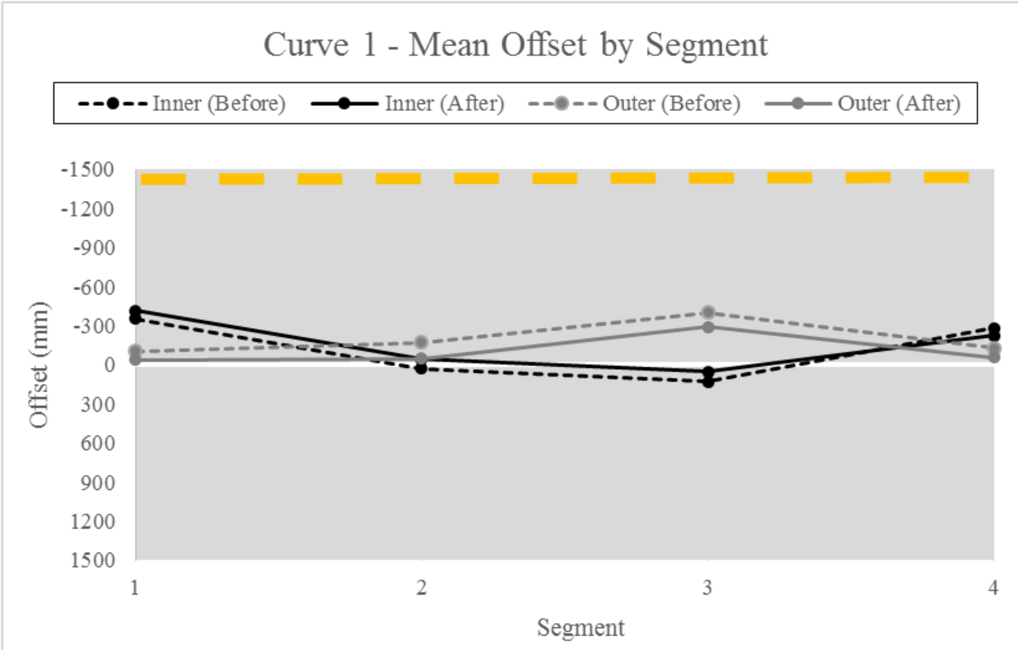

Figure 10. Curve 1 - Mean offset by segment

The ANOVA results for the observational study are shown in Table 6. The majority of factors and interactions were found to be significant for both speed and offset. Values in boldface indicate significant results ($p < 0.05$).

Table 6. ANOVA results for Curve 1 (observational study)

Curve 1 (Retroreflective Posts) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Inner	0.8180	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	Outer	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Night	Inner	**0.0149**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	Outer	**0.0001**	0.2667	0.0557	**<.0001**	**<.0001**	**<.0001**

Values in boldface indicate significant results.

Figure 11 shows the mean speed by point in day and night conditions. In both cases, the mean speed for the inner lane actually increased after the installation of the new treatment, with the exception of point 1 in daytime conditions. The mean speed for the outer lane decreased at all points in both day and night, but the difference was only significant at the point of entry (point 1) for the nighttime conditions.

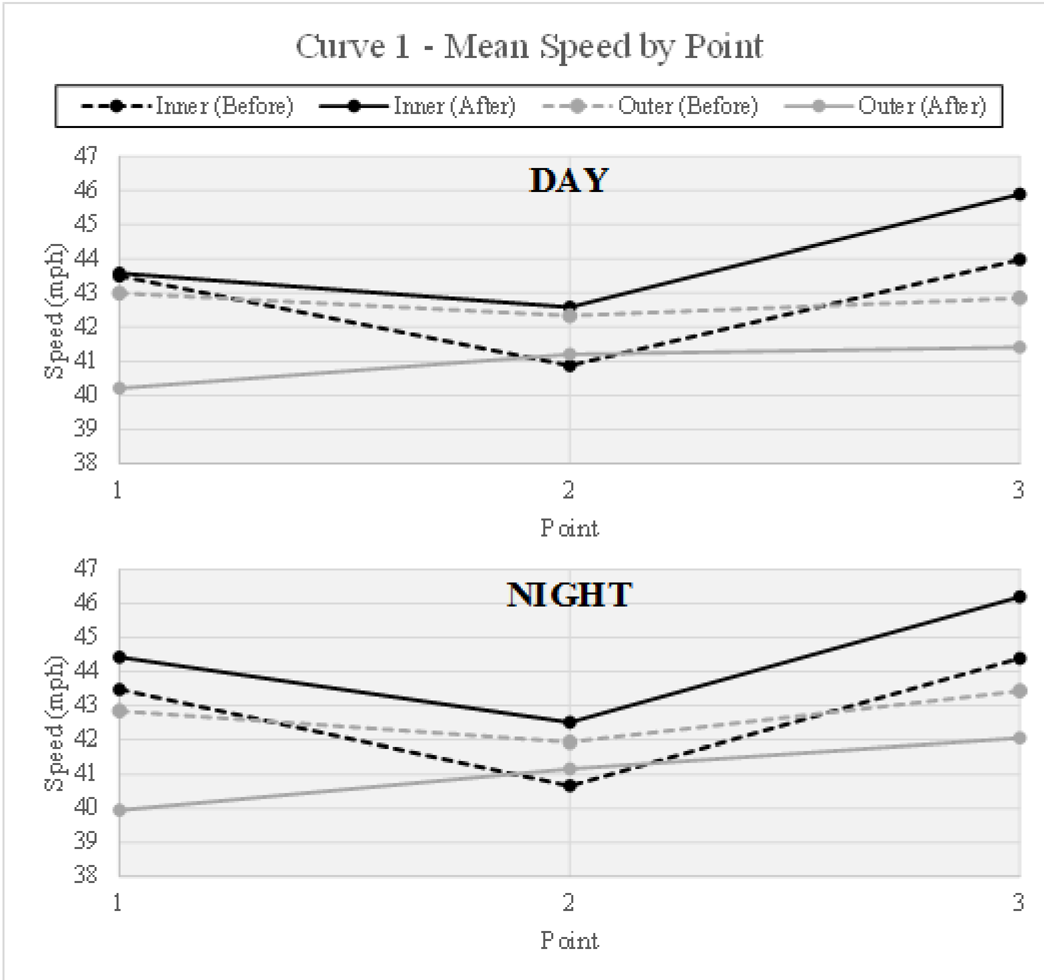

Figure 11. Curve 1 - Mean speed by point

The mean offset was significantly affected at all points for all conditions; however, the difference at point 1 for the inner lane was very small (Figure 12). After the addition of the retroreflective posts, traffic in the inner lane shifted further to the right, toward the inside edge of the curve at points 2 and 3. Similarly, traffic in the outer lane entered the curve closer to the right edge at point 1, but then shifted left toward the inside of the curve in points 2 and 3. Traffic in both lanes seemed to follow more of a racing line through the curve, in which they entered the curve further to the outside, and then hugged the inside of the curve as they navigated through. At points 1 and 2, vehicles were typically further from the center of the lane after the new treatment.

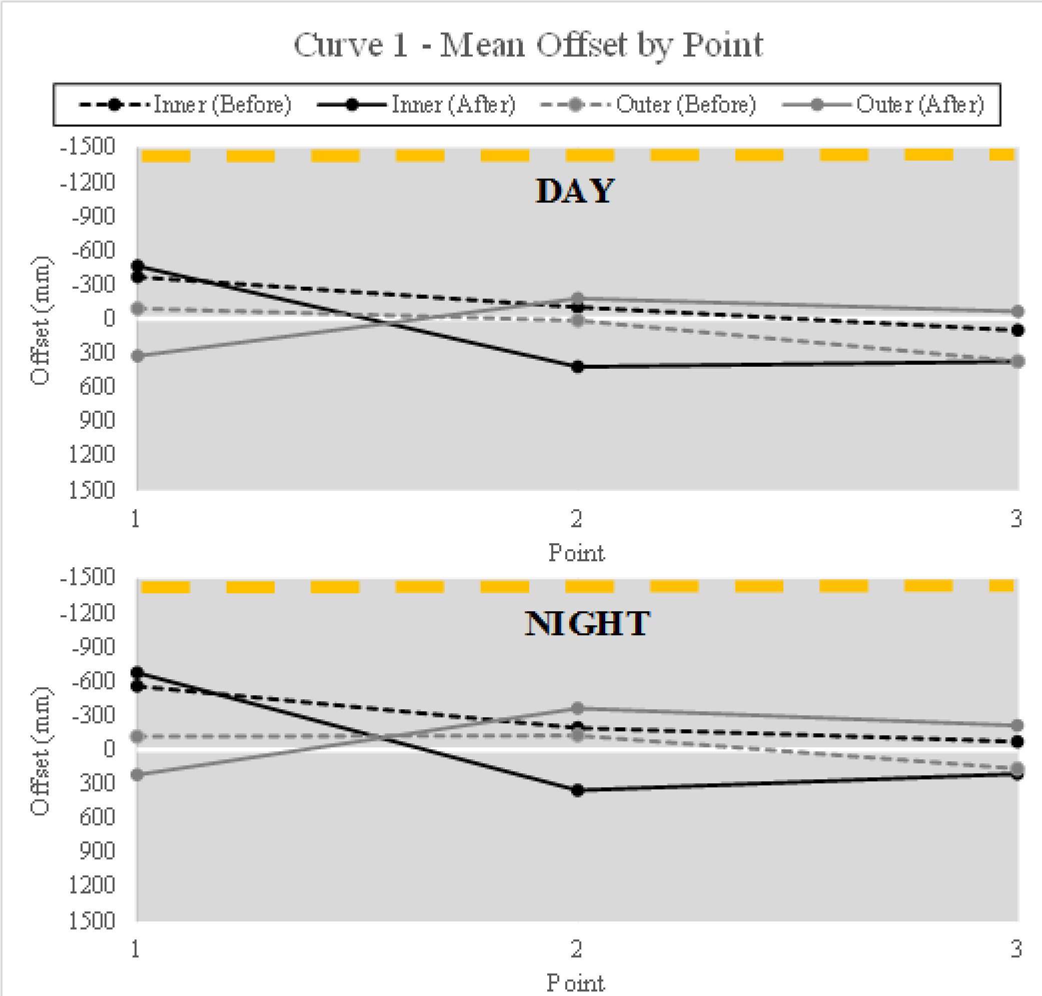

Figure 12. Curve 1 - Mean offset by point

Curve 1 Summary

The addition of the retroreflective material to the posts of the existing chevrons had opposite effects for traffic in the inner lane vs the outer lane. Traffic in the inner lane tended to speed up, and traffic in the outer lane tended to slow down. Table 7 shows the change in the 85th percentile speed, the percentage of vehicles exceeding the advisory speed, and the percentage of lane encroachments. The 85th percentile speed and the percentage of vehicles exceeding the advisory speed was calculated for each lane using the data at points 1 and 2 (the entry and middle points of the curve), as these are the most critical locations for speed when navigating a curve. The percentage of encroachments was calculated using all points. Changes greater than 1mph or 1% are highlighted in red. Changes less than -1mph or -1% are highlighted in green.

Table 7. Change in 85th percentile speed, percent exceeding advisory speed, and percent encroachments (observational)

85th Percentile Speeds (mph)					
Time		Lane	Before	After	Change
Day		Inner	46.8	48.3	1.4
		Outer	47.4	44.9	-2.5
Night		Inner	46.3	48.2	1.9
		Outer	47.5	44.8	-2.7
Percent Over Advisory Speed Limit (35mph)					
Time	Lane	Over Limit	Before	After	Change
Day	Inner	>5 mph	42.1%	39.5%	-2.6%
		>10 mph	22.6%	26.5%	3.9%
		>15 mph	4.4%	7.0%	2.6%
		>20 mph	0.4%	1.0%	0.6%
	Outer	>5 mph	42.9%	45.1%	2.1%
		>10 mph	26.4%	13.2%	-13.2%
		>15 mph	4.6%	1.4%	-3.2%
		>20 mph	0.0%	0.2%	0.2%
Night	Inner	>5 mph	44.4%	39.8%	-4.6%
		>10 mph	20.9%	32.5%	11.6%
		>15 mph	3.4%	6.1%	2.7%
		>20 mph	0.2%	0.8%	0.6%
	Outer	>5 mph	35.1%	42.4%	7.3%
		>10 mph	26.4%	14.7%	-11.8%
		>15 mph	5.2%	0.5%	-4.6%
		>20 mph	1.1%	0.0%	-1.1%
Percent Encroachments					
Time	Lane	Line	Before	After	Change
Day	Inner	Center	1.1%	1.3%	0.2%
		Edge	0.0%	2.2%	2.2%
	Outer	Center	0.3%	2.0%	1.6%
		Edge	2.2%	0.0%	-2.2%
Night	Inner	Center	3.0%	2.9%	-0.1%
		Edge	0.0%	1.3%	1.3%
	Outer	Center	3.0%	5.7%	2.6%
		Edge	0.8%	0.0%	-0.8%

(pink) = an increase greater than 1mph or 1%

(green) = a decrease greater than 1mph or 1%

For the 85th percentile speed, the treatment had opposite effects for the inner and outer lane, with the 85th percentile speed increasing for the inner lane and decreasing for the outer lane in both day and night conditions. Similarly, the percentage of vehicles exceeding the advisory speed by 10mph or more was significantly reduced for the outer lane, but increased for the inner lane. Because traffic in both lanes tended to drive closer to the inside of the curve with the new treatment, there was an increase in edge line encroachments for the inner lane, and an increase in center line encroachments for the outer lane.

Curve 9

The existing treatments for curve 9 consisted of a CWS, and several chevrons. The new treatment consisted of adding retroreflective material to the posts of the existing chevrons (Figure 13). The treatment was visible from both directions. The distance from the point of curvature to the first chevron was approximately 180ft for both lanes. This curve was not included in the human-factors data because it was located on a different roadway than the other curves. The ANOVA results for the observational study are shown in Table 8. Values in boldface indicate significant results ($p < 0.05$).

Figure 13. Curve 9 treatment – retroreflective chevron posts

Table 8. ANOVA results for Curve 9 (observational study)

Curve 9 (Retroreflective Posts) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Inner	0.2840	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	Outer	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0006**	0.3668
Night	Inner	0.8740	**<.0001**	**0.0001**	**<.0001**	**<.0001**	**<.0001**
	Outer	0.1175	**<.0001**	**0.0093**	**<.0001**	**0.0191**	0.0557

Values in boldface indicate significant results.

For traffic in the inner lane, the mean speed decreased significantly at point 2, but increased at point 3 (Figure 14). For traffic in the outer lane, the opposite was true; the mean speed increased at point 2, and decreased at point 3. The mean speed for both lanes converged at point 2. Similar patterns were seen across day and night conditions, but the speeds tended to be slightly higher at night.

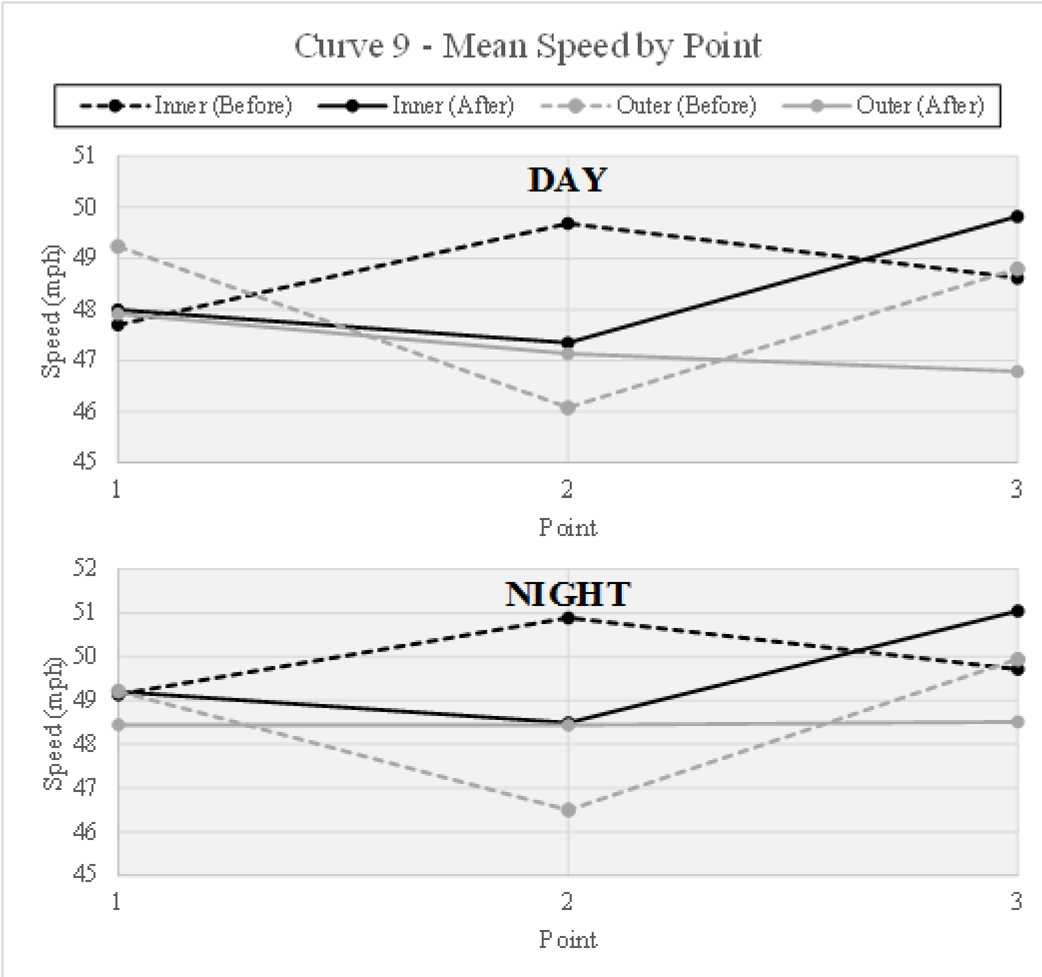

Figure 14. Curve 9 - Mean speed by point

For the inner lane, the mean offset was closer to the center of the lane at points 1 and 2 following the installation of the reflective posts, but was slightly further from center at point 3. For traffic in the outer lane, the offset was shifted left at point 1, but virtually unchanged at points 2 and 3. The mean offset for both lanes was more consistent through the curve following the installation of the reflective posts.

