Means to Reduce Operating Speeds on Curves

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SYNOPSIS

Sharp horizontal curves can pose dangers to the driver when dealing with speed adjustment, vehicle placement, and judgment of the appropriate operating speed. Roadway designers use various warning methods to aid drivers in such situations. Two primary methods of achieving this are warning signs and pavement markings. There is a suspicion however that these devices are often misinterpreted or disregarded by drivers. Therefore, the effectiveness of signs and markings is reduced and often the intended reduction in operating speeds is not achieved. Safety concerns regarding the effectiveness of these devices arise which could be prevented by a proper and judicious placement of signs and markings. The objective of this study is to evaluate the use of several warning signs and pavement markings at problematic rural horizontal curves, and to evaluate their effectiveness in relation to speed reduction.

Several types of warning signs and pavement markings were used to determine methods and combinations that could reduce operating speeds more effectively. All of the sites studied had an existing horizontal alignment sign with speed plaque in advance of the curve. The treatments applied included one-direction large arrow signs, chevron alignment signs, the new sign that combines horizontal alignment and advisory speed, addition of flags to the existing sign, addition of flashing lights to the existing sign, post delineators, and transverse lines. All these treatments were applied to three curves and speed data were collected over a two-day period at four locations approaching and in the curve over a distance of approximately 350 m.

The results indicate that the most promising treatments in reducing operating speeds are flashing lights and transverse lines. These treatments typically showed speed reductions ranging from 5% to 10%. An analysis of the over the 85^{th} percentile speeds for these treatments showed also significant reductions ranging from 12% to 18%. This indicates that there was a greater impact for the higher operating speeds, which could be considered more important than the smaller overall reductions noted. Another treatment that also showed some potential for reducing speeds is the new combination sign.

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INTRODUCTION

The basic premise for geometric design of roadways is to provide a safe and efficient facility. However, there are other constraints, such as financial and geographic, which forbid the ideal roadway design from being materialized. These less than ideal situations can lead to the use of geometric conditions that may require sharper curves, limited sight distances, steeper grades, and other issues that could affect the driver's ability to follow the intended design. The prevalent problem with such designs is that they do not provide any information or clues to the driver as to what is the appropriate operating speed. Sharp horizontal curves can pose dangers to the driver when dealing with speed adjustment, vehicle placement, and judgment of the appropriate operating speed. Roadway designers have introduced many warning methods to aid drivers in realizing and using the appropriate operating speed at dangerous roadway locations. Therefore, a prime location to test some of these warning methods is at horizontal curves that have some of these undesirable characteristics.

Two primary methods of conveying roadway information to the driver are warning signs and pavement markings. According to the Manual on Uniform Traffic Control Devices (MUTCD), "warning signs call attention to unexpected conditions … to situations that might not be readily apparent to road users" and "alert road users to conditions that might call for a reduction of speed or an action in interest of safety and efficient traffic operations" (MUTCD, 2000). Also according to the MUTCD, "markings on highways have important functions in providing guidance and information for the road user" and can be "used to supplement other traffic control devices". The MUTCD notes that an important characteristic of the pavement markings as opposed to the warning sign is that they allow the driver to focus on the roadway but still acknowledge the warning.

There is a suspicion however that warning signs and pavement markings are often misinterpreted or disregarded by drivers. In these cases the effectiveness of signs and markings is reduced and often the intended reduction in operating speeds is not achieved. Moreover, the absence of adjusting the operating speeds may some times lead to a crash. Thus, safety concerns regarding the effectiveness of these devices arise which could be prevented by a proper and judicious placement of signs and markings. A recent review of safety and speeds noted that there is a higher likelihood for a crash when traveling at higher or lower speeds than the average speed (Stutser et al 1998).

The objective of this work is to evaluate the use of several warning signs and pavement markings at problematic rural horizontal curves, and to evaluate their effectiveness in relation to speed reduction. The specific tasks undertaken to complete this study was an evaluation of standard warning signs and pavement markings, installation of a variety of treatments and speed measurement, analysis of the collected data, and development of recommendations regarding the effectiveness of the various treatments.

LITERATURE REVIEW

A literature review was completed to gain a better understanding of the effectiveness of warning signs and pavement markings at reducing operating speeds. There have been many innovative approaches in the implementation of warning signs and pavement markings and these advances assisted in determining what were the best measures to apply in this study.

Pavement Markings

The MUTCD states that the two most common types of pavement markings are longitudinal (i.e., center and edgeline markings) and transverse markings (i.e., crosswalk lines, intersection stop lines, etc.). Pavement markings come in many shapes, sizes, and functionalities. Regardless of their immediate purpose, pavement markings are used to inform and warn drivers, pedestrians, and bicyclists of local and federal regulations and potentially hazardous locations. The MUTCD states that the most inherent function of pavement markings is that they allow motorists to focus on the roadway where the danger is located, as opposed to signs or lights located off the roadway (MUTCD, 2000). Typical pavement markings are placed in advance of the impending roadway hazard to allow motorists to react accordingly and provide them with a sufficient amount of time to determine their proper reaction. Normally, the redesign and reconstruction of the roadway is the most efficient means of addressing potential hazards, but when redesign and reconstruction are not feasible, pavement markings can be used to alleviate or moderate these situations (Storm, 2000).

Transverse pavement markings, or optical speed bars, are stripes located at horizontal curve tangents, roundabout approaches, intersection approaches, construction areas, and freeway off ramps (Meyers, 1999). The goal of transverse markings is to reduce speed and improve safety at potentially hazardous locations. The markings are placed in advance of the location in question and perpendicularly to the path of traffic, to decrease vehicle speed before the location is reached. The spacing between stripes is reduced and they decrease in thickness, as they get closer to the location (Griffin and Reinhardt, 1996). The purpose of these markings is to create an optical illusion, which would force drivers to slow down. The line spacing and size is intended to give the driver a sense of acceleration, regardless whether the vehicle is actually accelerating. This impression of acceleration will give drivers the indication they are traveling faster than intended, which in turn will force them to decrease their operating speed.

A set of three applications of transverse pavement markings conducted by Enuston (1972) examined their effectiveness on operating speeds. Each application was at a different type of facility and included approach to a construction zone at an Interstate facility, a curve approach at a two-lane rural highway, and an approach to an overpass. A different roadway length and number of lines was used in each application to address the specifics of each site. Speed measurements were taken at the approach and along the treatment and comparisons were made before and after the installation. Mixed results were obtained for each site regarding the effectiveness of the transverse lines in reducing operating speeds. For the work zone approach, the results indicate a minimal speed reduction which decreased with time and attributed it to a "novelty" effect. The second site also included rumble strips and this combination had a larger initial speed reduction, but eventually the average speed began to return to the initial average speed. Moreover, the rumble strips reduced speeds dramatically, and the average speed increased considerably when the rumble strips were removed. In the third study, the average speeds were reduced following the treatment installation without any change in speed variation.