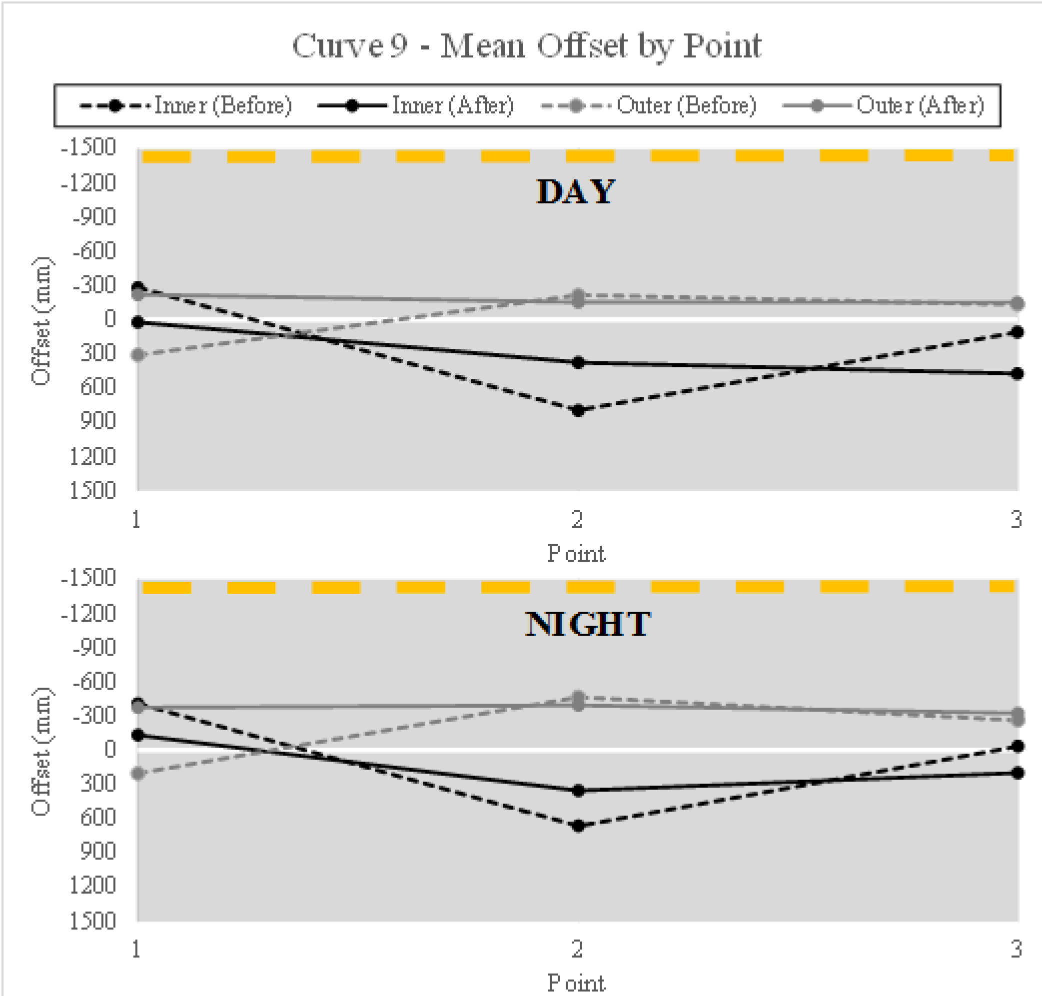

Figure 15. Curve 9 - Mean offset by point

Curve 9 Summary

The large reduction in mean speed at point 2 for inner lane traffic resulted in a decrease of the 85th percentile speed (Table 9). Although the speed for the outer lane increased at point 2, this was offset by a decrease in point 1, so the result was still a slight decrease in 85th percentile speed. With the exception of nighttime, outer lane traffic going between 5 and 10 mph over the advisory speed, the percentage of vehicles exceeding the advisory speed (45 mph) decreased across the board. There was also very little change in the percentage of speeding vehicles. Although speeds were overall reduced, center line encroachments increased; particularly for traffic in the inner lane.

Table 9. Change in 85th percentile speed, percent speeding, and percent encroachments (observational)

85th Percentile Speeds (mph)					
Time		**Lane**	**Before**	**After**	**Change**
Day		Inner	53.7	52.6	-1.2
		Outer	52.1	51.7	-0.4
Night		Inner	54.3	54.0	-0.3
		Outer	52.4	53.0	0.5
Percent Over Advisory Speed Limit (45mph)					
Time	**Lane**	**Over Limit**	**Before**	**After**	**Change**
Day	Inner	>5 mph	30.6%	27.3%	-3.2%
		>10 mph	8.8%	5.7%	-3.1%
		>15 mph	1.0%	0.1%	-0.9%
		>20 mph	0.1%	0.2%	0.1%
	Outer	>5 mph	26.4%	25.4%	-0.9%
		>10 mph	4.4%	3.1%	-1.3%
		>15 mph	0.2%	0.4%	0.2%
		>20 mph	0.2%	0.0%	-0.2%
Night	Inner	>5 mph	40.4%	32.0%	-8.4%
		>10 mph	10.3%	7.5%	-2.9%
		>15 mph	2.0%	1.4%	-0.6%
		>20 mph	0.5%	0.4%	-0.1%
	Outer	>5 mph	25.4%	32.7%	7.3%
		>10 mph	6.1%	5.5%	-0.6%
		>15 mph	1.2%	0.9%	-0.3%
		>20 mph	0.2%	0.0%	-0.2%
Percent Encroachments					
Time	**Lane**	**Line**	**Before**	**After**	**Change**
Day	Inner	Center	1.3%	6.4%	5.1%
		Edge	7.8%	1.0%	-6.8%
	Outer	Center	2.8%	2.3%	-0.5%
		Edge	0.3%	0.1%	-0.2%
Night	Inner	Center	1.5%	10.8%	9.3%
		Edge	4.7%	0.9%	-3.8%
	Outer	Center	5.0%	6.0%	1.0%
		Edge	0.2%	0.0%	-0.2%

(red) = an increase greater than 1mph or 1%

(green) = a decrease greater than 1mph or 1%

Sequentially Flashing Chevrons

Curve 2

There was no existing treatment for curve 2 other than a Winding Road sign upstream of the curve. The new treatment consisted of four chevron signs with LEDs around the perimeter of the chevrons that flashed in sequence when an approaching vehicle was detected by radar (Figure 16). This treatment was bidirectional. The distance from the point of curvature to the first chevron was approximately 30ft for both lanes. The ANOVA results for the human-factors study are shown in Table 10. Values in boldface indicate significant results ($p < 0.05$).

Figure 16. Curve 2 treatment – sequentially flashing chevrons

Table 10. ANOVA results for Curve 2 (human-factors study)

Curve 2 (Sequentially Flashing Chevrons) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Inner	Age	0.6267	0.9624	0.8957	0.3730	0.7514	0.3516	0.2403	0.0557
	Treatment	0.4006	0.4056	0.8468	0.0995	0.1750	0.4505	0.1259	0.5588
	Age*Treatment	0.8511	0.6998	0.7150	0.8195	0.3072	0.6949	0.2620	0.6585
Outer	Age	0.9858	0.9382	0.9444	0.8218	0.6530	0.5696	0.8447	0.9127
	Treatment	**0.0283**	**0.0372**	0.0716	0.2506	**0.0005**	0.2038	0.0623	0.6806
	Age*Treatment	0.6407	0.8309	0.4487	0.4188	0.9468	0.8384	0.3388	0.8174

Values in boldface indicate significant results.

Following the installation of the sequential chevrons, the mean speed was reduced at each segment for both lanes of travel. However, the change was only statistically significant in segments 1 and 2 for the outer lane (Figure 17). Although the largest difference in means occurred at point 3 for the outer lane, the difference was not statistically different due to the variance.

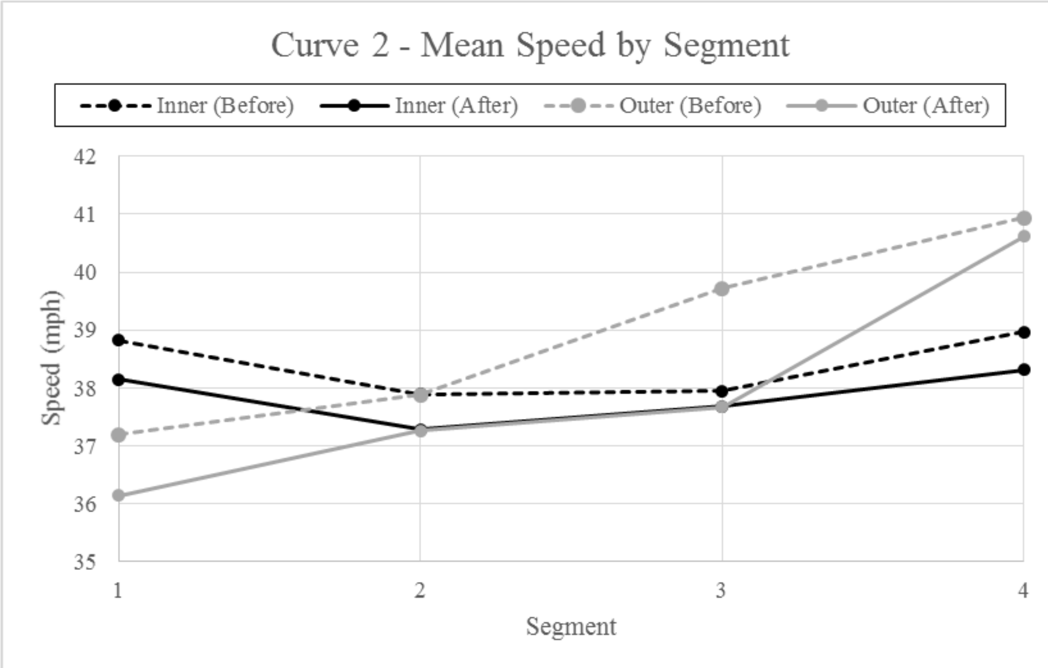

Figure 17. Curve 2 – Mean speed by segment

The mean offset was only significantly changed at segment 1 for the outer lane (Figure 18). The difference was small, however, with a change of just 153 mm. Overall, the treatment did not have much effect on participants' offset through the curve.

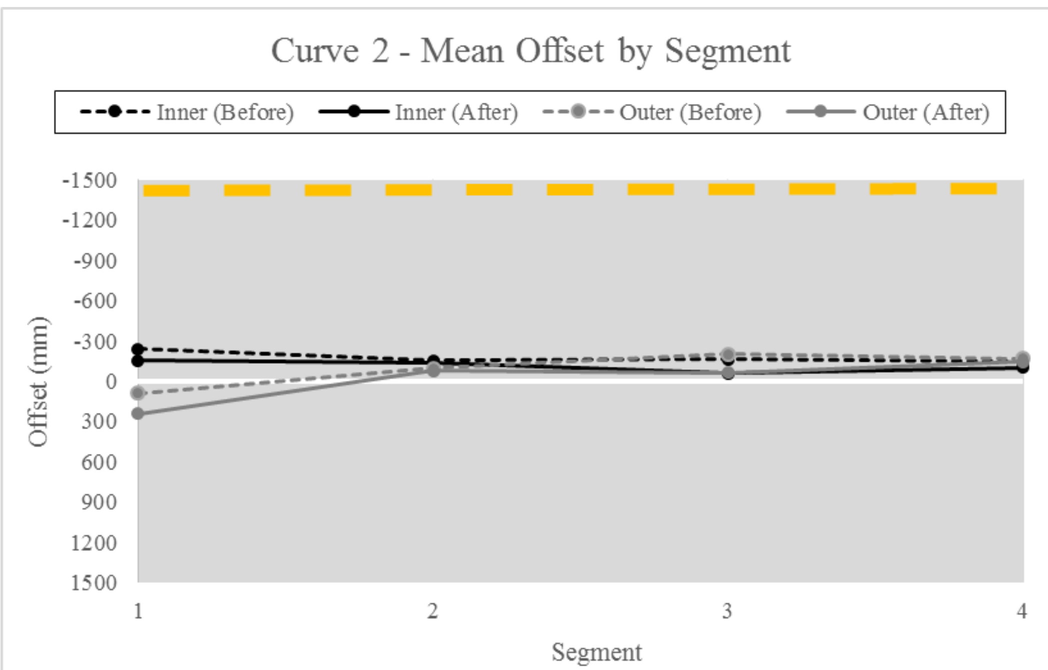

Figure 18. Curve 2 - Mean offset by segment

The ANOVA results for the observational study are shown in Table 11. Values in boldface indicate significant results ($p < 0.05$).

Table 11. ANOVA results for Curve 2 (observational study)

Curve 2 (Sequential Chevrons) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Inner	0.6713	**<.0001**	0.1760	**<.0001**	**0.0003**	**<.0001**
	Outer	**<.0001**	0.0518	0.4519	**<.0001**	**<.0001**	**<.0001**
Night	Inner	**0.0353**	**0.0017**	**<.0001**	**<.0001**	0.7254	**<.0001**
	Outer	**<.0001**	0.2649	**0.0081**	0.1765	**<.0001**	**0.0029**

Values in boldface indicate significant results.

For daytime conditions, the only significant changes occurred at point 2 for the inner lane where the mean speed decreased by 2.8 mph, and point 1 for the outer lane where the mean speed increased by 2.2 mph (Figure 19). In nighttime conditions, the change in speed was significant for all points except point 2 for the outer lane. The mean speed for the inner lane decreased at points 1 and 2, but increased at point 3. The mean speed for the outer lane increased at point 1, but decreased at point 3.

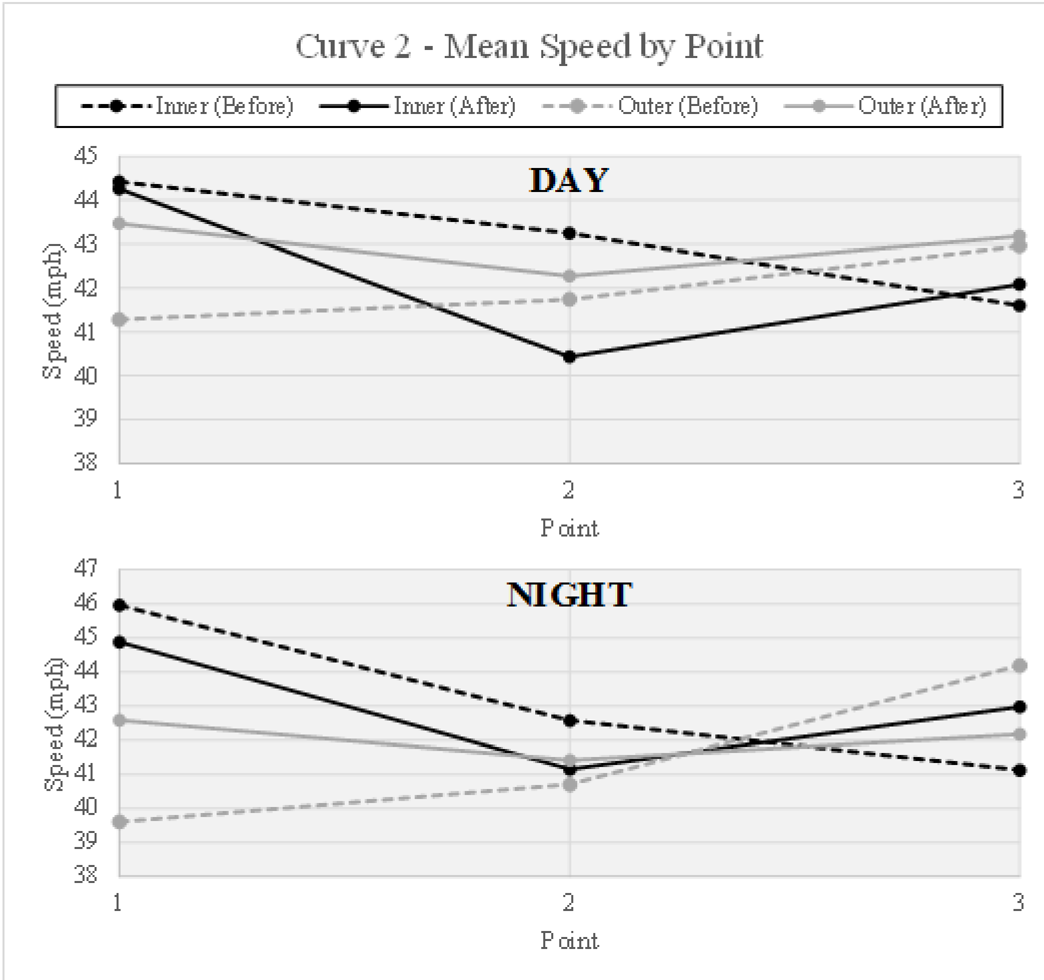

Figure 19. Curve 2 - Mean speed by point

For traffic in the inner lane, the mean offset shifted much closer to the center at point 3 in both daytime and nighttime conditions (Figure 20). Although some of the changes at points 1 and 2 were significant, the differences were very small. The mean offset for traffic in the outer lane shifted further away from the center (toward the right) at point 2, and then further back toward the left at point 3. The sequential chevrons tended to make the offset more consistent for the inner lane traffic, but less consistent for the outer lane traffic.

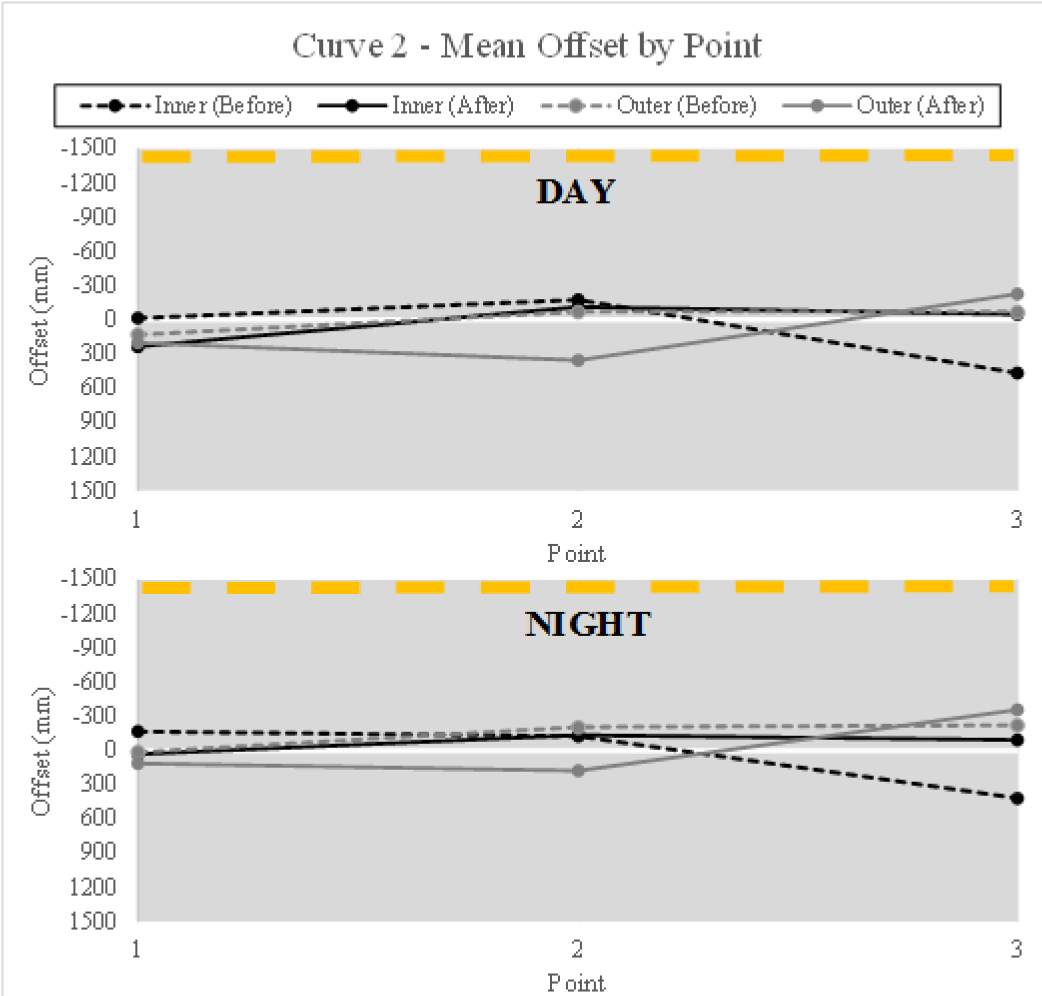

Figure 20. Curve 2 - Mean offset by point

Curve 2 Summary

The addition of the sequential chevrons had the opposite effect for traffic in the inner lane, and traffic in the outer lane. For the inner lane, the 85th percentile speed decreased whereas it increased for the outer lane. Additionally, the percentage of vehicles traveling 10mph or more over the advisory speed decreased for the most part in the inner lane, but had several large increases for the outer lane. The percentage of lane encroachments also decreased for the inner lane, but increased for the outer lane.

Table 12. Change in 85th percentile speed, percent speeding, and percent encroachments (observational)

85th Percentile Speeds (mph)				
Time	Lane	Before	After	Change
Day	Inner	48.4	47.1	-1.3
	Outer	44.8	46.9	2.1
Night	Inner	49.3	47.6	-1.7
	Outer	43.7	47.1	3.5

Percent Over Advisory Speed Limit (30mph)					
Time	Lane	Over Limit	Before	After	Change
Day	Inner	>5 mph	14.5%	25.1%	10.7%
		>10 mph	40.9%	37.6%	-3.3%
		>15 mph	32.4%	23.2%	-9.2%
		>20 mph	8.4%	6.3%	-2.1%
	Outer	>5 mph	27.0%	20.1%	-6.9%
		>10 mph	54.2%	45.8%	-8.4%
		>15 mph	13.5%	27.5%	14.0%
		>20 mph	1.5%	3.3%	1.9%
Night	Inner	>5 mph	16.0%	21.7%	5.6%
		>10 mph	34.8%	41.4%	6.6%
		>15 mph	31.0%	23.8%	-7.2%
		>20 mph	12.8%	8.5%	-4.3%
	Outer	>5 mph	39.6%	25.2%	-14.4%
		>10 mph	43.3%	46.9%	3.6%
		>15 mph	8.2%	23.8%	15.6%
		>20 mph	8.2%	0.0%	-8.2%

Percent Encroachments					
Time	Lane	Line	Before	After	Change
Day	Inner	Center	2.1%	1.0%	-1.1%
		Edge	1.7%	0.2%	-1.5%
	Outer	Center	0.6%	1.3%	0.7%
		Edge	0.2%	0.9%	0.7%
Night	Inner	Center	2.0%	0.6%	-1.5%
		Edge	0.5%	0.0%	-0.5%
	Outer	Center	4.4%	5.7%	1.3%
		Edge	0.0%	0.5%	0.5%

(pink) = an increase greater than 1mph or 1%

(green) = a decrease greater than 1mph or 1%

Blinking Curve Warning Sign

Curve 3

There was no existing treatment for curve 3 other than a winding road sign upstream of the curve. The new treatment was a blinking curve warning sign which had LEDs embedded around the perimeter of the sign (Figure 21). When an approaching vehicle was detected, the LEDs would blink continuously. This treatment was only visible from one approach, so only traffic in the inner lane of the curve saw the sign. The distance from the point of curvature to the sign was approximately 50ft. The ANOVA results of the human-factors study are shown in Table 13. Values in boldface indicate significant results ($p < 0.05$).

Figure 21. Curve 3 treatment – blinking curve warning sign

Table 13. ANOVA results for Curve 3 (human-factors study)

Curve 3 (Blinking CWS) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Inner	Age	0.6784	0.3820	0.6112	0.6993	0.5093	0.4634	0.6998	0.9863
	Treatment	0.5328	0.2360	**0.0051**	**0.0239**	0.0676	**0.0257**	0.0766	0.0753
	Age*Treatment	0.2638	0.2488	0.0975	0.0646	0.8405	0.6327	0.3134	0.2927

Values in boldface indicate significant results.

The mean speed for participants was reduced slightly after the installation of the blinking CWS (Figure 22). However, the difference was only significant in segments 3 and 4 (-1 mph and -0.7 mph, respectively).

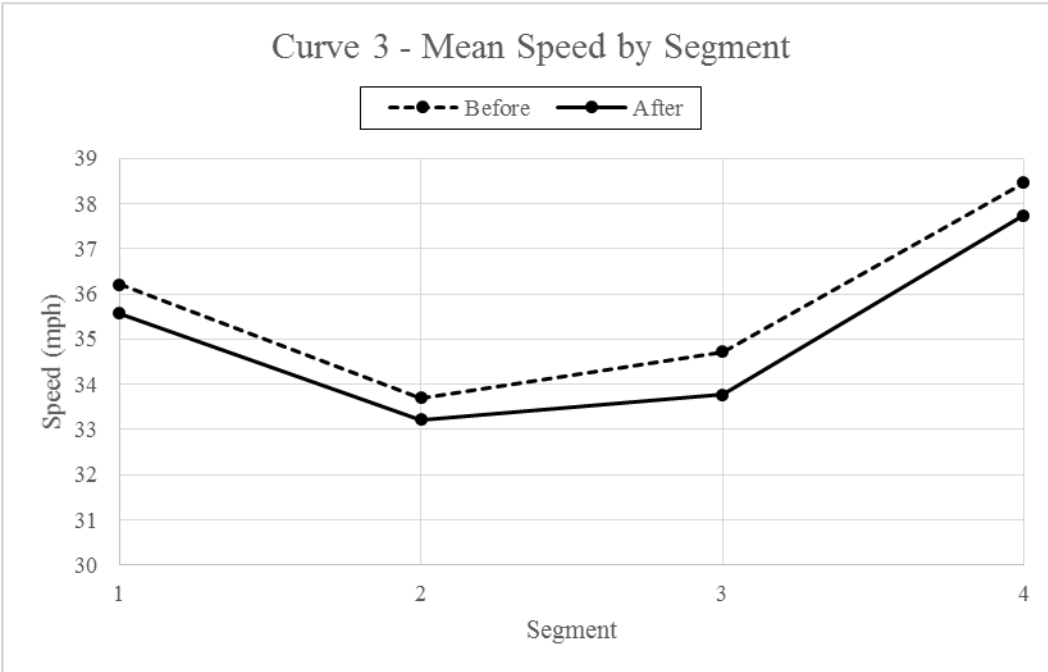

Figure 22. Curve 3 - Mean speed by segment

While the treatment did have a significant effect on the mean offset in segment 2, the difference was only 66 mm (Figure 23). This difference is likely not practically significant, in that the offset is virtually the same, and it would not likely have any impact on the safety of the curve.

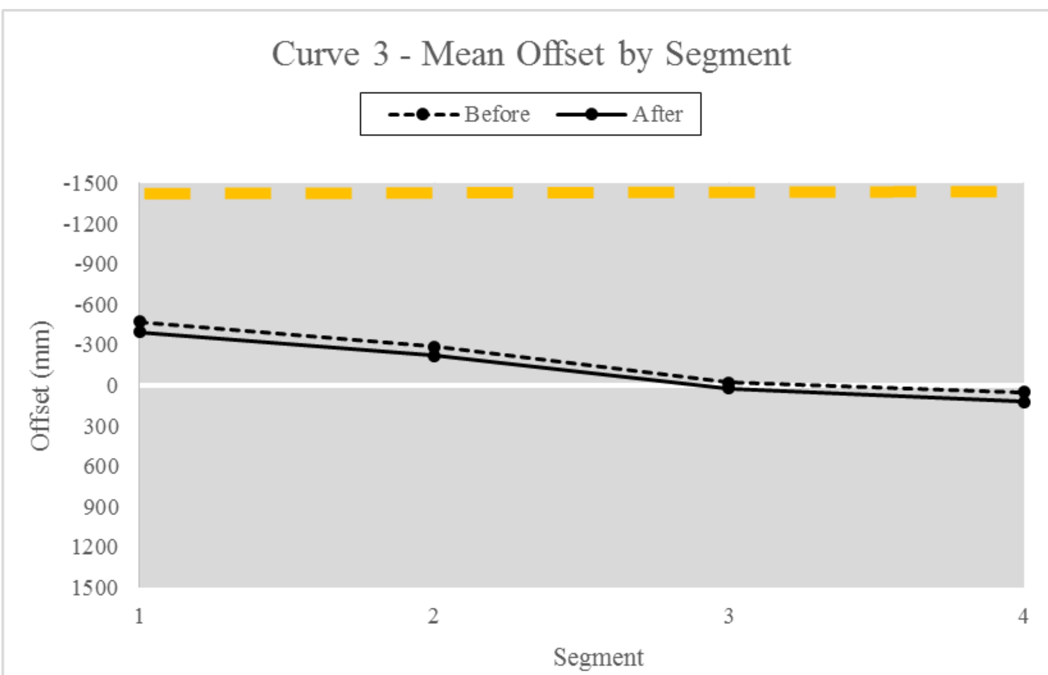

Figure 23. Curve 3 - Mean offset by segment

The ANOVA results for the observational study are shown in Table 14. The treatment had a significant effect ($p < 0.05$) in all conditions.

Table 14. ANOVA results for Curve 3 (observational study)

Curve 3 (Blinking Chevron) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	Point 2	Point 3	Point 1	Point 2	Point 3
Day	Inner	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Night	Inner	**<.0001**	**0.0284**	**<.0001**	**<.0001**	**<.0001**	**<.0001**

Values in boldface indicate significant results.

Figure 24 shows the mean speed for each point for both day and night conditions. During both times, traffic entered the curve at a higher mean speed (+3.2 mph and +4.7 mph, respectively). However, between points 1 and 2, traffic decelerated at a greater rate, resulting in a lower mean speed at point 2 (-3.4 mph and -1.3 mph, respectively). The mean speed was also lower for both day and night conditions as traffic exited the turn at point 3 (-5.2 mph and -4.3 mph, respectively).

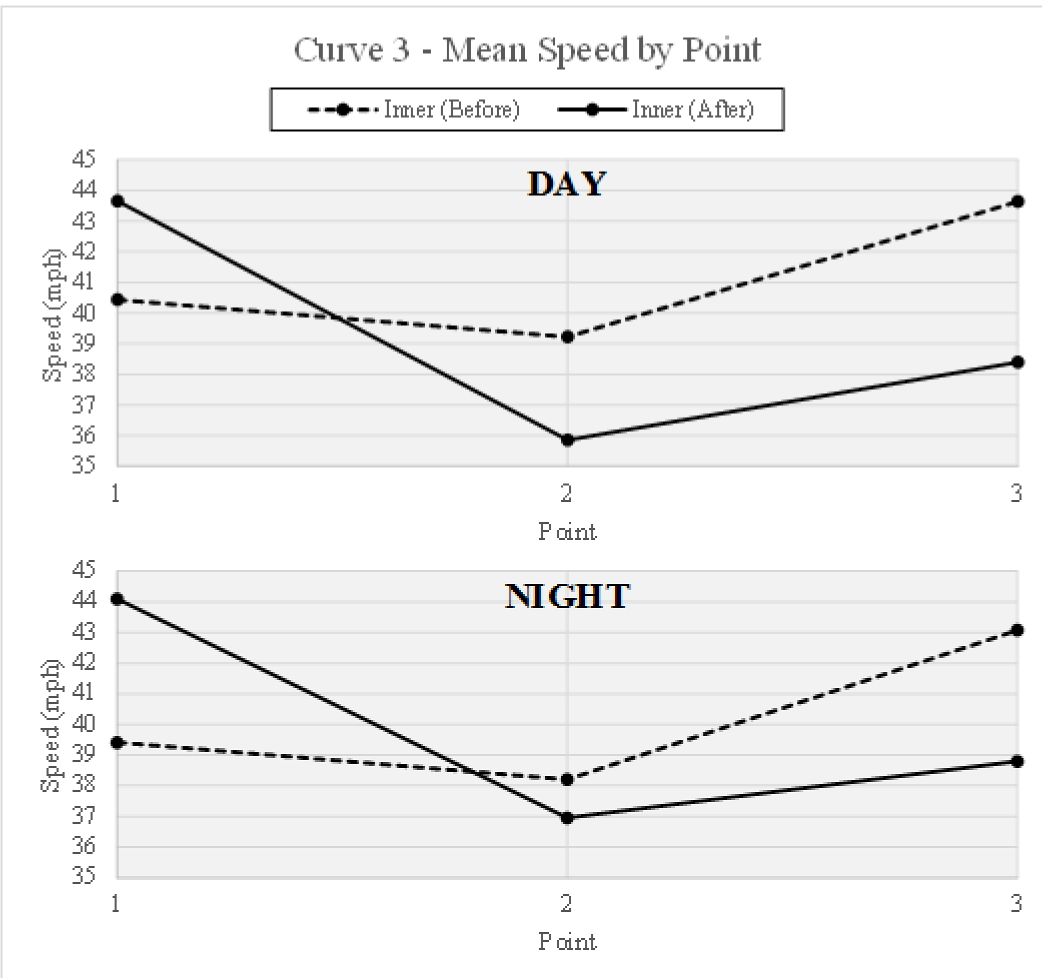

Figure 24. Curve 3 - Mean speed by point

Prior to the installation of the blinking CWS, traffic tended to enter the curve, and pass through the middle point with a mean offset very close to the center of the lane. As they accelerated out of the curve, the offset shifted left toward the center lane line. After the sign was installed, the offset at point 2 shifted left, away from the center (by 389 mm during the day, and 470 mm at night), but then back toward the right, closer to the center at point 3.

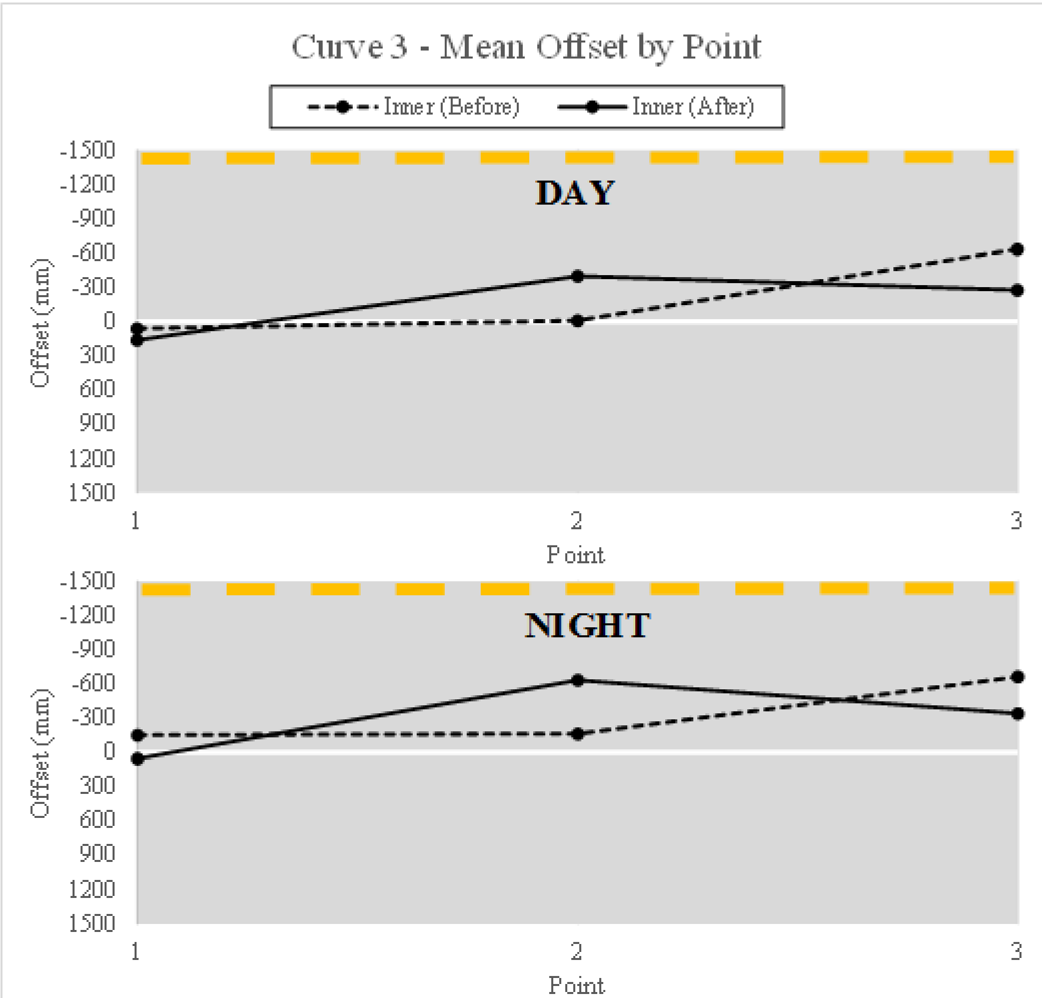

Figure 25. Curve 3 - Mean offset by point

Curve 3 Summary

The installation of the blinking CWS did not make any practical difference on participants' mean speed or offset in the human-factors study, but significantly affected both in the observational study. Traffic entered the curve at a significantly higher mean speed, but quickly decelerated and maintained a lower mean speed in points 2 and 3. It is unclear why the speed increased at point 1. It's possible that the sign, which was placed on the inside of the curve, distracted drivers or made it more difficult to see the curvature of the roadway as they approached, which lead to a failure to reduce their speed in the approach to the curve.