In studies where transverse markings were placed at a roundabout approach significant speed reductions were noted. Denton (1971) described a situation where yellow transverse markings were inserted at the approach of a traffic roundabout in Scotland. After monitoring speed for approximately three weeks before and after the installation of the markings it was concluded that the average speed decreased considerably, with the biggest decrease coming during morning hours (9-11 am). Havell (1983) implemented white transverse pavement markings prior to a traffic circle in South Africa. The results indicated a 10 percent speed reduction approximately 100 m from the roundabout entry. Speed measurements taken eight months later showed that the speed reductions still held and it was concluded that this reduction would continue to be observed in the future.

Backus (1976) implemented transverse pavement markings across two-lanes of traffic on a four-lane highway, approaching a horizontal curve and the speed was measured 100 feet from the point of curvature. It was determined that before the insertion of the pavement markings, the 35 mph speed limit was exceeded 60 percent of the time, and 18 percent of the traffic exceeded 40 mph. After the installation of the markings, the percentage of traffic exceeding 35 mph decreased by 35 percent, and the percentage of traffic exceeding 40 mph decreased by 10 percent. The experiment also yielded a decrease in average mean speed of 2.5 mph, which Backus concluded was statistically significant.

A study that experimented with transverse markings at the approaches of 5 separate intersections has also been completed (Jarvis, 1989). The markings were a yellow thermoplastic material, 2 feet wide and a different distance between lines was used where the distance was reduced closer to the intersection. The results indicate that speeds decreased significantly as drivers entered the marked area, but after reaching their maximum speed reduction, drivers gradually returned to normal speeds, showing no signs of improvement. An innovative conclusion that Jarvis hypothesized is that the markings acted merely as a hazard warning - this can be attributed to drivers reducing speeds at the beginning of the pattern and then returning to normal speeds – and not a tool of affecting driver operating speeds. Another conclusion of the research was that the gradual declination in the distance between the transverse markings was not necessary and that equal spacing of the markings would allow a larger number of markings to be used at the area first observed by the driver.

Helliar-Symons (1981) analyzed accidents at 42 roundabouts in which yellow bar "carriageway" markings had been inserted on the tangent portion leading to the roundabout. The research concluded that the lines reduced speed-related accidents by 57 percent, appeared to maintain their effectiveness for at least four years, were highly cost-beneficial, were more effective in daylight than at night, and appeared to be more effective when the road surface was wet than when it was dry.

Warning Signs

The MUTCD states "warning signs call attention to unexpected conditions on or adjacent to a highway or street and to situations that might not be readily apparent to road user." A main objective of warning signs is that they give a sufficient amount of time for drivers to react to forthcoming roadway hazards (MUTCD, 2000). The application of warning signs can be based on an engineering study or engineering judgment. If the warning sign placement is performed from an engineering study, then the required time for a proper reaction needs to be considered. This time is the total time needed to react to a warning sign based on Perception, Identification (understanding), Emotion (decision making), and Volition (execution of decision) (PIEV). The PIEV times can vary accordingly, based on the dimensions of the roadway, posted or 85th-percentile speed, and the hazards associated with the roadway.

The most common type of warning sign in advance of a curve is the horizontal alignment sign. This sign is often accompanied by an advisory speed plaque, which is located below the horizontal alignment sign. The common function of this warning sign is to alert drivers of the impending change in the horizontal curvature of the roadway. The advisory speed plaque suggests a safe speed, other than the posted speed limit, that should be used to safely negotiate the curve. The excessive use and commonality of the horizontal alignment sign is probably the reason that the sign is often ignored. It is so often used that it "tends to breed disrespect for all signs" (MUTCD, 2000). Therefore, drivers will pay less attention to warning signs if they are used too frequently, thus creating an unsafe environment.

Hawkins (1994) conducted a study to examine the effects of supplemental warning plaques in addition to standard signing. The study used pedestrian crossings and railroad crossings to conduct the research. Drivers were surveyed after traversing sites with the sign alone and with supplemental plaques in addition to the sign. The purpose of this study was to determine whether the principles on which the current system of warning signs is based should be changed to improve driver comprehension. According to Hawkins, supplemental plaques can provide drivers additional information such as distance to the potential hazard, length of potential hazard, direction or location of hazard, recommended speed, and other miscellaneous identification or response information.

The combination horizontal alignment/advisory speed sign is a relatively new sign that combines the horizontal alignment sign with the advisory speed plaque onto a single sign. This sign is used to supplement the horizontal alignment sign with advisory speed plaque and is installed at the point of curvature, after the horizontal alignment sign. This signing reiterates the warning conveyed from the horizontal alignment sign as the driver approaches the curve. The sign duplication (2 warning signs) is envisioned to work as a stronger indication of the potential hazard. The one-direction large arrow sign is most commonly used to demarcate an upcoming change in the horizontal alignment of the roadway. The large arrow sign should be placed at the beginning of the curve, perpendicular to traffic. The sign should be placed at a location that allows the sign to be seen for a sufficient distance from the tangent of the curve. The ample distance will provide drivers an adequate amount of time to make a decision based on the change in alignment.

Common warnings located on warning signs are flags, flashing lights, and spotlights. The goal of these types of warnings is to give the driver a different warning perspective. For instance, bright, orange flags on a horizontal alignment sign are definitely not a usual occurrence. The typical warning sign is frequently ignored, but if something atypical was attached to the sign, it could possibly alert drivers in an uncharacteristic manner, forcing them to slow down or alter their driving behavior. Several studies have been performed to determine the effectiveness of warning signs accompanied by flashing lights. Lyles (1980) examined the use of flashing lights that supplemented warning signs at a rural intersection with poor sight distance. The flashing lights caused a 1.6 to 3.2 mph speed reduction compared with only a 0.8 mph speed reduction without the flashing lights. In another study, Lyles (1981) used flashing lights with the existing warning signs that warned drivers of construction zones on rural highways. The flashing lights resulted in a 3 to 4 mph speed reduction for short work zones and a 7.5 mph speed reduction for long work zones. Zegeer (1975) studied a situation where flashing lights were used with school zone speed restriction signs. The flashing lights reduced average speeds by 3.6 mph, and on roads with speed limits of 55 mph the average speed was reduced by 10 mph. Hanscome (1976) studied a situation where flashing lights were used to warn of the possibility of skidding due to wet weather. The flashing lights reduced average speeds by 9 percent for wet conditions.