Although the mean speed decreased at point 3, that point was not included in the calculation of the 85th percentile speed, since points 1 and 2 are more critical. The result is that the 85th percentile speed increased slightly in both day and night conditions. Interestingly, the percentage of vehicles exceeding the advisory speed by 15mph or less decreased, but those exceeding the advisory speed by 15 mph or more increased (Table 15). Although speeds were increased in some parts of the curve, the percentage of encroachments was reduced, particularly center line encroachments at night.

Table 15. Change in 85th percentile speed, percent speeding, and percent encroachments (observational)

85th Percentile Speeds (mph)					
Time		**Lane**	**Before**	**After**	**Change**
Day		Inner	44.3	44.6	0.3
Night		Inner	44.1	45.1	1.0
Percent Over Advisory Speed Limit (30mph)					
Time	**Lane**	**Over Limit**	**Before**	**After**	**Change**
Day	Inner	>5 mph	37.5%	30.0%	-7.5%
		>10 mph	39.0%	30.8%	-8.2%
		>15 mph	10.5%	16.0%	5.5%
		>20 mph	1.1%	4.4%	3.2%
Night	Inner	>5 mph	32.1%	32.4%	0.3%
		>10 mph	35.8%	31.1%	-4.7%
		>15 mph	7.8%	17.1%	9.3%
		>20 mph	2.2%	4.8%	2.6%
Percent Encroachments					
Time	**Lane**	**Line**	**Before**	**After**	**Change**
Day	Inner	Center	1.8%	1.2%	-0.6%
		Edge	0.0%	0.0%	0.0%
Night	Inner	Center	10.7%	2.7%	-7.9%
		Edge	0.3%	0.0%	-0.3%

(pink) = an increase greater than 1mph or 1%
(green) = a decrease greater than 1mph or 1%

On-Pavement Signage

Curve 4

There was no existing treatment for curve 4 other than a winding road sign upstream of the curve. The new treatment consisted of on-pavement signage which included a curved arrow and the word "SLOW" (Figure 26). The treatment was applied in the approach for both sides of the curve. The distance from the OPS to the point of curvature was approximately 167ft in the outer lane, and 115ft in the inner lane. The ANOVA results for the human-factors study are shown in Table 16. Values in boldface indicate significant results ($p < 0.05$).

Figure 26. Curve 4 treatment – on-pavement signage

Table 16. ANOVA results for Curve 4 (human-factors study)

Curve 4 (On-pavement Signage) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Inner	Age	0.2403	0.2906	0.4971	0.5412	0.0946	0.6698	0.4946	0.4782
	Treatment	0.3094	**0.0294**	0.1951	0.1932	0.5147	0.0776	0.5000	0.1901
	Age*Treatment	0.7748	0.2980	0.9368	0.7988	0.4008	0.7129	0.9817	0.3393
Outer	Age	0.7916	0.7661	0.5061	0.5801	0.6936	0.7291	0.9654	0.8986
	Treatment	0.5504	0.6099	0.8616	0.5198	0.6095	**0.0180**	0.6389	0.5458
	Age*Treatment	0.6466	0.7166	0.7236	0.6538	0.8878	**0.0142**	0.1660	0.3647

Values in boldface indicate significant results.

The only significant effect of the treatment on speed was for the inner lane at segment 2, where the speed was reduced by 1.4 mph (Figure 27). Although the mean speed was reduced in other locations for the inner lane, these were not statistically significant. The mean speed for the outer lane was virtually unchanged.

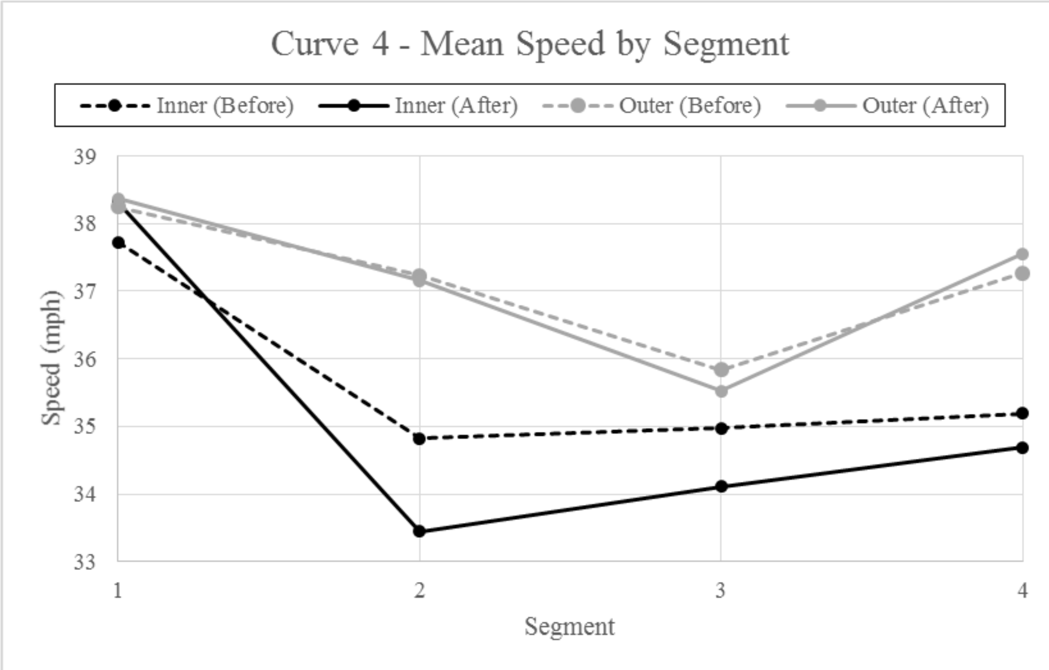

Figure 27. Curve 4 – Mean speed by segment

For the mean offset, Treatment was only significant for the outer lane in segment 2. However, the difference was very small (65 mm), and not practically important (Figure 28).

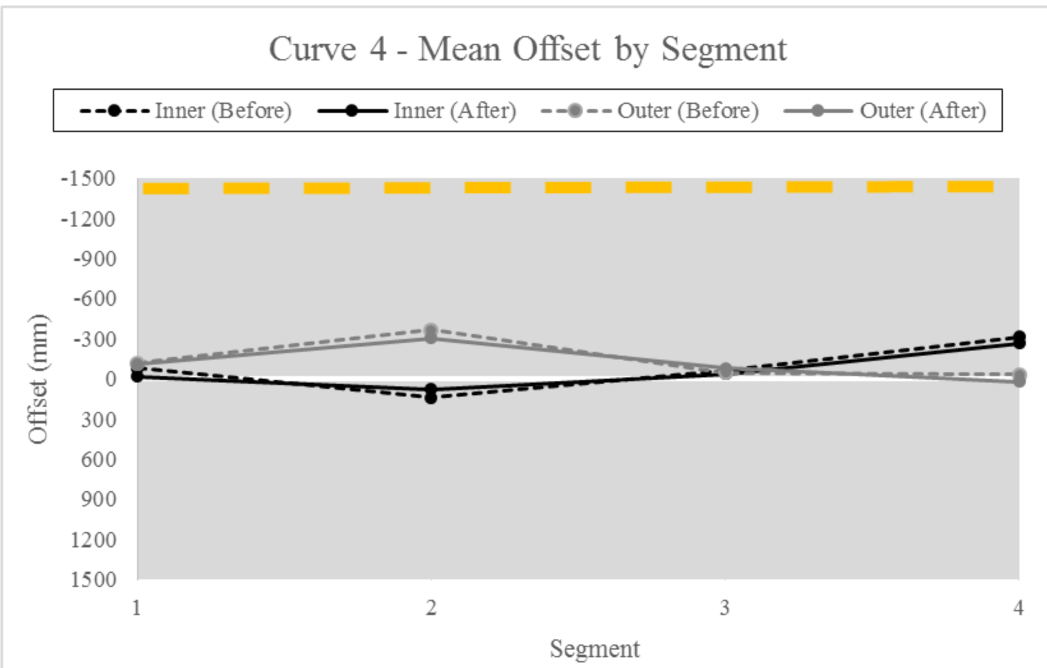

Figure 28. Curve 4 - Mean offset by segment

The ANOVA results for the observational study are shown in Table 17. Values in boldface indicate significant results ($p < 0.05$).

Table 17. ANOVA results for Curve 4 (observational study).

Curve 4 (On-pavement Signage) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Inner	0.0951	0.4228	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	Outer	**0.0039**	0.1546	0.0913	**<.0001**	**<.0001**	**<.0001**
Night	Inner	0.7243	0.9478	**<.0001**	0.1433	**<.0001**	**0.0008**
	Outer	**0.0249**	0.3165	0.2703	**<.0001**	**<.0001**	**<.0001**

Values in boldface indicate significant results.

For traffic in the inner lane, the mean speed was only significantly changed at point 3, where it increased by 1.7 mph during the day, and 2.8 mph at night (Figure 29). For the outer lane, however, the mean speed was significantly changed at point 1, where it decreased by 1.3 mph during the day, and 1 mph at night.

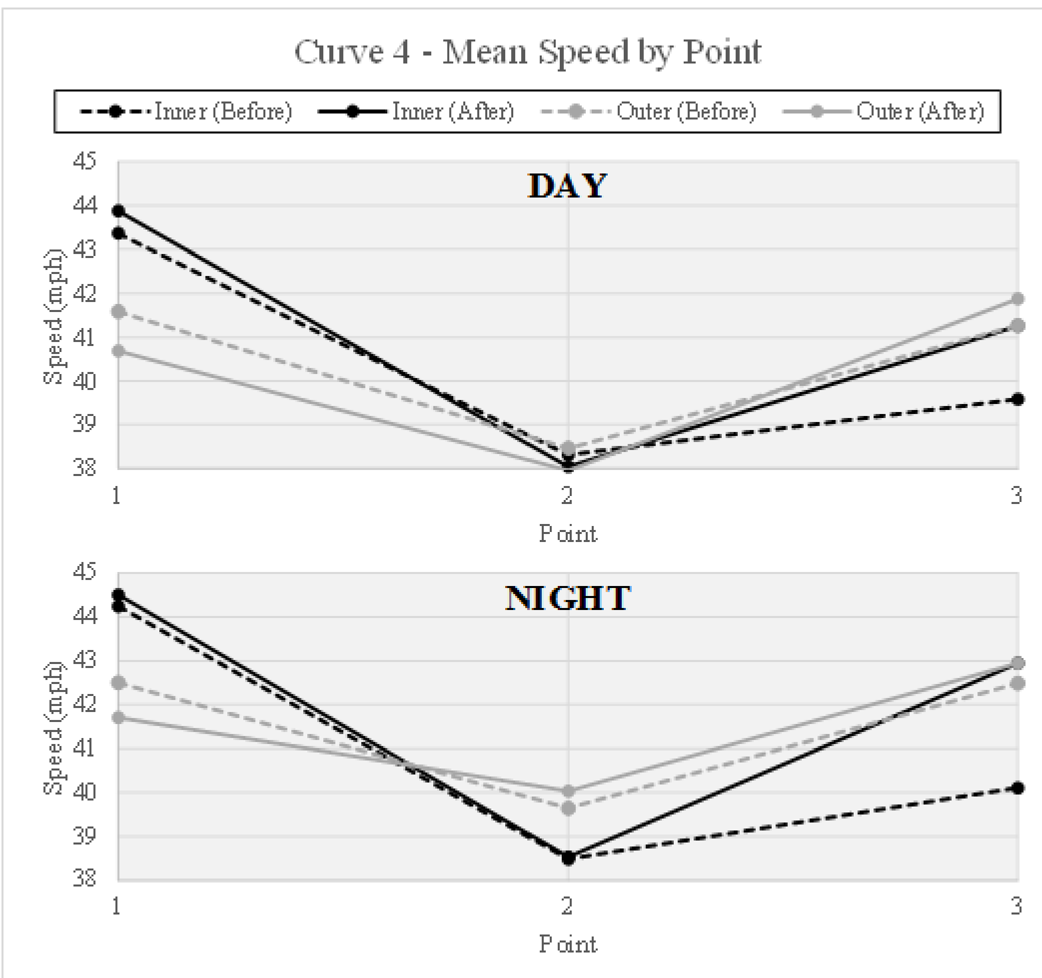

Figure 29. Curve 4 - Mean speed by point

After the installation of the on-pavement signage, the mean offset tended to be closer to the center of the lane for both the inner and outer lanes across day and night conditions (Figure 30). The offset was also more consistent, changing very little from point to point.

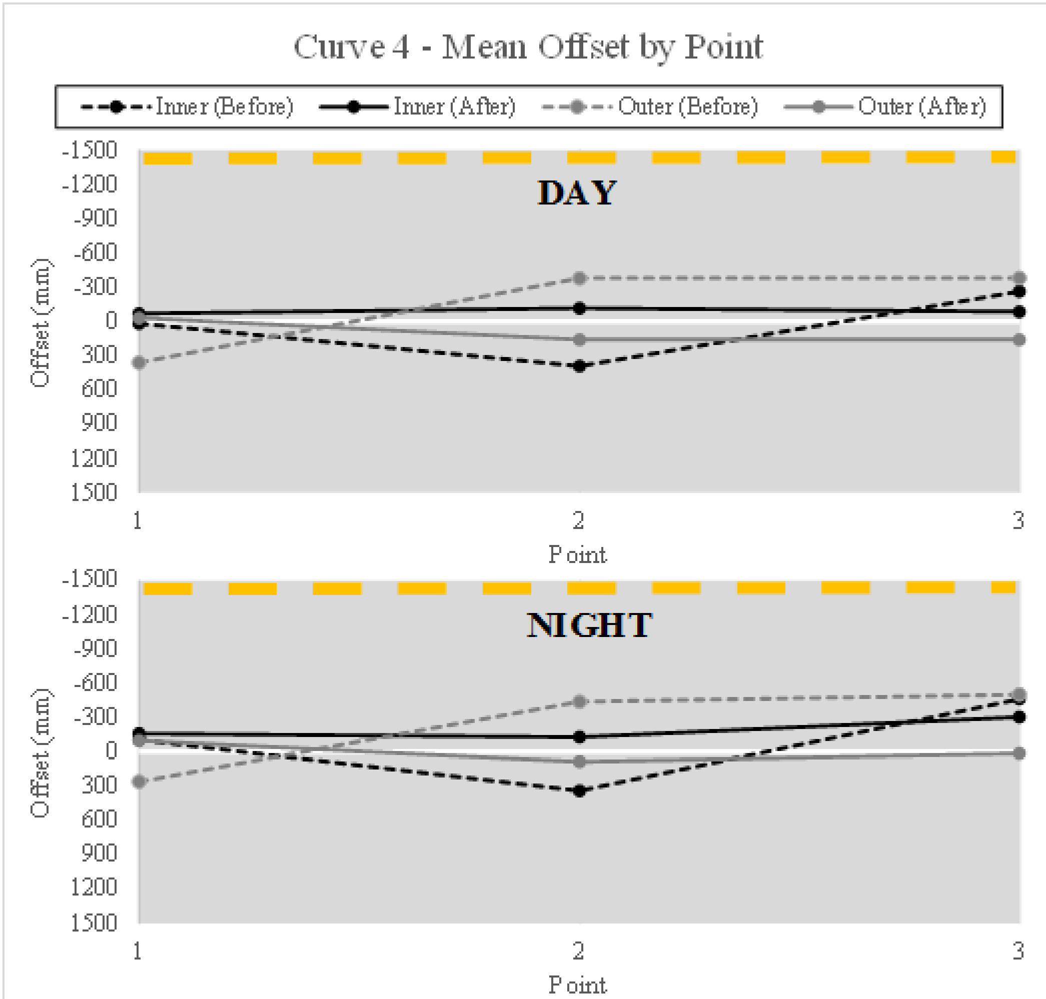

Figure 30. Curve 4 - Mean offset by point

Curve 4 Summary

The 85th percentile speed across points 1 and 2 was relatively unchanged (Table 18). While there were some increases in the percentage of vehicles exceeding the advisory speed limit, there were also several decreases. The mean offset in the observational study was, in general, closer to the center of the lane, and more consistent throughout the curve. This is reflected in the percentage of encroachments which decreased in all conditions, but particularly center line encroachments for vehicles in the inner lane.

Table 18. Change in 85th percentile speed, percent speeding, and percent encroachments (observational).

85th Percentile Speeds (mph)				
Time	Lane	Before	After	Change
Day	Inner	45.4	45.3	-0.1
	Outer	44.6	43.8	-0.8
Night	Inner	46.2	46.0	-0.2
	Outer	45.1	45.1	0.0

Percent Over Advisory Speed Limit (30mph)					
Time	Lane	Over Limit	Before	After	Change
Day	Inner	>5 mph	30.6%	31.0%	0.4%
		>10 mph	37.5%	36.9%	-0.6%
		>15 mph	16.2%	18.4%	2.1%
		>20 mph	4.4%	3.6%	-0.8%
	Outer	>5 mph	36.1%	39.1%	3.1%
		>10 mph	38.4%	37.4%	-1.0%
		>15 mph	12.2%	8.0%	-4.3%
		>20 mph	1.4%	0.8%	-0.6%
Night	Inner	>5 mph	28.3%	25.1%	-3.2%
		>10 mph	36.1%	35.4%	-0.6%
		>15 mph	18.0%	20.0%	2.0%
		>20 mph	6.0%	6.3%	0.3%
	Outer	>5 mph	32.6%	34.2%	1.6%
		>10 mph	43.6%	42.2%	-1.3%
		>15 mph	14.7%	13.9%	-0.7%
		>20 mph	2.0%	2.2%	0.1%

Percent Encroachments					
Time	Lane	Line	Before	After	Change
Day	Inner	Center	1.8%	0.7%	-1.1%
		Edge	0.3%	0.0%	-0.3%
	Outer	Center	0.9%	0.5%	-0.5%
		Edge	0.1%	0.4%	0.3%
Night	Inner	Center	3.8%	1.5%	-2.3%
		Edge	0.0%	0.0%	0.0%
	Outer	Center	1.5%	0.5%	-1.0%
		Edge	0.0%	0.0%	0.0%

[pink] = an increase greater than 1mph or 1%

[green] = a decrease greater than 1mph or 1%

Curve 7

The existing treatments for curve 7 included a CWS on each end of the curve. The new treatment consisted of on-pavement signage which included a curved arrow and the word "SLOW" (Figure 16). The same treatment was applied to both sides of the curve. The distance from the OPS to the point of curvature was approximately 236ft in the inner lane, and 95ft in the outer lane. The ANOVA results for the human-factors study are shown in Table 19. Values in boldface indicate significant results ($p < 0.05$).