Janoff and Hill (1986) studied a situation where a flashing beacon (not attached to the warning sign, but located after it) was installed at a severe curve on a four-lane rural highway. The site had originally a 35 mph speed limit sign, but was changed following public complaints dealing with speeding and negligent driving. The roadway was retrofitted with a reduced speed limit (25 mph) and edge, center, and post mounted delineators. The improvements did not reduce the speeds at the curve or the frequency of crashes. Then, a single flashing light was installed at the curve, mounted on a pole adjacent to the roadway. Accident data was compared for a 22-month period before the installation of the light and a 22-month period after the installation. The installation of the flashing light decreased the number of crashes from 14 to 7, and decreased the number of speed/lost-control type of crashes from 11 to 1.

According to the MUTCD, the chevron alignment sign can be used to provide greater emphasis and guidance when there is a change in the horizontal alignment of the roadway. More than one chevron sign is used at a time, and at least two chevron signs should be visible at all times as the driver navigates through the curve until the change in alignment eliminates the need for the signs. Chevron alignment signs can be used with or without standard delineators or the large arrow sign and are to be placed on the outside portion of the curve, perpendicular to oncoming traffic. Like the large arrow sign, chevrons should be visible from an adequate distance before the curve, to give the driver enough time to react accordingly. A study performed by Zador et al (1986) evaluated the effects of chevrons, post-mounted delineators, and raised pavement markers on driver behavior at rural, horizontal curves. Their research found that when chevrons were added to these locations, vehicles moved away from the centerline of the roadway. The experiment was performed at several sites, and the speed changes were inconsistent (i.e., some sites had a speed reduction, while others had a speed increase).

According to the MUTCD, "delineators are particularly beneficial at locations where the alignment might be confusing or unexpected, such as … curves" (MUTCD, 2000). Delineators are good methods of guidance[1] especially at night, because they are reflective and are at a comparable height to the headlights of vehicles. It is essential that delineators be spaced at a constant distance with several delineators visible at all times, when used at locations of changing horizontal alignment. The study by Zador et al (1986) found that speeds increased by approximately 1.5 mph at horizontal curves after the installation of post delineators. The study also found that vehicles tend to move towards the centerline of the roadway after the installation of post delineators on right horizontal curves, and have no placement effect for left horizontal curves. The authors concluded that an argument could be made that the speed increases found in the chevron and post delineator cases, reflect the adaptation of the drivers to an increased level of information about the upcoming roadway conditions, giving them an advantage in maneuvering through the curves.

Recent work on establishing the links between safety and speed indicated that there is such a relationship and the likelihood to be involved in a crash increases with departure from the average travel speed (Stuster, 1998). The use of means that could reduce such variance among speeds was a recommendation of the study. Therefore, the proper use and installation of warning signs could assist on achieving this goal.

Literature Review Summary

Operating speeds can effectively be reduced if warning signs and pavement markings are installed at hazardous roadway locations. The literature review showed the following.

1. Pavement markings can reduce operating speeds effectively. These markings act as a visual warning, they alter human perception, and they enable drivers to pay attention to the roadway without having to look off to the side of the roadway to see a warning sign.
2. Warning signs have also been found to reduce operating speeds at dangerous roadway sections and thus affect safety, and they seem to be even more beneficial if coupled with other warning signs or devices. Typical warning signs (i.e., curve warning signs, speed plaques, chevrons, etc.) are often overlooked due to their frequent use, but if additional warning signs or devices (i.e., combination horizontal alignment/advisory speed sign, flashing lights, flags, etc.) are used with the commonly used warning sign, drivers will often times acknowledge the warning sign when normally they would not, or they may react quicker to the warning.
3. Speed reductions due to warning signs and pavement markings vary from site to site, so it is very difficult to accurately predict what kind of results will occur.
4. The literature dealing with warning signs and flashing lights explained that where flashing lights are used and the hazard is not obvious, that regardless of the type of accompanying sign, a speed reduction of 2 to 3 mph can be expected; where the hazard is more clearly explained by the sign, the speed reduction is likely to be greater and the driver will probably pay closer attention.

[1] The MUTCD claims that delineators are guidance devices and not warning devices.

METHODOLOGY

The research plan focused on identifying potential sites where different treatments were to be introduced and speed measurements would be taken to estimate the effectiveness of each treatment. A request for candidate sites was made to each Kentucky Transportation Cabinet District office and a list of potential sites was developed. Each site proposed was evaluated through a site visit where the alignment was examined and documented. The existing warning signs and pavement markings were noted and any particular elements of the sites were recorded. A list of sites was developed and sites were selected based on their traffic volume, geometry, and crash history. Three sites were selected and the results are presented here.

The speeds were measured for existing and newly treated conditions at three locations throughout the curve approach. The devices were placed throughout the tangent and curve section on the curve approach, and a time and speed for each vehicle that passed over them was measured. This allowed for following individual vehicles throughout the system and then determining their speed reduction as they progressed through the study area. The location for the speed measurement devices differed for each site because of the existing geometry and traffic control. A contributing factor was the distance from the existing warning sign to the point of curvature. This distance dictated the position of the first speed measuring device in advance of the existing warning sign. Regardless of this distance, the three devices were placed in advance of the exiting warning sign, at the warning sign, and at the point of curvature at equal distances. Automated speed measuring devices (HI-STAR) were used and data reduction software was developed to correctly identify and track individual vehicles through the curve. Speed data was collected for free-flowing vehicles, i.e. trailing vehicles were eliminated from the data base and only the speed of the lead vehicle was used.

All treatments were given a five-day waiting period before the speed was measured. The treatment was removed after the data collection and the next treatment was installed with a new five-day waiting period. The waiting periods between treatments was implemented so that local traffic could be more familiar with the treatment and in turn, not give false speed-readings due to potential novelty effects. For instance, if a local driver navigates the same road every day, and then sees something different, then this driver is likely to slow down more than usual. If the drivers are given a few days to become familiar with the new situation, the recorded speeds will be more accurate and will allow for a better evaluation of the effectiveness of the treatment.

Several types of warning signs and pavement markings were considered for use in this study to determine which methods and combinations are those that could reduce operating speeds more effectively (treatment samples are shown in Figure 1). All of the sites that were studied had an existing horizontal alignment sign with speed plaque in advance of the curve. The advisory speed was set following the procedures outlined in the MUTCD using a ball bank indicator and it was assumed that they were properly set. The common treatments for all sites include: 1) addition of flags to the exiting curve warning sign; 2) addition of flashers to the existing curve warning sign; 3) installation of the combinational horizontal alignment/advisory speed sign placed at the point of curvature in addition to the exiting curve warning sign; 4) addition of flashing lights to both signs (existing and new); 5) installation of post delineators on the right hand side; and 6) installation of transverse pavement lines. For one of the sites, large arrows were installed because they were not part of the existing treatment.