Figure 31. Curve 7 treatment – on-pavement signage

Table 19. ANOVA results for Curve 7 (human-factors study)

Curve 7 (On-pavement Signage) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Inner	Age	0.9403	0.9102	0.7446	0.8763	0.4112	0.8398	0.1496	0.9414
	Treatment	0.3843	0.2407	0.9222	0.5631	**0.0013**	0.1837	0.8508	0.7573
	Age*Treatment	0.5210	0.6359	0.1340	0.3261	0.9451	0.9240	0.1927	0.6842
Outer	Age	0.9206	0.4493	0.5808	0.3717	0.4043	0.3138	0.9144	0.5800
	Treatment	0.5570	0.1003	0.8722	0.1487	**0.0014**	0.0979	0.0674	0.6079
	Age*Treatment	0.8010	0.9716	0.5052	0.9887	0.7541	0.9573	0.5533	0.8137

Values in boldface indicate significant results.

The treatment did not have a significant effect on speed in this curve. Significant effects were found for offset in segment 1 of both lanes. The mean offset shifted 245 mm to the left for participants in the inner lane, and 163 mm to the left for participants in the outer lane (Figure 32). There were larger differences in the mean offset in segment 2; however, these were not statistically significant.

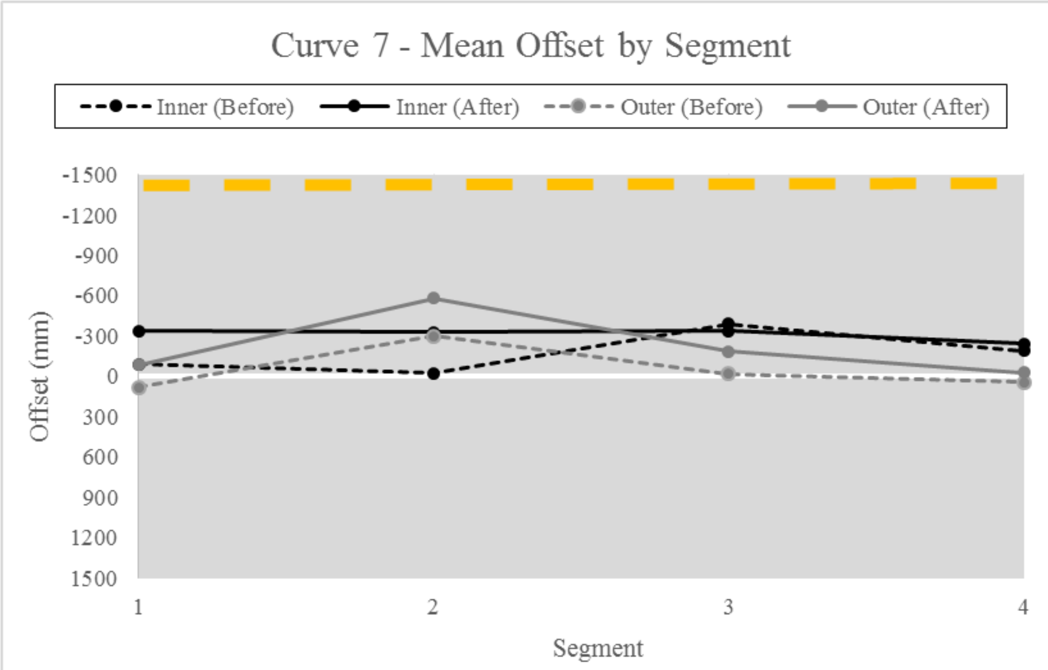

Figure 32. Curve 7 - Mean offset by segment

The ANOVA results for the observational study are shown in Table 20. Values in boldface indicate significant results ($p < 0.05$).

Table 20. ANOVA results for Curve 7 (observational study)

Curve 7 (On-pavement Signage) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Inner	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	Outer	**<.0001**	**<.0001**	**<.0001**	**0.0197**	**<.0001**	0.1258
Night	Inner	**<.0001**	**<.0001**	**<.0001**	**0.0005**	**<.0001**	**0.0018**
	Outer	**0.0014**	**0.0002**	**<.0001**	**<.0001**	**<.0001**	0.9256

Values in boldface indicate significant results.

The mean speed increased at all points for both lanes, in both day and night conditions (Figure 33). Across all points, and day and night conditions, the average increase in speed was 2.9 mph for the inner lane, and 1.8 mph for the outer lane.

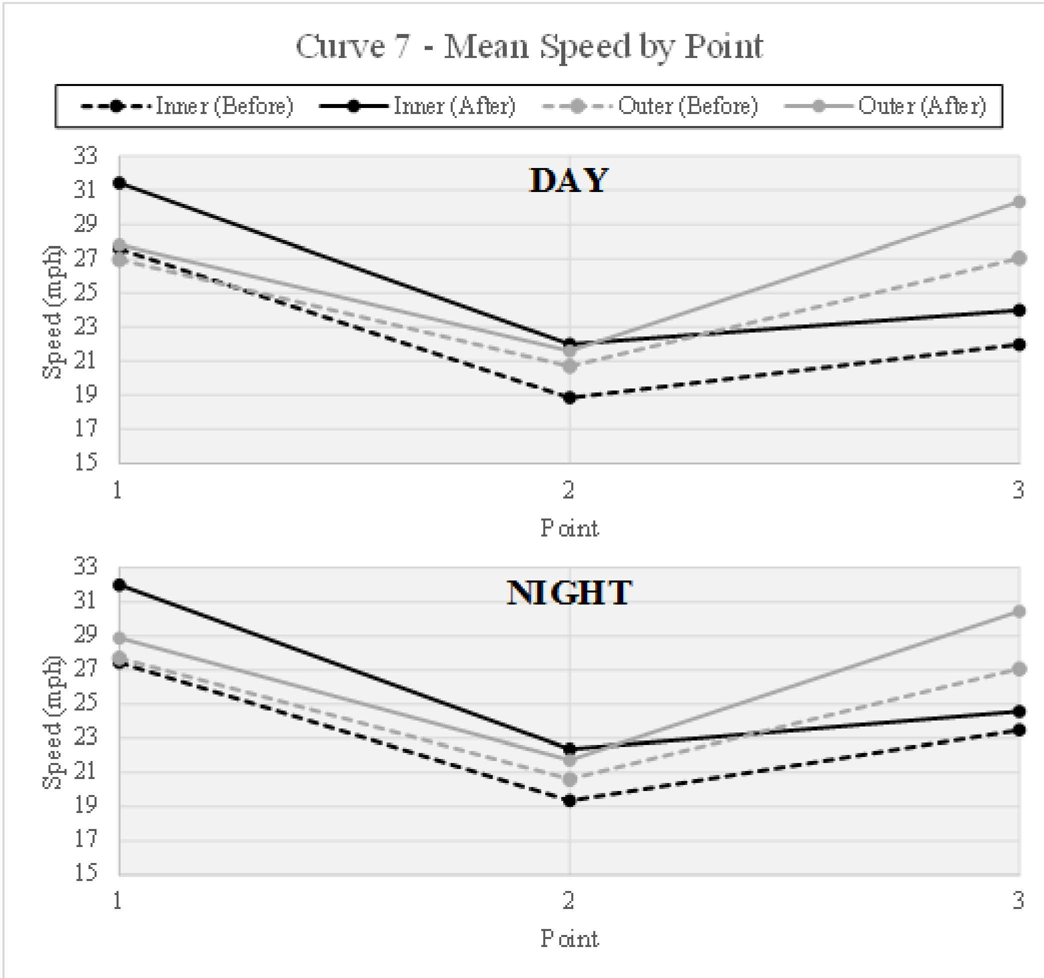

Figure 33. Curve 7 - Mean speed by point

For traffic in the inner lane, the offset was much closer to the center of the lane at points 2 and 3 after the installation of the on-pavement signage (Figure 34). For the outer lane, the offset was similarly much closer to the center at point 2, but did not change at point 3.

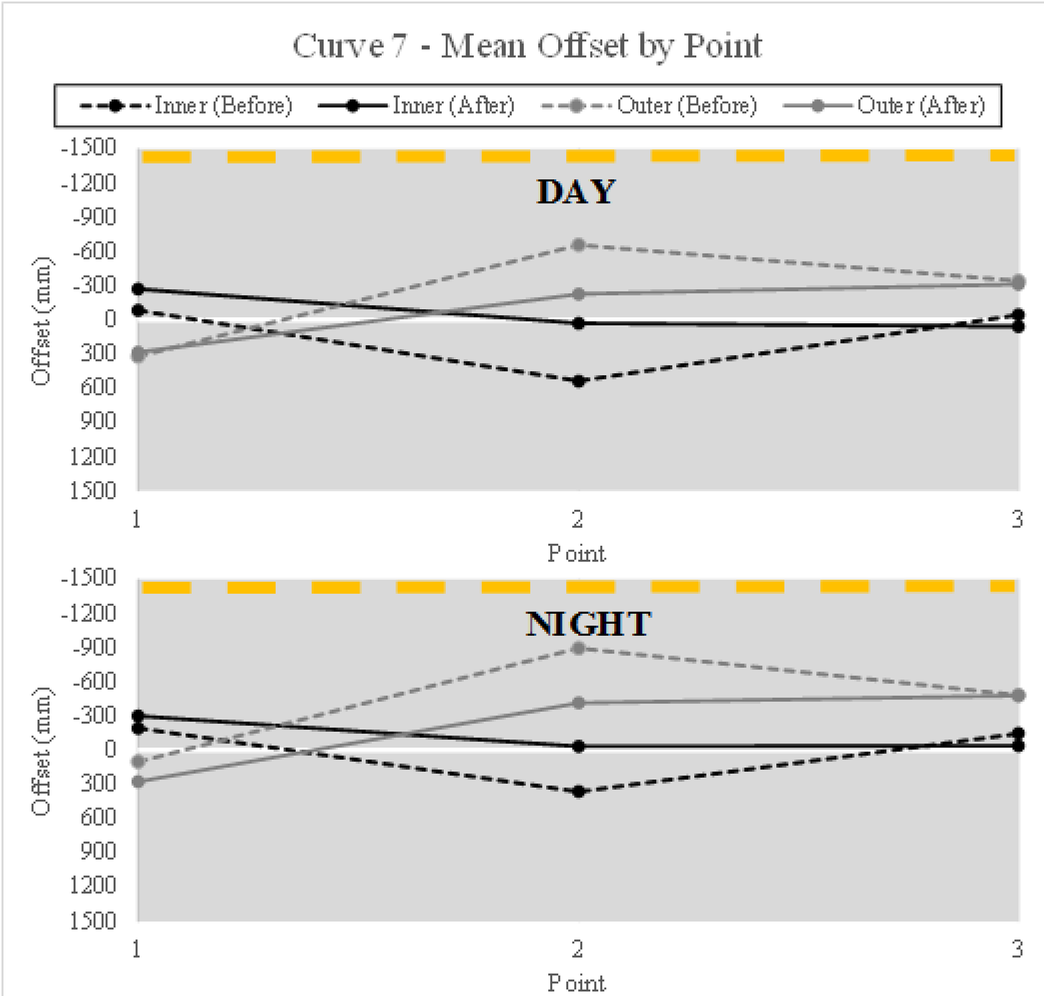

Figure 34. Curve 7 - Mean offset by point

Curve 7 Summary

The mean speed was found to increase at all points for the observational data. As a result, the 85th percentile speed for both lanes increased after the installation of the on-pavement signage (Table 21). The 85th percentile speeds were nearly double the advisory speed (15 mph), though still well below the posted speed limit. The percentage of vehicles traveling 10 to 15 mph over the advisory speed decreased in nearly all conditions, however, the percentage increased for nearly every other range of speeds. The percentage of encroachments decreased in several areas, but center line encroachments increased for vehicles traveling in the inner lane. The roadway in curve 7 was repaved and remarked between data collection sessions, so these results may be a result of the improved pavement and lane marking conditions rather than the selected treatment.

Table 21. Change in 85th percentile speed, percent speeding, and percent encroachments (observational)

85th Percentile Speeds (mph)					
Time		Lane	Before	After	Change
Day		Inner	25.6	28.9	3.2
		Outer	26.0	28.0	2.0
Night		Inner	25.7	29.3	3.5
		Outer	27.9	28.8	0.9
Percent Over Advisory Speed Limit (15mph)					
Time	Lane	Over Limit	Before	After	Change
Day	Inner	>5 mph	20.8%	42.3%	21.5%
		>10 mph	30.5%	18.3%	-12.2%
		>15 mph	10.2%	21.0%	10.8%
		>20 mph	0.8%	6.4%	5.6%
	Outer	>5 mph	44.3%	40.5%	-3.8%
		>10 mph	26.9%	35.6%	8.7%
		>15 mph	7.2%	13.8%	6.6%
		>20 mph	0.5%	0.7%	0.2%
Night	Inner	>5 mph	25.6%	42.5%	16.8%
		>10 mph	30.6%	17.0%	-13.6%
		>15 mph	8.7%	25.5%	16.8%
		>20 mph	0.2%	7.9%	7.7%
	Outer	>5 mph	33.0%	37.7%	4.8%
		>10 mph	38.5%	35.3%	-3.2%
		>15 mph	14.3%	20.1%	5.8%
		>20 mph	0.7%	0.5%	-0.2%
Percent Encroachments					
Time	Lane	Line	Before	After	Change
Day	Inner	Center	1.8%	12.4%	10.5%
		Edge	4.1%	0.1%	-4.0%
	Outer	Center	3.0%	1.5%	-1.4%
		Edge	0.1%	0.0%	-0.1%
Night	Inner	Center	3.1%	8.3%	5.2%
		Edge	1.4%	0.1%	-1.3%
	Outer	Center	8.4%	3.3%	-5.2%
		Edge	0.0%	0.0%	0.0%

(red) = an increase greater than 1mph or 1%

(green) = a decrease greater than 1mph or 1%

Dynamic Curve Warning Sign

Curve 5

There was no existing treatment for curve 5 other than a winding road sign located upstream of the curve. The new treatment consisted of a DCWS which activated when a vehicle was detected driving faster than the advisory speed. When activated, the sign consisted of two flashing dots, a curve sign, and a "SLOW DOWN" message (Figure 35). This treatment was only applied to one side of the curve, so it was only visible for vehicles travelling in the outer lane. The distance from the point of curvature to the sign was approximately 20ft. The ANOVA results for the human-factors study are shown in Table 22. Values in boldface indicate significant results ($p < 0.05$).

Figure 35. Curve 5 treatment – dynamic curve warning sign

Table 22. ANOVA results for Curve 5 (human-factors study)

Curve 5 (DCWS) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Outer	Age	0.5899	0.5433	0.5385	0.6687	**0.0044**	0.2485	0.9387	0.4688
	Treatment	**0.0423**	**0.0210**	0.1605	0.3343	0.6890	0.1036	0.0933	0.2962
	Age*Treatment	0.9751	0.3344	0.7712	0.6310	0.3021	0.0696	0.3349	0.4368

Values in boldface indicate significant results.

The treatment had a significant effect on speed in segments 1 and 2 of the outer lane, in which the mean speed decreased by just over 1 mph (Figure 36). The treatment did not have any effect on the mean offset. However, there was an age effect in segment 1. In this segment, older drivers entered the curve further to the left with a mean offset of -291 mm, while younger participants entered with a mean offset of -102 mm.

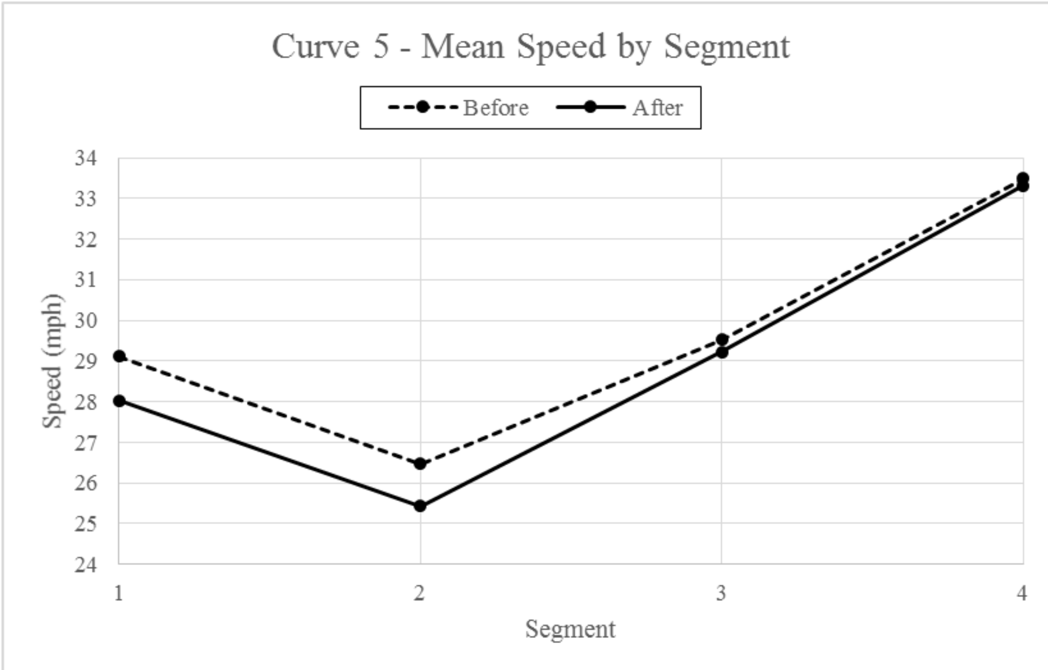

Figure 36. Curve 5 - Mean offset by segment

The ANOVA results for the observational study are shown in Table 23. Values in boldface indicate significant results ($p < 0.05$).

Table 23. ANOVA results for Curve 5 (observational study)

Curve 5 (DCWS) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Outer	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0003**
Night	Outer	0.0614	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.5111

Values in boldface indicate significant results.

At point 1, the mean speed was significantly reduced by 1.3 mph in daytime conditions, but was not affected at night. At points 2 and 3, the mean speed was significantly higher in all conditions (Figure 37). The mean speed at point 2 increased by 2.9 mph during the day and 2.2 mph at night. The mean speed at point 3 increased by 9.9 mph during the day, and 11.5 mph at night.