To test for differences among various treatments and determine which treatment has the potential for a greater speed reduction, a series of statistical tests were used. The general null hypothesis is that no treatment has any effect on the speed reduction. To test this, two different tests were employed. The first tests the difference in average speeds, and the second examines the variances of the speed distributions. The test for the average speeds allows for simple comparisons between averages and identifies whether a treatment affected the average speeds. This is achieved with a z-test. Similarly, the 85^{th} percentile speeds and the over the 85^{th} percentile speeds were tested to determine any treatment effects. The second test examines whether the treatments have impacted the distribution of the speeds by forcing more drivers to drive at similar speeds, i.e. reducing the variance among speeds.

The two tests use the Bonferroni test to determine if the two null hypotheses (the average speeds are equal and the variances are equal) can be rejected. This test was first tested for all cases. The alternate hypotheses are that at least two of the average speeds are not equal and that at least two of the variances are not equal. If the Bonferroni test determines that the null hypotheses should be rejected, then the Dunnett C test is performed. The Dunnett C test is used for non-homogeneous variances and determines which treatments affected the average speeds and variances significantly.

RESULTS

The goal of this project was to evaluate the effectiveness of the treatments used on these sites. The data was analyzed using the average speeds, average speeds for day and night, overall changes in average speeds from one measurement location to another, percentage changes in average speeds from one measurement location to another, 85th percentile speeds, over the 85th percentile speeds, variances, and frequency distributions. Advisory speeds were set for all sites according to the AASHTO procedure using a bulb-bank indicator and these speeds were posted on the signs.

Site 1

This site had a warning sign with an advisory speed of 15 mph and 8 chevrons located on the outside of the curve. The treatments along with their corresponding average speeds and the percent reduction (in relation to the existing conditions) for each measurement location can be seen in Table 1. The data for the flashing lights was not available due to equipment malfunction.

Table 1 Speed measurements and percent change

	Speeds (mph)				Percent Change		
Treatment	1	2	3	Total reduction	1	2	3
Existing	51.1	46.6	43.4	-7.7	-	-	-
Flags	50.9	46.9	43.3	-7.6	-0.4	0.6	-0.2
Arrow	51.4	47.4	43.9	-7.5	0.6	1.7	1.2
New sign	52.0	47.9	44.3	-7.7	1.8	2.8	2.1
Delineators	52.1	48.2	44.1	-8.0	2.0	3.4	1.6
Lines	51.8	47.8	44.1	-7.7	1.4	2.6	1.6

The average speeds indicate that no treatment had any significant effect on the operating speeds for this curve. The initial vision for this project was to determine which treatments have the potential to reduce operating speeds the most. However, the data for this site indicate that there is almost no speed difference among the speeds at each location and for some treatments speeds increased. The percentage change in the average speed shows that the biggest change can be seen at the second measurement location (at the existing warning sign). Therefore, the second measurement location was used to perform a statistical analysis to determine if there is any statistical significance among the treatments.

Ideally, the standard deviations associated with these treatments should decrease as vehicles travel through the curve. Treatments with smaller standard deviations have more than likely forced drivers to navigate the curve at a safer speed, which in turn decreases the range of speeds and the variance. It can be assumed that treatments with smaller standard deviations have vehicles operating in a safer manner, since there will be little difference between speeds. Even though the existing treatment had smaller average speeds when compared to the other treatments, Figure 1 shows that its standard deviation is much larger than the other treatments. The treatments have not decreased the average speeds, but they have considerably decreased the standard deviations and thus resulted in more consistent operating speeds.

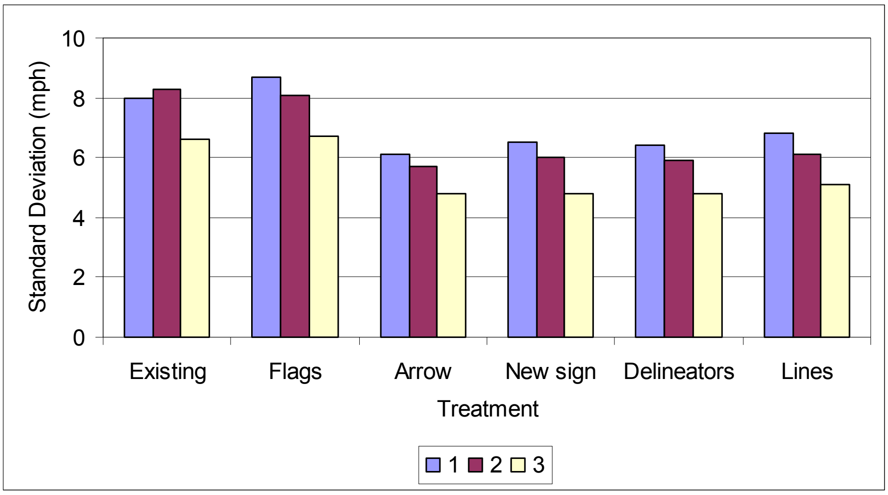

Figure 1 Standard deviations by measurement point (mph)

The variance is a parameter that reflects consistency in the speed measurements or the lack of it (Milton and Arnold, 1986). In other words, the variance is a measure of the distributional spread of the speeds as they compare to the mean. The Bonferroni test, which is used for cases of equal variances, revealed that the variances were not equal; therefore the null hypothesis was rejected. A new test was performed in order to determine which treatments were significantly changed. The Dunnett C test, which is used for non-homogeneous variances with high sample sizes, was then performed to determine which treatments affected the speed measurements significantly. The Dunnett C test revealed that the large arrow sign, the combination warning sign, the post delineators, and the transverse lines significantly affected the average speed for this site.

The statistical analysis determined that the increased speeds for the last four treatments were significantly changed, because of the treatment itself. One can only speculate as to why the average speeds increased. A potential reason could be that the new treatments increased the driver comfort level, thus allowing the drivers to navigate the curve faster. Another possibility could be that the drivers' disregard for new warning signs and markings had no effect on attracting the drivers' attention. A third reason could be that the additional warnings had no effect at all on operating speeds, and that the lower speeds for the existing treatment could be caused by any number of random possibilities such as weather, construction, or crashes.

A third approach that can be used to examine changes in the average speeds from the existing treatment is to observe the 85^{th} percentile speeds. The 85^{th} percentile speeds are larger than the average speeds (as would be expected), but the difference in change in the 85^{th} percentile speeds between treatments and existing conditions could follow a similar trend to that of the average speed changes. The measurement location that showed the largest change in 85^{th} percentile speeds should be a good indication of where drivers decide to change their speed the most dramatically in order to navigate the curve safely (Table 2). As mentioned before, the second measurement location shows the biggest change in average speed and this is also true for the 85^{th} percentile speeds. The data indicate that 85^{th} percentile speeds increased: a phenomenon that could not be explained in any other way other than the presence of the treatments may have created a feeling of a "safer" condition and the treatments had the exactly opposite effect.

Table 2 85^{th} percentile speeds and percent change

	Speeds (mph)				Percent Change		
Treatment	1	2	3	Total reduction	1	2	3
Existing	55.7	51.2	46.5	-9.2	-	-	-
Flags	56.4	52.0	47.3	-9.1	10.4	11.6	9.0
Arrow	56.2	51.4	47.2	-9.0	10.0	10.3	8.8
New sign	56.9	52.6	47.7	-9.2	11.4	12.9	9.9
Delineators	57.1	52.8	47.4	-9.7	11.7	13.3	9.2
Lines	56.8	52.5	47.6	-9.2	11.2	12.7	9.7

Another expectation was that the treatments may affect the speeds of vehicles exceeding the 85^{th} percentile speed. The data indicated that motorists exceeding the 85^{th} percentile speed showed a more dramatic speed reduction by the third measurement location as compared to the average and 85^{th} percentile speeds (Table 3). This could be considered as a positive indication, since these drivers could be considered as the ones that may have a larger crash potential. It should be noted here that the analysis was performed using the vehicles that were exceeding the 85^{th} percentile speed at the first measurement location by examining their speed change as they proceeded to the other two measurement locations.

Table 3 Over 85^{th} percentile speeds and percent change

	Speeds (mph)				Percent Change		
Treatment	1	2	3	Total reduction	1	2	3
Existing	60.4	55.3	50.0	-10.4	-	-	-
Flags	60.8	55.4	49.9	-10.9	19.0	18.9	15.0
Arrow	60.2	53.4	47.7	-12.5	17.8	14.6	9.9
New sign	60.1	53.3	48.2	-11.9	17.6	14.4	11.1
Delineators	61.0	53.8	48.5	-12.5	19.4	15.5	11.8
Lines	60.6	53.7	48.1	-12.5	18.6	15.2	10.8

Although the average speeds in Table 1 indicate that there was no significant reduction in operating speeds, the analysis for the time of day indicated that average nightly speeds were noticeably reduced. For instance, at the first measurement location, the warning sign with flags had almost a 4% (1.9 mph) reduction in average speed as compared to daytime speeds (Figure 2—numbers refer to measurement location and D: day; N: night). This could be possibly attributed to the distance that the flags can be seen from, when headlights shine on them. Some other noticeable nighttime reductions were at the third measurement location, where several treatments experienced a 4-5% average speed reduction. So even though the overall speed reductions for this site are minimal (or nonexistent for most cases), the nighttime average speeds show a promising attribute in that several of the locations do show a significant reduction in speed. Obviously, a dark environment has few distractions away from the roadway and therefore drivers would focus more on the road, warning signs, and pavement markings. Therefore, the drivers pay closer attention to the attributes of the roadway and adjust their speeds accordingly.

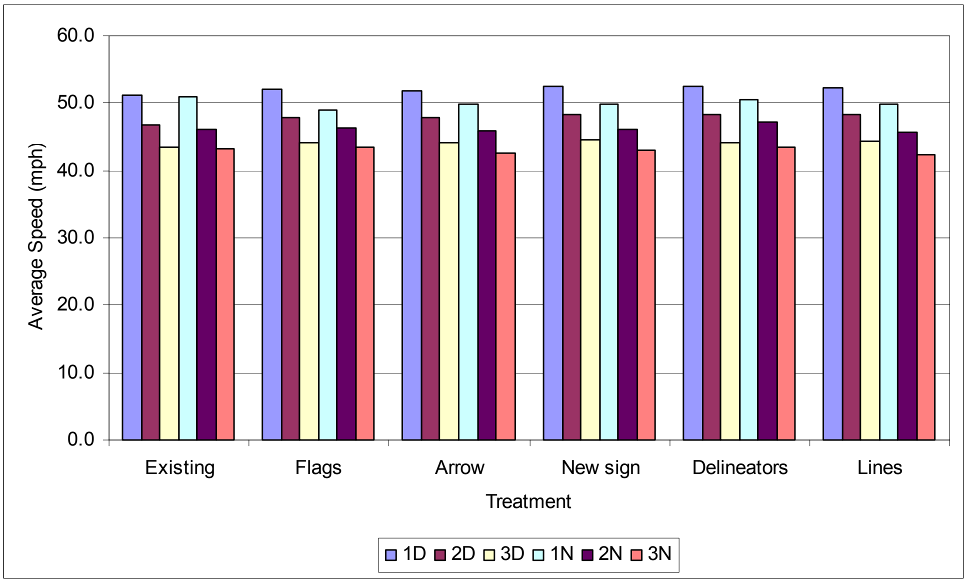

Figure 2 Average speeds by day (D) and night (N)

Site 2

The second site had also a speed warning sign with an advisory speed of a 35 mph, 3 chevrons located on the outside of the curve, and a large arrow sign also located on the outside of the curve. Six treatments were applied at this site (Table 4). A noteworthy speed reduction of 1.6% (0.9 mph) at the first measurement location, involved the use of flags attached to the existing curve warning sign. The probable cause for the speed reduction involving this treatment and no others at the first measurement location is that it was the most visible treatment from a longer distance (400 ft) than any of the others during daylight hours. The flashing lights could also have been seen from this distance, but only during the night. The remaining treatments did not show any significant changes at this measurement location. There were several treatments that experienced significant average speed reductions at the second measurement location, i.e. at the location of the existing curve warning sign. The flag treatment and transverse lines treatment experienced an average speed reduction of 2.6% (1.3 mph) and 2.9% (1.5 mph), respectively. The measurements at the third location demonstrated a reduction in average speed from all the treatments as compared to the existing conditions. The most significant reductions were from the flag, flashing lights on both signs, and the transverse line treatments. The flag treatment had an average speed reduction of 3.0% (1.3 mph), the two warning signs with flashing lights treatment had an average speed reduction of 3.4% (1.5 mph), and the transverse line treatment showed an average speed reduction of nearly 6% (2.7 mph).