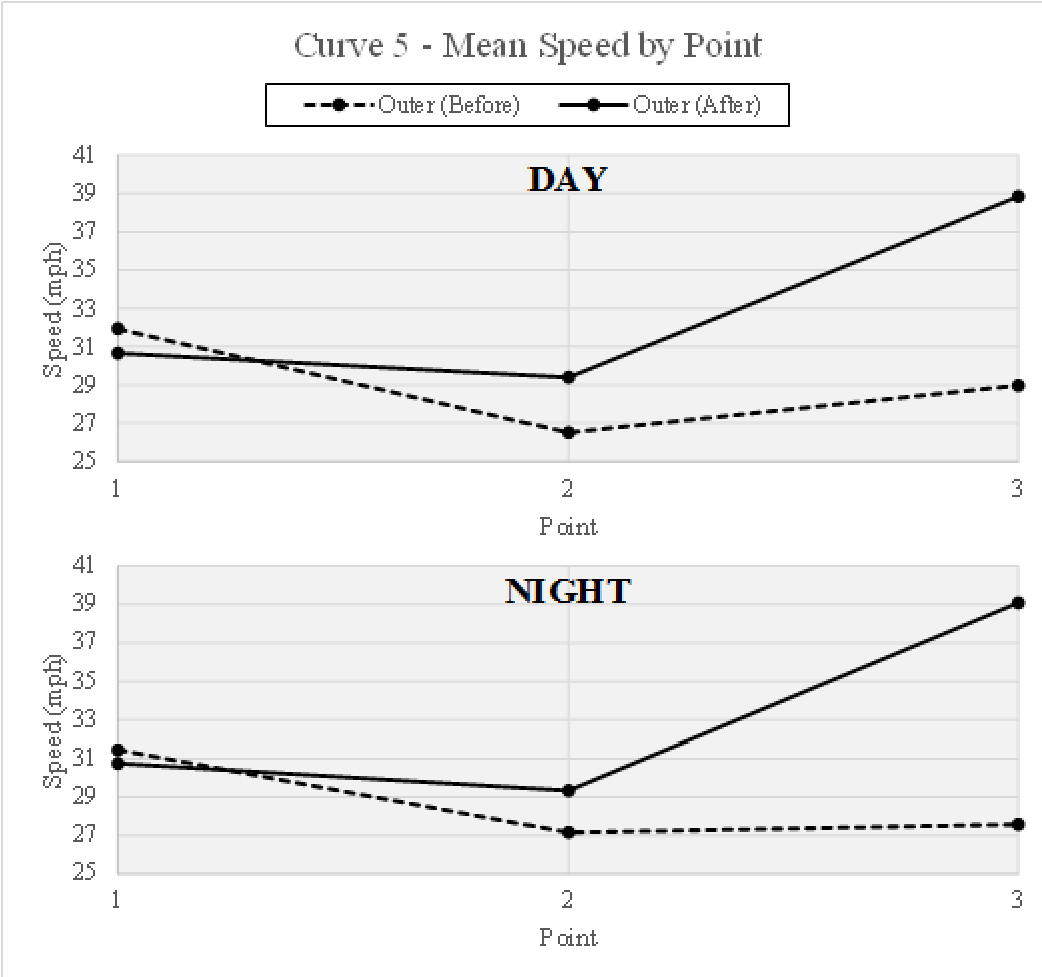

Figure 37. Curve 5 - Mean speed by point

Though traffic speeds increased at points 2 and 3, the mean offset was closer to the center of the lane at all three points for day and night conditions, with the exception of point 3 at night (Figure 38). The offset was most affected at point 1, in which the mean shifted approximately 700 mm to the left.

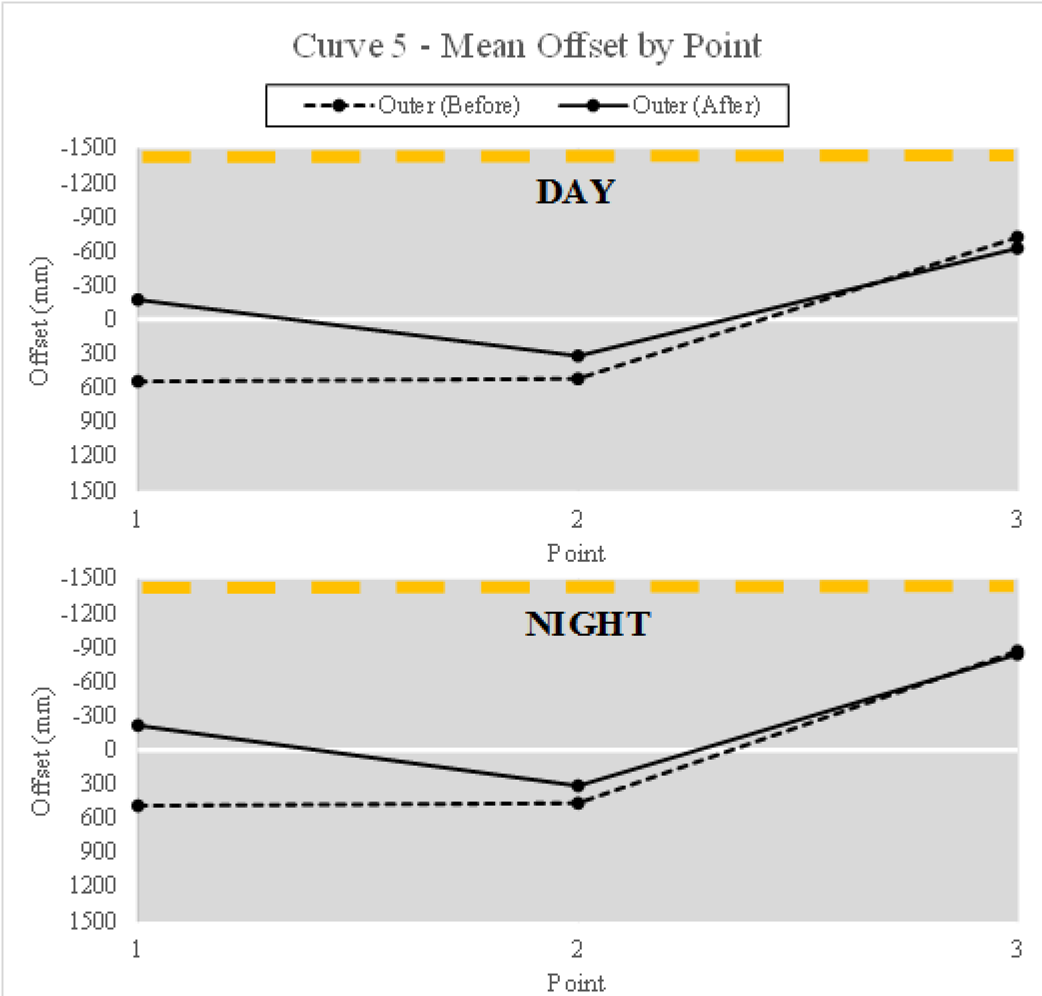

Figure 38. Curve 5 - Mean offset by point

Curve 5 Summary

After the installation of the DCWS, the mean speed increased significantly at point 2, resulting in a higher 85th percentile speed (Table 24). The percentage of vehicles exceeding the advisory speed also increased slightly. Although the mean offset tended to be closer to the center of the lane at points 1 and 2, it also shifted closer to the center lane line. This resulted in an increase in the percentage of center line encroachments, and a decrease in edge line encroachments.

Table 24. Change in 85th percentile speed, percent speeding, and percent encroachments (observational)

85th Percentile Speeds (mph)					
Time		Lane	Before	After	Change
Day		Outer	33.9	34.3	0.4
Night		Outer	32.7	34.6	1.9
Percent Over Advisory Speed Limit (25mph)					
Time	Lane	Over Limit	Before	After	Change
Day	Outer	>5 mph	45.6%	48.1%	2.5%
		>10 mph	12.1%	9.0%	-3.0%
		>15 mph	0.6%	0.5%	-0.1%
		>20 mph	0.0%	0.1%	0.1%
Night	Outer	>5 mph	37.2%	44.1%	6.8%
		>10 mph	5.3%	11.3%	6.0%
		>15 mph	0.3%	0.9%	0.6%
		>20 mph	0.0%	0.2%	0.2%
Percent Encroachments					
Time	Lane	Line	Before	After	Change
Day	Outer	Center	2.2%	3.6%	1.4%
		Edge	1.4%	0.6%	-0.8%
Night	Outer	Center	5.0%	6.6%	1.6%
		Edge	1.9%	0.4%	-1.5%

(pink) = an increase greater than 1mph or 1%
(green) = a decrease greater than 1mph or 1%

Curve 8.1

There was no existing treatment for curve 8.1 other than a winding road sign located upstream of the curve. The new treatment consisted of a DCWS which activated when a vehicle was detected driving faster than the advisory speed. When activated, the sign consisted of four flashing dots, a curve sign, and a "SLOW DOWN" message (Figure 39). The sign was only visible from one direction. The distance from the point of curvature to the sign was approximately 60 ft. Human-factors data were not collected for this curve due to a malfunction in the sign which occurred during data collection. The ANOVA results for the observational study are shown in Table 25. Values in boldface indicate significant results ($p < 0.05$).

Figure 39. Curve 8.1 treatment – dynamic curve warning sign

Table 25. ANOVA results for Curve 1 (observational study).

Curve 8.1 (DCWS) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Outer	**<.0001**	**<.0001**	0.4579	**<.0001**	**<.0001**	0.0962
Night	Outer	**<.0001**	**<.0001**	**0.0089**	**<.0001**	**0.0066**	**<.0001**

Values in boldface indicate significant results.

After the installation of the DCWS, the mean speed at point 1 increased by 6.6 mph during the day, and 5.4 mph at night (Figure 40). However, at the middle point of the curve, the mean speed was actually 1.8 mph lower during the day, and 3 mph lower at night, because traffic decelerated between points 1 and 2, rather than accelerate as they had before.

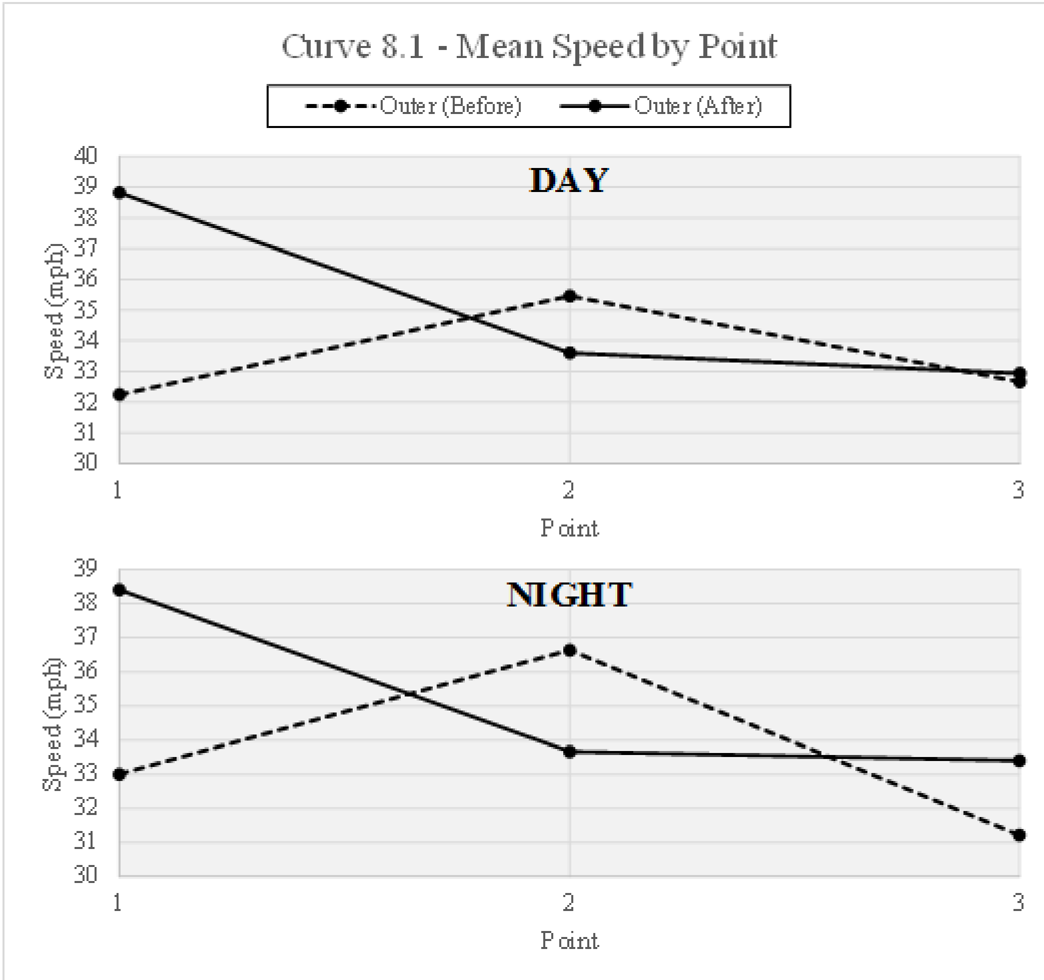

Figure 40. Curve 8.1 - Mean speed by point

The addition of the DCWS caused the mean offset to shift closer to the center of the lane for both day and night conditions, though the offset was closest to the center during the day (Figure 41). The offset was also consistent throughout the curve for each condition, with very little change from point to point.

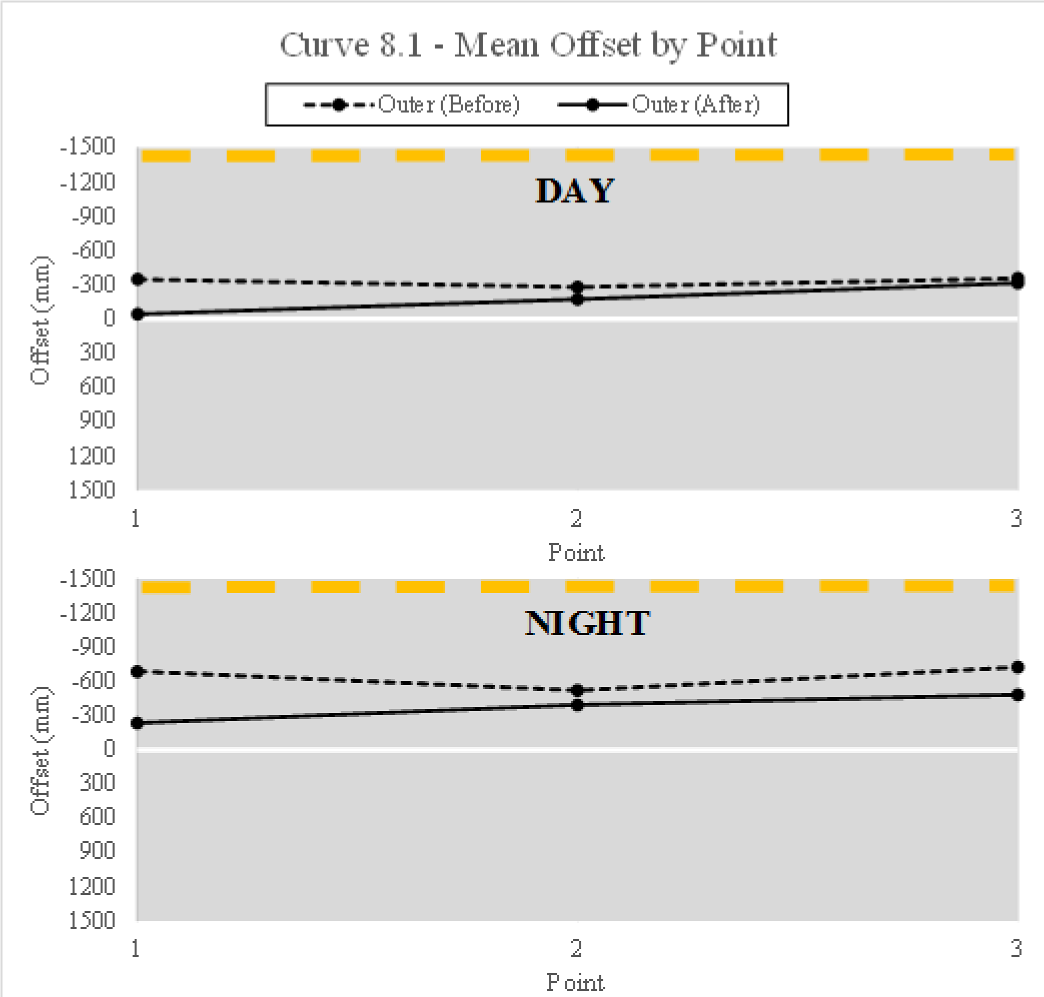

Figure 41. Curve 8.1 - Mean offset by point

Curve 8.1 Summary

The significantly higher mean speed at point 1 resulted in a slight increase to the 85th percentile speed for the curve, particularly during the day (Table 26). The percentage vehicles exceeding the advisory speed by 5 to 10 mph was reduced; however, the percentage increased for vehicles traveling 10 mph or more over the advisory speed. In spite of the increased speeds, vehicles tended to stay closer to the center of the lane, and center line encroachments decreased significantly.

Table 26. Change in 85th percentile speed, percent speeding, and percent encroachments (observational)

85th Percentile Speeds (mph)					
Time		Lane	Before	After	Change
Day		Outer	38.2	40.3	2.1
Night		Outer	39.2	39.8	0.6
Percent Over Advisory Speed Limit (30mph)					
Time	Lane	Over Limit	Before	After	Change
Day	Outer	>5 mph	39.9%	37.2%	-2.7%
		>10 mph	6.9%	18.8%	11.9%
		>15 mph	0.4%	3.2%	2.8%
		>20 mph	0.0%	0.1%	0.1%
Night	Outer	>5 mph	45.4%	41.7%	-3.7%
		>10 mph	10.5%	16.1%	5.6%
		>15 mph	1.0%	1.0%	0.0%
		>20 mph	0.0%	0.0%	0.0%
Percent Encroachments					
Time	Lane	Line	Before	After	Change
Day	Outer	Center	7.0%	1.3%	-5.6%
		Edge	0.1%	0.0%	-0.1%
Night	Outer	Center	22.6%	3.7%	-18.9%
		Edge	0.0%	0.0%	0.0%

(pink) = an increase greater than 1mph or 1%

(green) = a decrease greater than 1mph or 1%

Curve 8.2

There was no existing treatment for curve 8.2 other than a winding road sign located upstream of the curve. The new treatment consisted of a DCWS which activated when a vehicle was detected driving faster than the advisory speed. When activated, the sign consisted of four flashing dots, a curve sign, and a "SLOW DOWN" message (Figure 42). The sign was only visible for vehicles in the outer lane of the curve. The distance from the point of curvature to the sign was approximately 164 ft. Observational data were not collected at this curve, due to the proximity of a busy gas station adjacent to the curve. The ANOVA results for the human-factors study are shown in Table 27. The treatment had a significant effect on offset, but had no effect on speed.

Figure 42. Curve 8.2 treatment – dynamic curve warning sign

Table 27. ANOVA results for Curve 8.2 (human-factors study)

Curve 8.2 (DCWS) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Outer	Age	0.2388	0.1711	0.1375	0.1811	0.7119	0.3014	0.2100	0.0611
	Treatment	0.3636	0.6954	0.9534	0.4729	**<.0001**	**<.0001**	**0.0317**	0.2021
	Age*Treatment	0.0584	0.1517	0.3034	0.3014	**0.0154**	0.6826	0.2921	0.7269

Values in boldface indicate significant results.

After the installation of the DCWS, the mean offset for participants shifted away from the center of the lane in segments 1 and 2 by 401 mm and 359 mm, respectively (Figure 43). The offset was virtually unchanged in segments 3 and 4.

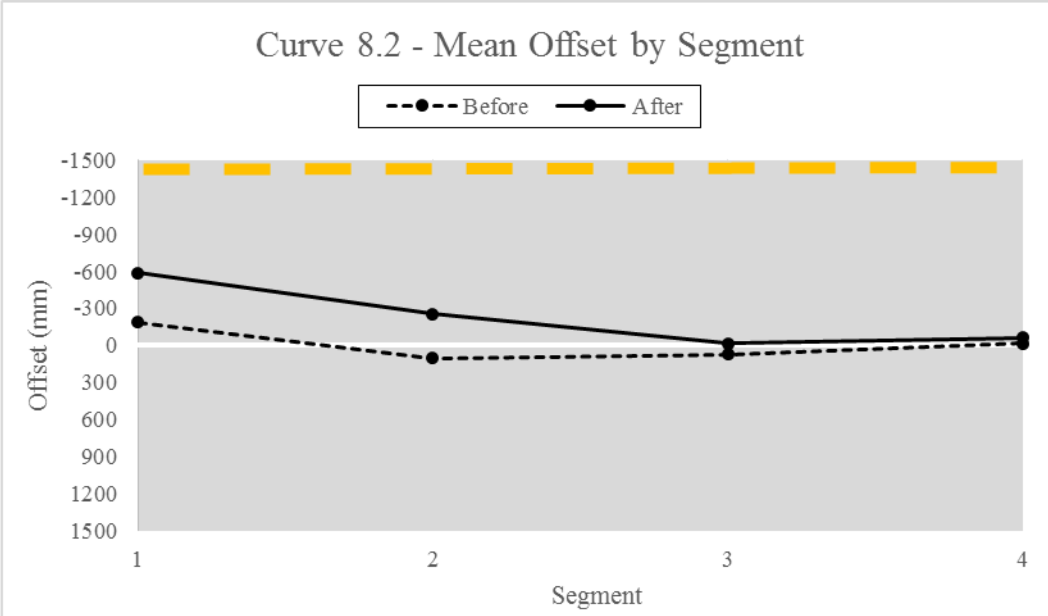

Figure 43. Curve 8.2 - Mean offset by segment

Curve 8.2 Summary

The addition of the DCWS to curve 8.2 had no effect on participants' speed. Participants' mean offset was further from the center of the lane at points 1 and 2, and less consistent throughout the curve.

Continuous Reflectors

Curve 6

There was no existing treatment for curve 6. The new treatment consisted of continuous reflectors; retroreflective strips installed within the groove of the guardrail which flanked the outside of the curve (Figure 44). The distance from the first reflector to the point of curvature was approximately 82ft for the inner lane, and 236ft for the outer lane. The ANOVA results for the human-factors study are shown in Table 28. For speed, the treatment was only significant for the inner lane in segment 4.

Figure 44. Curve 6 treatment – continuous reflectors

Table 28. ANOVA results for Curve 6 (human-factors study)

Curve 6 (Continuous Reflectors) - P Values									
Lane	**Source**	**Speed**				**Offset**			
		Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 1**	**Segment 2**	**Segment 3**	**Segment 4**
Inner	Age	0.1797	0.4605	0.1991	0.5899	0.7586	0.1054	0.0709	**0.0044**
	Treatment	0.0731	0.7368	0.2815	**0.0423**	0.0785	0.1235	0.8046	0.6890
	Age*Treatment	0.6313	0.9445	0.7665	0.9751	0.4243	0.4596	0.6594	0.3021
Outer	Age	0.7814	0.5621	0.4361	0.4809	0.5510	0.5527	0.0786	0.5077
	Treatment	0.0885	0.4700	0.4374	0.0765	0.6939	0.1744	0.1542	**0.0397**
	Age*Treatment	0.4903	0.4549	0.8473	0.3960	0.4847	0.8287	0.4091	0.8182

Values in boldface indicate significant results.

Figure 45 shows the mean speed by segment for curve 6. Although the mean speed increased slightly in several areas, the only significant change was for the inner lane in segment 4, where the mean speed was reduced by 1 mph.

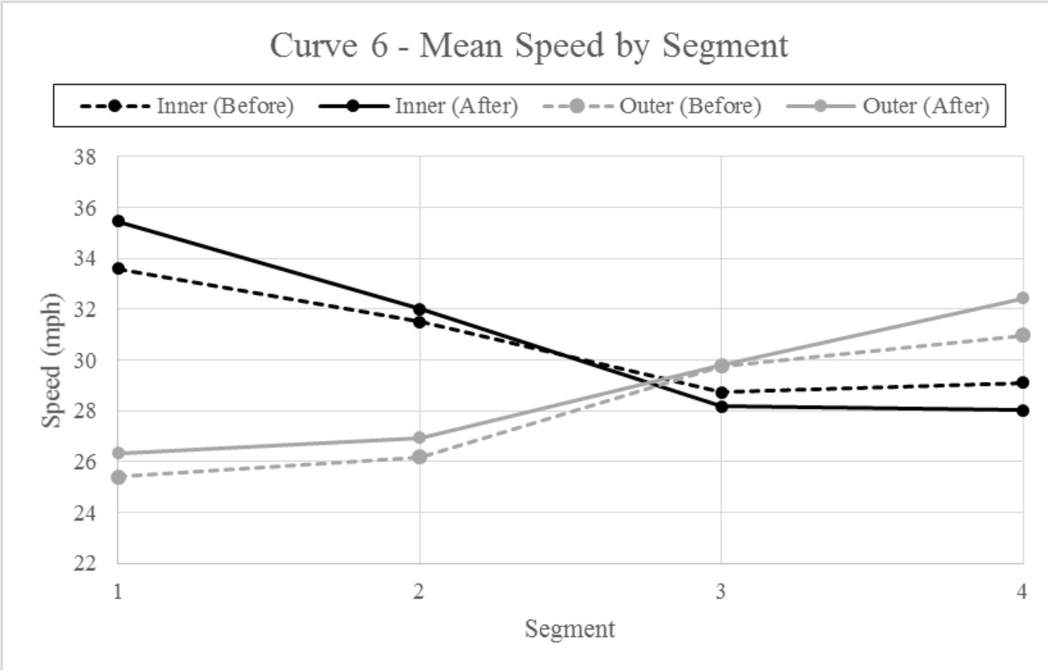

Figure 45. Curve 6 – Mean speed by segment

The treatment had a significant effect for offset only for segment 4 of the outer lane. However, the difference was quite small (65 mm) and not practically important (Figure 45).

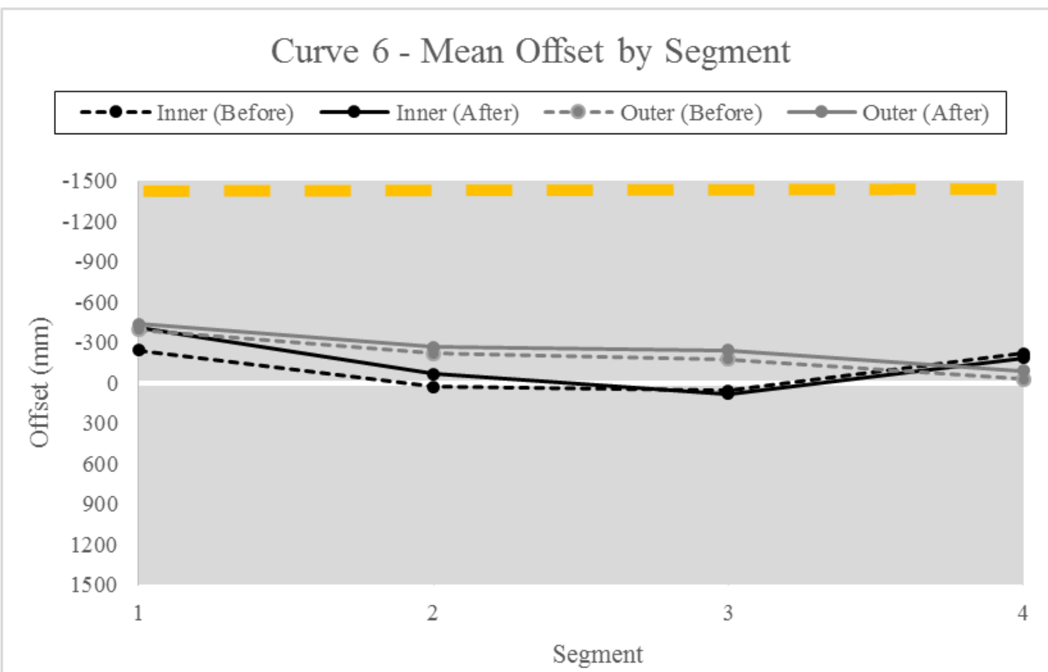

Figure 46. Curve 6 – Mean offset by segment

The ANOVA results for the observational study are shown in Table 29. Values in boldface indicate significant results ($p < 0.05$).

Table 29. ANOVA results for Curve 6 (observational study)

Curve 6 (Continuous Reflectors) - P Values							
Time	**Lane**	**Speed**			**Offset**		
		Point 1	**Point 2**	**Point 3**	**Point 1**	**Point 2**	**Point 3**
Day	Inner	**<.0001**	**<.0001**	**<.0001**	**0.0002**	**<.0001**	**<.0001**
	Outer	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Night	Inner	**0.0002**	0.0835	**<.0001**	**0.0040**	**<.0001**	**0.0001**
	Outer	**<.0001**	**<.0001**	0.1321	**<.0001**	**<.0001**	**<.0001**

Values in boldface indicate significant results.

The mean speed was significantly affected in all conditions, except at point 2 for the inner lane at night, and point 3 for the outer lane at night. This result is interesting because the continuous reflectors likely would not be noticeable during the day. This section of the roadway was repaved and remarked between data collection sessions, so this may account for the differences. The mean speed increased significantly at all points for the inner lane, and at points 1 and 2 for the outer lane during the day (Figure 47). At night, the speed was increased at points 1 and 3 for the inner lane, and at points 1 and 2 for the outer lane.

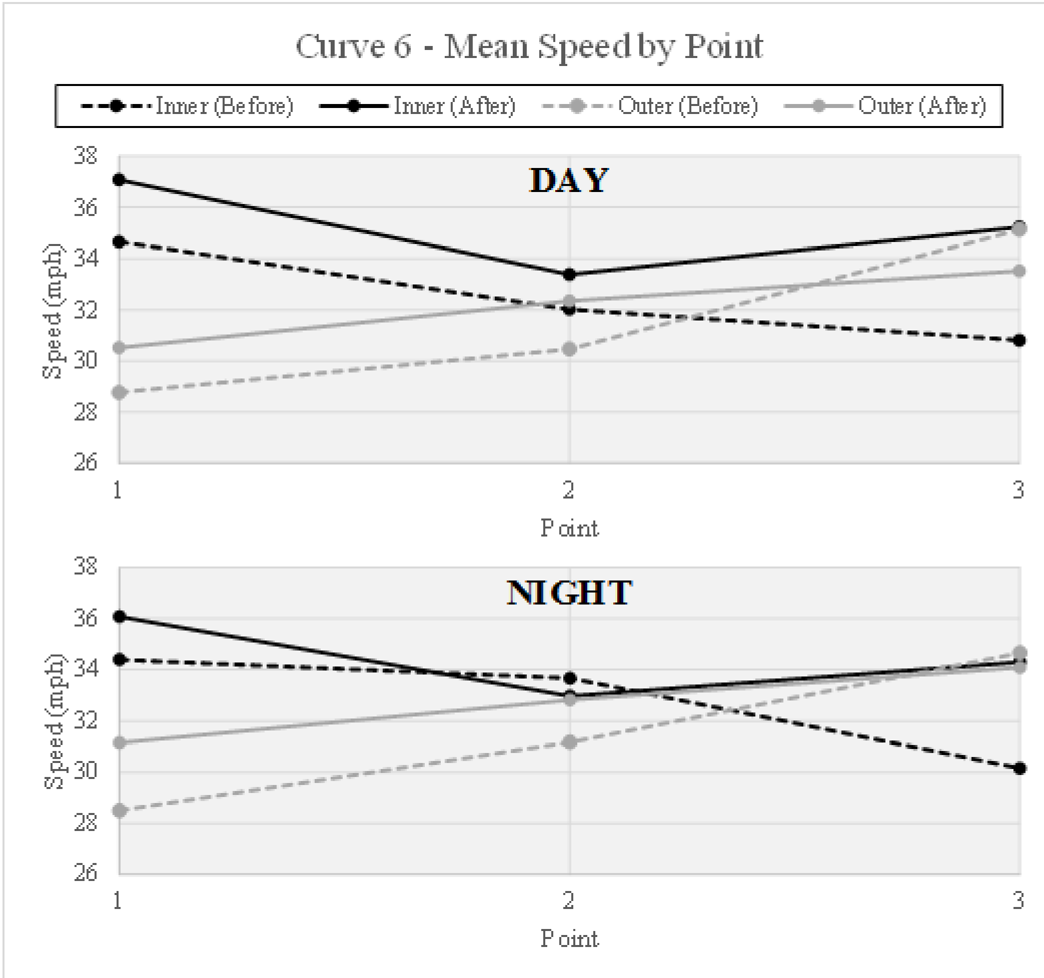

Figure 47. Curve 6 - Mean speed by point

For the inner lane, the mean offset was much closer to the center of the lane at point 2, but slightly further from center at point 3. For the outer lane, the offset was closer to center at points 2 and 3, and was more consistent throughout the curve (Figure 48).

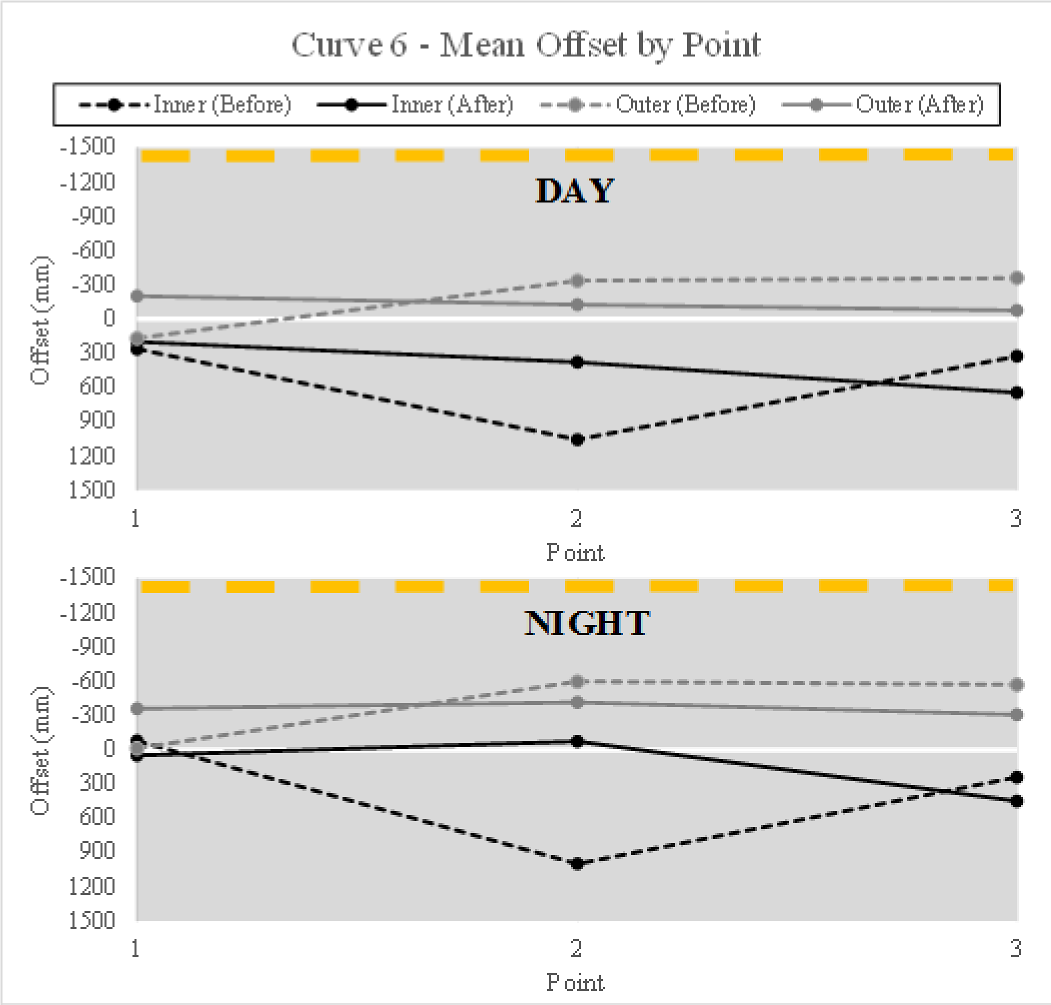

Figure 48. Curve 6 - Mean offset by point

Curve 6 Summary

The addition of the continuous reflectors, and potentially the repaving and remarking of the roadway, resulted in higher speeds at most locations of the curve, which lead to higher 85th percentile speeds (Table 30). The percentage of vehicles exceeding the advisory speed by 5 to 10 mph decreased for the inner lane, but those exceeding by 10 mph or more increased in both lanes. In spite of the increased speed, drivers tended to do a better job navigating the curve in terms of the offset; particularly at point 2. As a result, there were very large reductions in the percentage of encroachments.