Table 4 Speed measurements and percent change

Treatment	Speeds (mph)				Percent Change		
	1	2	3	Total reduction	1	2	3
Existing	52.2	48.8	45.8	-6.3	-	-	-
Flags	51.3	47.6	44.5	-6.9	-1.6	-2.6	-3.0
Flasher	52.7	48.8	45.6	-7.1	1.1	-0.1	-0.5
New sign	52.5	48.7	45.0	-7.5	0.6	-0.4	-1.8
Both flashers	53.0	48.4	44.3	-8.7	1.6	-0.9	-3.4
Delineators	52.8	49.4	45.3	-7.5	1.2	1.0	-1.2
Lines	52.1	47.4	43.1	-9.0	-0.1	-2.9	-5.9

The data in Table 4 indicate that the third measurement location experienced the largest overall speed reduction. Standard deviations also demonstrate the highest reduction at the same location (Figure 3). The statistical analysis performed focused on the third measurement location as well. The test for equal variances revealed that the average speeds and variances were not equal. The test for non-homogeneous variances revealed that the warning sign with flags, both signs with flashing lights, and the transverse lines significantly affected the average speed and variances. Therefore, it can be concluded that these three treatments had a direct impact on the reduction of speeds when compared to the existing conditions.

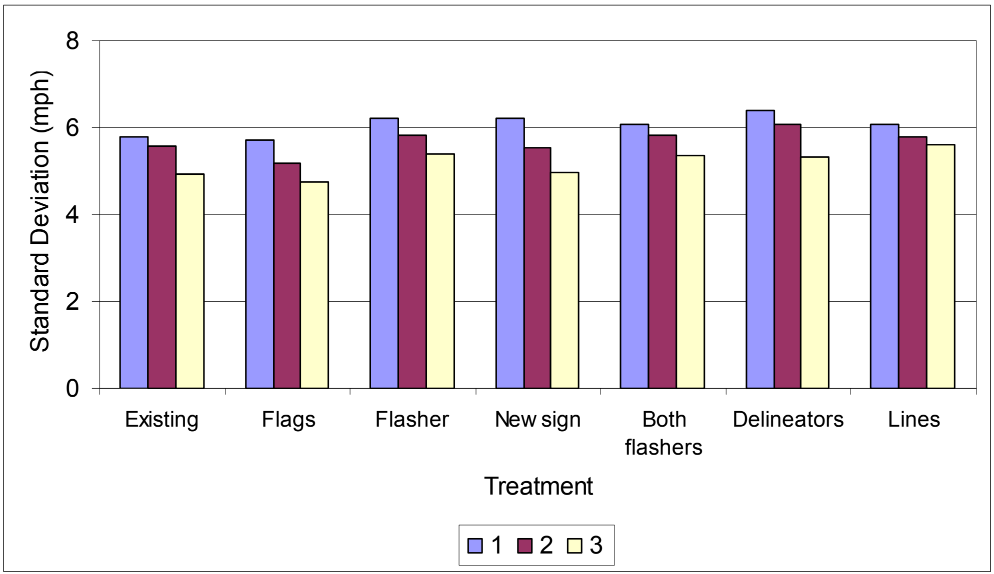

Figure 3 Speed standard deviations by measurement point

The examination of the 85th percentile speeds and the over 85th percentile speeds showed similar results as those presented above in the statistical analysis. The use of flags, flashers at both signs, and transverse lines reduced the most the 85th percentile speed between the first and last location: all by approximately 16 percent (Table 5). All treatments had a significant reduction in the over 85th percentile speeds with the transverse lines producing a reduction of more than 20% by the third measurement location (Table 6).

Table 5 85th percentile speeds and percent change

Treatment	Speeds (mph)				Percent Change		
	1	2	3	Total reduction	1	2	3
Existing	57.1	53.1	49.5	-7.6	-	-	-
Flags	56.1	51.5	47.7	-8.4	7.5	5.4	4.1
Flasher	57.4	53.4	49.7	-7.7	10.0	9.3	8.3
New sign	57.5	53.1	48.7	-8.7	10.1	8.6	6.3
Both flashers	57.3	53.1	47.9	-9.4	9.8	8.8	4.5
Delineators	57.7	54.3	49.7	-8.0	10.6	11.1	8.4
Lines	56.8	51.8	47.7	-9.1	8.9	6.1	4.0

Table 6 Over 85th percentile speeds and percent change

Treatment	Speeds (mph)				Percent Change		
	1	2	3	Total reduction	1	2	3
Existing	61.0	55.9	50.7	-10.4	-	-	-
Flags	60.3	53.9	48.7	-11.5	15.5	10.4	6.3
Flasher	61.3	55.5	50.5	-10.8	17.5	13.5	10.2
New sign	61.8	55.6	50.4	-11.3	18.4	13.8	10.1
Both flashers	61.0	54.4	48.8	-12.2	16.9	11.4	6.5
Delineators	61.3	55.9	49.6	-11.7	17.5	14.4	8.2
Lines	60.4	54.0	47.9	-12.5	15.8	10.6	4.5

The analysis of the time of day indicated that there are significant differences between day and night conditions especially for the treatments that involved the addition of flashers or lights (Figure 4). The flag and transverse lines treatments showed an average speed reduction during daytime hours of 2.9% (1.4 mph) and 3.3% (1.6 mph) respectively. The treatments with the addition of the flag, the flashing lights on the existing warning sign, and the flashing lights on both warning signs exhibited a reduction of average nighttime speeds of 1.4% (0.7 mph), 1.0% (0.5 mph), and 1.5% (0.8 mph), respectively.

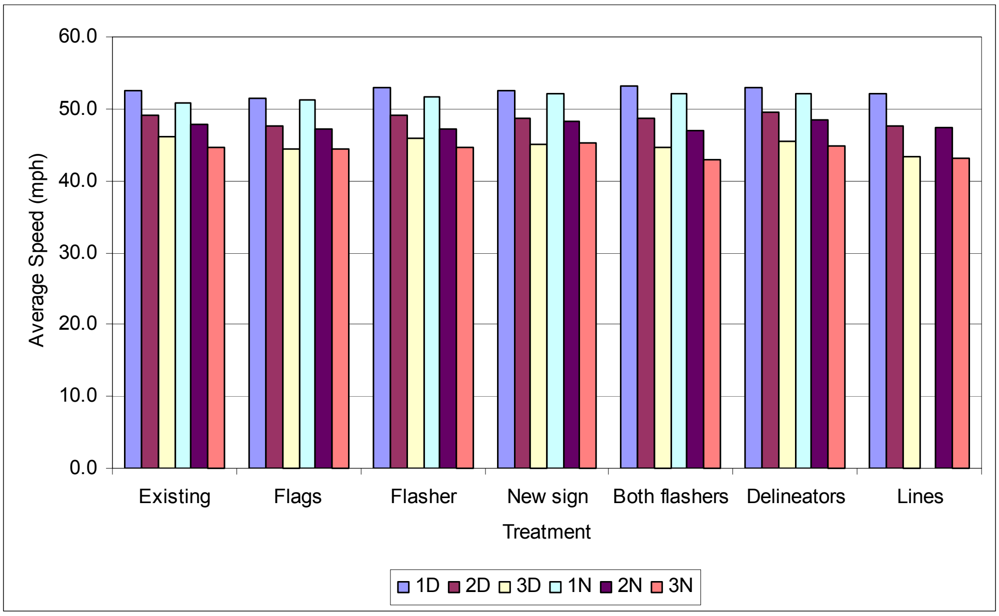

Figure 4 Average speeds by day(D) and night (N)