Table 30. Change in 85th percentile speed, percent speeding, and percent encroachments (observational).

85th Percentile Speeds (mph)					
Time		Lane	Before	After	Change
Day		Inner	36.5	38.6	2.0
		Outer	33.1	35.0	1.9
Night		Inner	37.9	38.0	0.0
		Outer	33.5	35.0	1.4
Percent Over Advisory Speed Limit (25mph)					
Time	**Lane**	**Over Limit**	**Before**	**After**	**Change**
Day	Inner	>5 mph	54.4%	42.2%	-12.1%
		>10 mph	26.0%	39.7%	13.6%
		>15 mph	2.3%	10.0%	7.7%
		>20 mph	0.2%	0.5%	0.3%
	Outer	>5 mph	44.1%	50.5%	6.3%
		>10 mph	5.7%	15.4%	9.8%
		>15 mph	0.0%	0.5%	0.5%
		>20 mph	0.1%	0.0%	-0.1%
Night	Inner	>5 mph	48.9%	41.6%	-7.3%
		>10 mph	33.2%	40.1%	6.9%
		>15 mph	5.3%	5.3%	0.0%
		>20 mph	0.5%	0.4%	-0.1%
	Outer	>5 mph	40.2%	56.2%	16.0%
		>10 mph	7.4%	16.1%	8.7%
		>15 mph	0.8%	1.3%	0.6%
		>20 mph	0.2%	0.0%	-0.2%
Percent Encroachments					
Time	**Lane**	**Line**	**Before**	**After**	**Change**
Day	Inner	Center	0.4%	0.1%	-0.2%
		Edge	29.5%	1.8%	-27.7%
	Outer	Center	4.3%	1.4%	-2.9%
		Edge	0.1%	0.0%	-0.1%
Night	Inner	Center	3.2%	11.3%	8.2%
		Edge	19.2%	1.3%	-17.9%
	Outer	Center	16.0%	5.5%	-10.5%
		Edge	0.0%	0.0%	0.0%

[pink] = an increase greater than 1mph or 1%

[green] = a decrease greater than 1mph or 1%

DISCUSSION

A summary of results from the observational study (day and night) and human factors study (night only) are shown in Table 31. This table shows the change in mean speed and the change in absolute offset (the absolute distance from the center of the lane, regardless of direction) at only the most critical locations. For the observational data, the change in speed is shown for point 1, where drivers first entered the curve. For the human factors data, the change in speed is shown for segment 2, which was the area from the point of curvature to the middle point. The drivers' speeds at these locations would indicate how well the warning or delineation system provided clues about the curvature of the roadway before a driver reached the point of curvature. For the absolute offset, the observational data show the change at point 2, while the human factors data show the change for segments 2 and 3 combined. Changes in speed greater than +/- 1 mph, and changes in absolute offset greater than +/- 100 mm are highlighted.

Table 31. Summary of results

<table>
<tr><th colspan="8">Change in Mean Speed and Absolute Offset</th></tr>
<tr><th rowspan="2">Treatment Type</th><th rowspan="2">Treatment</th><th rowspan="2">Curve</th><th rowspan="2">Lane</th><th colspan="2">Observational Data</th><th colspan="2">Human Factors Data</th></tr>
<tr><th>Delta Speed (mph)</th><th>Delta Abs. Offset (mm)</th><th>Delta Speed (mph)</th><th>Delta Abs. Offset (mm)</th></tr>
<tr><td rowspan="10">Passive</td><td rowspan="4">Retroreflective Posts</td><td rowspan="2">1</td><td>Inner</td><td>0.39</td><td>234</td><td>-1.7</td><td>-35</td></tr>
<tr><td>Outer</td><td>-2.81</td><td>73</td><td>-0.05</td><td>-51</td></tr>
<tr><td rowspan="2">9</td><td>Inner</td><td>0.13</td><td>-314</td><td></td><td></td></tr>
<tr><td>Outer</td><td>-1.16</td><td>-28</td><td></td><td></td></tr>
<tr><td rowspan="4">OPS</td><td rowspan="2">4</td><td>Inner</td><td>0.43</td><td>-184</td><td>-1.35</td><td>-24</td></tr>
<tr><td>Outer</td><td>-0.87</td><td>-144</td><td>0.17</td><td>33</td></tr>
<tr><td rowspan="2">7*</td><td>Inner</td><td>4.15</td><td>-104</td><td>0.48</td><td>-38</td></tr>
<tr><td>Outer</td><td>0.84</td><td>-278</td><td>0.8</td><td>101</td></tr>
<tr><td rowspan="2">Continuous Reflectors</td><td rowspan="2">6*</td><td>Inner</td><td>2.37</td><td>-650</td><td>0.49</td><td>16</td></tr>
<tr><td>Outer</td><td>2.13</td><td>-157</td><td>0.77</td><td>57</td></tr>
<tr><td rowspan="6">Active</td><td>Blinking CWS</td><td>3</td><td>Inner</td><td>3.65</td><td>229</td><td>-0.5</td><td>-30</td></tr>
<tr><td rowspan="3">DCWS</td><td>5*</td><td>Outer</td><td>-1.13</td><td>-54</td><td>-1.06</td><td>60</td></tr>
<tr><td>8.1</td><td>Outer</td><td>6.37</td><td>-110</td><td></td><td></td></tr>
<tr><td>8.2</td><td>Outer</td><td></td><td></td><td>0.39</td><td>76</td></tr>
<tr><td rowspan="2">Sequential Chevrons</td><td rowspan="2">2</td><td>Inner</td><td>-0.36</td><td>-48</td><td>-0.54</td><td>-31</td></tr>
<tr><td>Outer</td><td>2.29</td><td>162</td><td>-0.6</td><td>-23</td></tr>
</table>

= an increase greater than 1 mph or 100 mm.

= a decrease greater than 1 mph or 100 mm.

*Results may have been affected by repaving and remarking of the curve.

The human factors data saw smaller changes than the observational data. This is likely due to the values being averaged over an entire segment, rather than captured at a single point. Additionally, the presence of an experimenter in the vehicle, as well as a smaller amount of data likely reduced the likelihood of large changes. The observational data suggest that the addition of the retroreflective material to the posts of the existing chevrons in curves 1 and 9 helped reduce traffic speeds for the outer lane. The sequential chevrons increased the speed and absolute offset in the outer lane, but slightly decreased these values in the inner lane. The blinking curve warning sign increased the speed and offset for the only lane it was visible from. The on-pavement signage had some of the largest reductions in the mean offset for both curves it was installed in (curves 4 and 7), but also had a large increase in speed for the inner lane. The results in curve 7 may have been affected by the repaving and remarking of the curve, however. The dynamic curve warning sign seemed to help reduce the absolute offset, but had mixed results for speed.

Table 32 shows another summary of changes for the observational data. The table lists the change in the 85th percentile speed, the percentage of vehicles exceeding the advisory speed, and the percentage of encroachments. Generally speaking, a decrease in these numbers is desired, as that would likely lead to improved safety. However, nearly every treatment that saw a decrease in one or more of these numbers also saw an increase in another. Additionally, the same treatment often had very different results for different curves (e.g., curves 1 and 9), or even within the same curve depending on which lane vehicles were travelling in (e.g., curves 1 and 2).

Table 32. Summary of changes (observational)

Change in 85th Percentile Speeds (mph)											
Time	Lane		Curve 1	Curve 2	Curve 3	Curve 4	Curve 5	Curve 6	Curve 7	Curve 8.1	Curve 9
Day	Inner		1.4	-1.3	0.3	-0.1		2.0	3.2		-1.2
	Outer		-2.5	2.1		-0.8	0.4	1.9	2.0	2.1	-0.4
Night	Inner		1.9	-1.7	1.0	-0.2		0.0	3.5		-0.3
	Outer		-2.7	3.5		0.0	1.9	1.4	0.9	0.6	0.5
Change in Percent Over Advisory Speed Limit (35mph)											
Time	Lane	Over Limit	Curve 1	Curve 2	Curve 3	Curve 4	Curve 5	Curve 6	Curve 7	Curve 8.1	Curve 9
Day	Inner	>5 mph	-2.6%	10.7%	-7.5%	0.4%		-12.1%	21.5%		-3.2%
		>10 mph	3.9%	-3.3%	-8.2%	-0.6%		13.6%	-12.2%		-3.1%
		>15 mph	2.6%	-9.2%	5.5%	2.1%		7.7%	10.8%		-0.9%
		>20 mph	0.6%	-2.1%	3.2%	-0.8%		0.3%	5.6%		0.1%
	Outer	>5 mph	2.1%	-6.9%		3.1%	2.5%	6.3%	-3.8%	-2.7%	-0.9%
		>10 mph	-13.2%	-8.4%		-1.0%	-3.0%	9.8%	8.7%	11.9%	-1.3%
		>15 mph	-3.2%	14.0%		-4.3%	-0.1%	0.5%	6.6%	2.8%	0.2%
		>20 mph	0.2%	1.9%		-0.6%	0.1%	-0.1%	0.2%	0.1%	-0.2%
Night	Inner	>5 mph	-4.6%	5.6%	0.3%	-3.2%		-7.3%	16.8%		-8.4%
		>10 mph	11.6%	6.6%	-4.7%	-0.6%		6.9%	-13.6%		-2.9%
		>15 mph	2.7%	-7.2%	9.3%	2.0%		0.0%	16.8%		-0.6%
		>20 mph	0.6%	-4.3%	2.6%	0.3%		-0.1%	7.7%		-0.1%
	Outer	>5 mph	7.3%	-14.4%		1.6%	6.8%	16.0%	4.8%	-3.7%	7.3%
		>10 mph	-11.8%	3.6%		-1.3%	6.0%	8.7%	-3.2%	5.6%	-0.6%
		>15 mph	-4.6%	15.6%		-0.7%	0.6%	0.6%	5.8%	0.0%	-0.3%
		>20 mph	-1.1%	-8.2%		0.1%	0.2%	-0.2%	-0.2%	0.0%	-0.2%
Change in Percent Encroachments											
Time	Lane	Line	Curve 1	Curve 2	Curve 3	Curve 4	Curve 5	Curve 6	Curve 7	Curve 8.1	Curve 9
Day	Inner	Center	0.2%	-1.1%	-0.6%	-1.1%		-0.2%	10.5%		5.1%
		Edge	2.2%	-1.5%	0.0%	-0.3%		-27.7%	-4.0%		-6.8%
	Outer	Center	1.6%	0.7%		-0.5%	1.4%	-2.9%	-1.4%	-5.6%	-0.5%
		Edge	-2.2%	0.7%		0.3%	-0.8%	-0.1%	-0.1%	-0.1%	-0.2%
Night	Inner	Center	-0.1%	-1.5%	-7.9%	-2.3%		8.2%	5.2%		9.3%
		Edge	1.3%	-0.5%	-0.3%	0.0%		-17.9%	-1.3%		-3.8%
	Outer	Center	2.6%	1.3%		-1.0%	1.6%	-10.5%	-5.2%	-18.9%	1.0%
		Edge	-0.8%	0.5%		0.0%	-1.5%	0.0%	0.0%	0.0%	-0.2%

= an increase greater than 1mph or 1% (pink)

= a decrease greater than 1mph or 1% (green)

One potential reason for the mix of results may be that increasing visibility on a curve may lead to increased speeds if the curve radius is relatively small, but not if the radius is relatively large. For example, curve 7 had the smallest radius and lowest advisory speed of all the curves in the study, but had the greatest increases in 85th percentile speeds, and the percentage of vehicles exceeding the advisory speed. Prior to the installation of the on-pavement signage, and the roadway being remarked, users familiar with the roadway would know that a sharp turn is ahead, but not being able to easily discern the curvature of the roadway leads them to slow down significantly. When the on-pavement signage was added, and the roadway was remarked, this likely increased drivers' visibility of the curve, making them feel more comfortable, so they did not slow down as much. In comparison, curve 9 had the largest radius and the highest advisory speed of all the curves in the study. In this scenario, drivers are not likely expecting a sharp turn, so they do not adjust their speed much when they see a few chevrons. However, after adding the retroreflective posts to the chevrons, the curve delineation likely stands out more, making them take notice, and adjust their speed. As a result, this curve had the best results for reducing the 85th percentile speed, and the percentage of vehicles exceeding the advisory speed.

This idea is supported by the data. Figure 49 shows the change in 85th percentile speed (for points 1 and 2) by the radius of the curve. A logarithmic trend line is shown, with the associated R^2 value. This relationship suggests that the smaller the curve radius, the more likely the speed would increase. The trend line suggests that curves with radii of approximately 575 ft or more would be more likely to see a decrease. However, the trend line is based on data from only 9 curves, and there is significant variation from the trend line. This relationship could also explain why two curves that get the same treatment may have different results, such as curves 1 and 9.

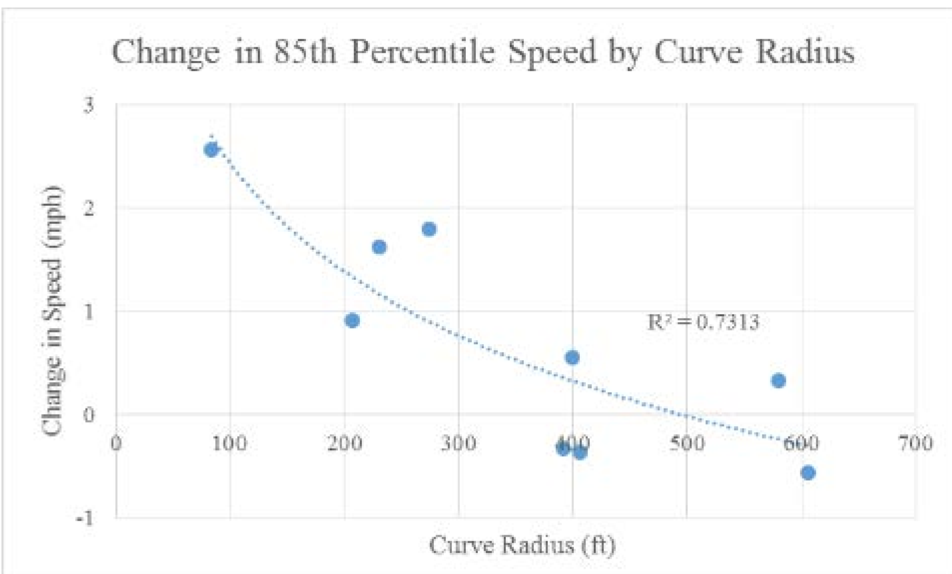

Figure 49. Change in mean speed by curve radius

Another reason for the seemingly contradictory results may be that curves are experienced differently depending on which direction a driver is traversing the curve. In curves 1 and 2, for example, traffic speeds increased in one direction, but decreased in the other, even though they experienced the same treatment. In the case of curve 1, drivers traveling in the inner lane came from a portion of the road that had few horizontal curves, whereas vehicles traveling in the outer lane came from a portion of the road that included numerous horizontal curves. The expectations of these drivers may be different, leading to different behaviors in the same curve. However, a treatment that reduces speed and encroachments in one lane but not the other may still provide an overall benefit if the majority of problems occur in that lane. For example, VDOT crash data shows that for curve 1, 3 crashes occurred in the inner lane, while 13 occurred in the outer lane, with the major crash causation listed as “Fixed Object – Off Road.” Therefore, the reduced speeds and edge line encroachments in the outer lane that resulted from the installation of the retroreflective post material may have a greater effect on the safety of the curve than the increased values for the inner lane.

Other factors which may have affected the results may include when data were recorded, and the amount of data recorded. Due to the number of curve points where data needed to be collected, only 24 hours of data were recorded for each. Although this still included thousands of data points, a larger amount of data collected several times throughout the year may have given a clearer picture of effects of the treatments.

For the dynamic curve warning signs in curves 5 and 8, the system only activated when it detected a vehicle exceeding the advisory speed. It’s possible some drivers may have intentionally driven faster in order to activate the sign, which may be why there was also an increase in the percentage of vehicles exceeding the advisory speed.

Curve 6, which received continuous reflectors in the guardrail, had the largest reductions in encroachments by several orders of magnitude. Some of these reductions occurred in daytime when the reflectors would not be effective at increasing visibility. It’s possible that these changes are largely due to the fact that this portion of the road was repaved and remarked between the before and after conditions. If this is the case, this suggests that clear road markings and a healthy road surface could have greater benefits for preventing encroachments than a road-side delineation system.

CONCLUSIONS

- *A treatment did not always have the same effect for both lanes of travel, even within the same curve.*

- *New or additional treatments to a curve sometimes increased vehicle speeds by giving drivers a clearer picture of the curve.*

- *The radius of the curve seemed to have an effect on the potential benefits of a treatment.*

- *Active delineation and warning systems did not present a clear advantage over passive systems. Passive systems will likely provide a similar benefit for a fraction of the cost.*

- *Adding retroreflective posts to existing chevrons was effective in reducing the speed and edge line encroachments for traffic in the outer lane; particularly in a curve with a smaller radius.*

- *Sequentially flashing chevrons were effective at reducing the speed and encroachments for traffic in the inner lane.*

RECOMMENDATIONS

1. VDOT's traffic engineering staff should consider using passive systems first since active warning and delineation systems did not provide a clear advantage.

   Two factors to consider when exploring curve warning treatments are as follows:

   - Active systems may be more beneficial in a visually complex area in which the warning or delineation system is competing for attention against other light sources in the area.

   - Curve characteristics and the specific problems that are identified in a safety assessment and budget should be the main considerations when selecting a system.

BENEFITS AND IMPLEMENTATION

Benefits

This study was conducted to assess the effectiveness of active and passive curve warning and delineation systems on a two-lane rural road with respect to driver speed and lane keeping. The benefit of implementing the study recommendation will be guidance on factors to consider when selecting curve warning treatments.

Implementation

Based on the results of this study, VDOT's Traffic Engineering Division, with the support of the Virginia Transportation Research Council and the Salem District traffic engineering staff who championed this project, will develop a best practices information sheet on factors to consider when selecting curve treatments. This may include a tiered approach and consideration of active curve warning devices when crash history is higher than average. VDOT's Traffic Engineering Division will distribute this information in draft form to the district traffic engineers and others (as appropriate) within 12 months after the publication of this report. A 30-day time period will be allotted for the districts to review and provide comments. Comments will be assessed by the Virginia Transportation Research Council and VDOT's Traffic Engineering Division and a final document issued within 90 days after the review period ends. The final document will aid VDOT staff in determining when to consider use of active curve warning devices.

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