Site 3

The third site also had a warning curve sign with an advisory speed of 40 mph speed and 3 chevrons located on the outside of the curve. Speed measurements were taken for six treatments (Table 7). The first speed measurement site showed no signs of average speed reduction, but instead showed some signs of increased average speed for all treatments. A noticeable increase was the warning sign and flashing lights treatment, which increased by 3.7% (2 mph). An unusual circumstance with this measurement location is the level of overall increased speed associated with the warning sign with flashing lights treatment. The second measurement site showed some relative speed reductions for three of the treatments. The warning sign with flashing lights had a decreased average speed of 4.2% (2.2 mph), the combination horizontal alignment/advisory speed sign had a decreased average speed of 5.3% (2.8 mph), and both warning signs with flashing lights had a decreased average speed of 5.8% (3.1 mph). These results may indicate that the drivers did not recognize or see the warnings, until after they passed the first measurement site. A possible reason for the sudden reduction in average speed for the second measurement could be the high level of speed (the average speed for all treatments combined was approximately 55 mph) associated with the first measurement. With a high speed, drivers would have less time to react to the warning, which could possibly result in a speed reduction after the first measurement location. The new combinational warning sign is located at the point of curvature (third measurement location) so it is possible that drivers would not see this warning until they get closer to the curve, which also could account for the large decrease in speed after the first measurement location. Another possible reason for this speed reduction is that the existing warning sign was a 36-inch sign (smaller than the 48-inch sign used in the other sites) which could reduce the initial visibility of the warning sign. The third measurement showed no signs of speed reduction and a very small speed increase. The warning sign with flashing lights had an increase of less than 3%, but no other treatments showed much change from the existing treatment.

Table 7 Speed measurements and percent change

	Speeds (mph)				Percent Change		
Treatment	1	2	3	Total reduction	1	2	3
Existing	53.4	53.4	48.5	-5.0	-	-	-
Flags	53.9	53.4	48.5	-5.4	0.8	-0.1	0.1
Flasher	55.4	51.2	49.6	-5.9	3.7	-4.2	2.3
New sign	54.6	50.6	48.7	-5.9	2.1	-5.3	0.5
Both flashers	54.6	50.3	48.8	-5.7	2.1	-5.8	0.7
Delineators	52.8	48.9	48.6	-4.2	-1.2	-8.5	0.3
Lines	52.9	50.2	49.6	-3.2	-1.1	-6.1	2.4

For this location the biggest changes in speed were noted at the second measurement location. Therefore, the statistical analysis was performed using the measured speeds from this location. The standard deviations showed larger changes at the third location and did not show any signifcant changes between the first and second measurement location for most of the treatments (Figure 5). The test for equal variances for the speeds of each treatment revealed that the average speeds and variances were not equal. The test for non-homogeneous variances revealed that the warning sign with flashing lights, the new combination warning sign, and both signs with flashing lights significantly affected the average speed and variances for this site. Therefore, it can be concluded that these three treatments had a direct impact on the reduction of speeds when compared to the existing conditions.

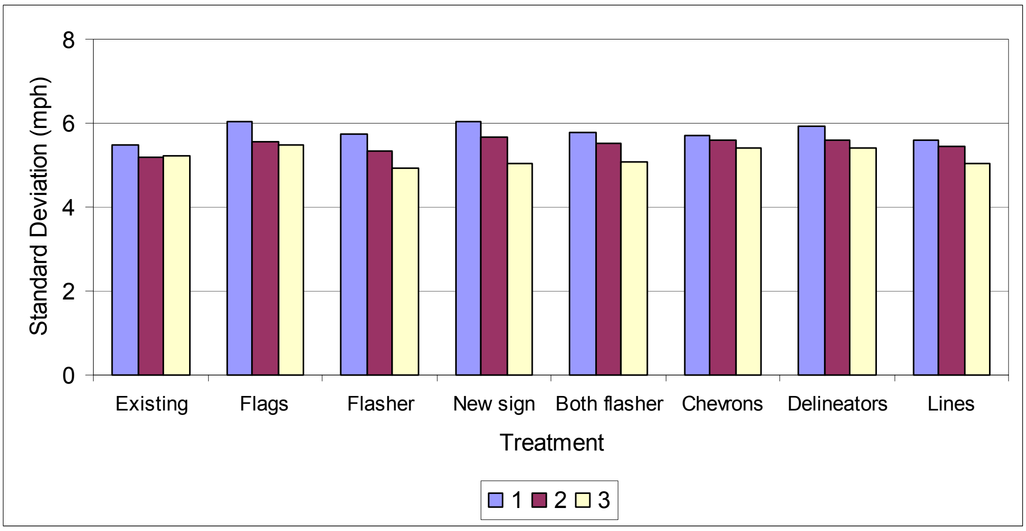

Figure 5 Speed standard deviations by measurement point

The 85th percentile speeds and percentage changes show a similar trend to that observed for the average speeds (Table 8) as well as the trends observed in the other two sites. However, the data for the average speeds greater than the 85th percentile speed (Table 9) were quite similar to the change in speed for the actual 85th percentile speed and thus, show no influence of any treatment on the higher speeds.

Table 8 85th percentile speeds and percent change

Treatment	Speeds (mph)				Percent Change		
	1	2	3	Total reduction	1	2	3
Existing	57.5	57.0	52.2	-5.3	-	-	-
Flags	58.1	57.6	52.3	-5.8	8.7	7.9	7.9
Flasher	59.6	55.2	53.4	-6.2	11.4	3.3	10.1
New sign	59.2	54.7	52.4	-6.8	10.8	2.3	8.2
Both flashers	59.2	54.3	52.4	-6.8	10.7	1.6	8.2
Delineators	57.2	53.4	52.7	-4.5	7.1	-0.1	8.8
Lines	56.8	53.9	53.4	-3.5	6.3	0.9	10.1

Table 9 Over 85th percentile speeds and percent change

Treatment	Speeds (mph)				Percent Change		
	1	2	3	Total reduction	1	2	3
Existing	61.1	58.8	52.4	-8.7	-	-	-
Flags	62.2	59.4	52.7	-9.5	16.4	11.1	8.9
Flasher	63.1	56.3	53.8	-9.3	18.1	5.5	11.1
New sign	63.2	56.8	53.5	-9.7	18.2	6.3	10.3
Both flashers	63.2	56.6	53.6	-9.5	18.2	6.0	10.7
Delineators	61.2	55.5	54.3	-6.9	14.5	4.0	12.1
Lines	60.2	55.6	53.7	-6.5	12.6	4.0	10.8

The time of day analysis showed similar overall results as noted in the other sites (Figure 6). An unexpected result was for the treatment of flashers where most speeds increased. During the daytime, this treatment essentially acts as the existing treatment would, considering the flashing lights do not flash during the day, but there was almost a 3% increase in speed for the nighttime, which does not correlate well with the previously observed results. Some promising readings to note are the nighttime average speed reductions for the warning sign with flashing lights (5.1%; 2.7 mph), the combination horizontal alignment/advisory speed sign (6.8%; 3.6 mph), and the flashing lights on both warning signs (7.5%; 4 mph).

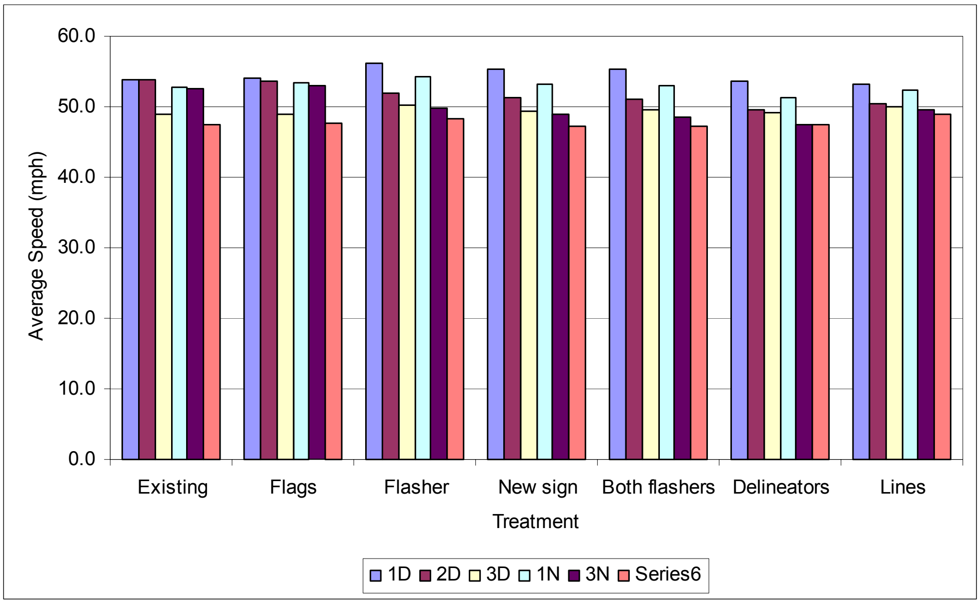

Figure 6 Average speeds by day (D) and night (N)

CONCLUSIONS

The problem with inconsistently designed roadways is that they do not lend any clues to the driver as to the appropriate action to take at hazardous or unexpected curves. Two methods of conveying necessary roadway information to the driver are warning signs and pavement markings. For this study, several warning signs and pavement markings were implemented at rural curves to evaluate their effectiveness to reduce operating speeds. A literature review was performed to evaluate past experiences with similar situations and to potentially determine which warning signs and pavement markings are the most effective. Several curves were chosen as potential study sites and these sites were narrowed down to sites that had a curve related crash history. Speeds were measured at three locations at each site involving several treatments. The speed data was then analyzed to determine what treatments were the most effective.

The data from the three sites gave mixed results as to the effectiveness of treatments in reducing operating speeds. The data for Site 1 indicates no major speed reductions for most of the treatments. In fact, most treatments experienced a slight increase in all speed measures. However, all treatments at this site reduced the speed variance considerably compared to the existing conditions. The data for Site 2 showed considerable speed reductions for all treatments. Moreover, the two treatments that experienced the most significant speed reductions were the flashing lights on both warning signs and the transverse lines. The data for Site 3 also showed speed reductions from some of the treatments. The treatments that experienced the most significant speed reductions were the existing warning sign with flashing lights, the new combination warning sign, and both warning signs with flashing lights.

A noteworthy finding of this work was that for all three sites, the average of the speeds over the 85^{th} percentile speed showed a reduction indicating that most treatments have the potential to affect high speeds more than the average or 85^{th} percentile speed. It can be concluded that some of the warning signs and pavement markings do moderately reduce the operating speeds of vehicles. The warning signs with flashing lights can reduce speeds and the new combination warning sign can also be quite effective with the addition of flashing lights. The transverse lines showed considerable speed reduction for Site 2 and probably would have seen similar results at Site 1if the pavement pattern was longer (it was adjusted after the Site 1 data collection to provide for longer warning period).

The objective of this work was to determine if anything can be done to reduce operating speeds by providing additional warning information to the driver. Based on these findings, some of the treatments have shown promising results but there are possible options that could even enhance these treatments. For example, the flashing lights were only working at nighttime, which might explain their increased effectiveness as compared to the existing conditions. Therefore, the use of lights that could be visible also at daytime could have the same impact. The use of rumble strips in addition to the transverse lines or a longer pattern of transverse lines might be two additional treatments that may have a significant effect. Rumble strips are an option that could accompany transverse lines or be used strictly by themselves. Based on past research, transverse lines over a greater length are more effective at reducing speeds. Transverse lines could also be carried out through the curve, instead of stopping at the point of curvature. Finally the use of larger signs, especially for the new combination sign, may also improve the effectiveness of the treatment because drivers could see it from a further distance away.

The results of the study indicate that there are some promising treatments that have the potential to impact operating speeds and particularly high speeds. The new combination curve warning and suggested speed seems to have a positive effect on reducing speeds and its use is encouraged. However, it is recommended that it should be used with caution to avoid overuse and thus be disregarded by the drivers. The use of flashing lights is recommended for most sites, since they at least have the potential to impact operating speeds at night. Even though the transverse lines showed mixed results, it is expected that they are promising and further research is warranted.

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Typical existing conditions

Large arrow

New combination sign

Warning sign with flags

New combination sign with flashers

Transverse lines

Figure 1 Samples of treatments