Peripheral Transverse Pavement Markings for Speed Control

Bryan Jeffrey Katz

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Committee Members:
Hesham Rakha, Ph.D., Committee Chair
Thomas Dingus, Ph.D.
H. Gene Hawkins, Ph.D.
Mark Robinson, Ph.D.
Samuel Tignor, Ph.D.

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PERIPHERAL TRANSVERSE PAVEMENT MARKINGS FOR SPEED CONTROL

BY: BRYAN JEFFREY KATZ

ABSTRACT

In the United States, speeding is considered to be a contributing factor in about 30 percent of fatal crashes (US DOT, 2000). In an attempt to reduce speeds on roadway segments where speed is considered to be a safety concern, various low cost countermeasures have been investigated. Such countermeasures include pavement markings that give a psychological appearance of narrowing and/or increasing speed have been considered as a relatively low-cost treatment. Perceptual cues are one potential method of influencing motorists to slow down, and ultimately, to save lives. These perceptual techniques might be useful at lowering speeds in a variety of driving situations such as work zones, curves, roundabouts, and toll plazas. Evaluations are required in order to determine the effectiveness of these various treatments at reducing speeds. This research project explored several possible perceptual countermeasures to try on the approaches to curves for reducing speeds. It was ultimately decided to evaluate the effects of peripheral transverse lines in reducing speeds.

Although there have been some limited evaluations of peripheral transverse markings in previous studies, no significant field evaluation has been performed and a recommended design for the markings has not been discussed. The projected results of the research effort is to determine pavement marking treatments with a high probability of success at reducing speeds, develop and design peripheral transverse markings based on site considerations, determine the effectiveness of the markings in the field, determine optimal pavement marking design using a driving simulator, and use a controlled research environment to finalize the design.

This dissertation contributes to the body of knowledge on speed reduction research through the development of low cost speed reduction strategies, the design of peripheral transverse lines for varying geometric conditions, evaluation of these treatments in the field, in the simulator, and on a controlled roadway, and to finally compare the benefits of each of the evaluation approaches.

In the field, peripheral transverse lines spaced at a frequency of 4 bars per second were evaluated in New York, Mississippi, and Texas. The markings were applied on approaches to curves in both rural and urban environments on both multi-lane and two-lane roadways. The authors concluded that overall, the pavement markings reduced speeds up to 59% compared to the baseline in the short term and 24% in the long term on overall vehicle speeds.

When evaluating design alternatives of peripheral transverse markings, a follow-up study was performed and compared baseline conditions to markings spaced at a constant interval, exponentially closer, at two bars per second, and at four bars per second. The peripheral transverse lines were effective in reducing centerline encroachment; however,

the results were inconclusive as to which particular marking spacing pattern was most effective. There was a large amount of variability in driving speeds using the driving simulator which made it ineffective at comparing designs.

The third evaluation was performed at the Virginia Tech Smart Road in which reductions in speed were compared to the baseline at two locations. While one curve had large preview distances and no effect due to the treatments, speed reductions on a freeway ramp type of curve resulted in a speed reduction 42% greater than the reduction in the baseline condition.

There are several advantages and disadvantages to evaluations in the field, simulator, and at a controlled research setting which are summarized in this dissertation. Overall, all three have potential of looking at different elements, but it was determined that variability when measuring speed in the driving simulator makes it more challenging as a tool for measuring speed reductions.

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DEDICATIONS

I would like to dedicate this dissertation to my wife, Katie who has provided a large amount of love, support, and encouragement. I would also like to dedicate this dissertation to all of the people who have aided me through the lifelong learning process that has resulted in my graduate studies as well as this dissertation. At Virginia Tech, this wouldn't have been possible without the support of the faculty of the Civil and Environmental Engineering department. From them, I have been given the gift of knowledge and professionalism that I have used in life to be a successful transportation engineer. However, learning does not begin at the University. I would also like to dedicate this dissertation to my parents, through whose encouragement and beliefs in the importance of lifelong learning, I have learned the most valuable lessons in life.

ATTRIBUTIONS

My advisor, Dr. Hesham Rakha, aided in the organization and the concepts to be discussed in Chapters 4, 5, and 6. He is therefore cited as an author on those papers. For Chapter 4, Dana Duke, an electronic technician with Science Applications International Corporation aided with the logistics an information retrieval on the data collection efforts for the project and was therefore given credit as an author on the paper. In Chapter 5, Dr. John Molino, a research psychologist with Science Applications International Corporation was investigating several other visibility issues as part of a larger study and supported me with working with the Highway Driving Simulator to develop the scenarios, and thus is given credit as an author in the paper.

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CHAPTER 1: INTRODUCTION

Statement of Problem

In the United States, speeding is considered to be a contributing factor in about 30 percent of fatal crashes (US DOT, 2000). In an attempt to reduce speeds on roadway segments where speed is considered to be a safety concern, various low cost countermeasures have been investigated. Such countermeasures include pavement markings that give a psychological appearance of narrowing and/or increasing speed have been considered as a relatively low-cost treatment. Perceptual cues are one potential method of influencing motorists to slow down, and ultimately, to save lives. These perceptual techniques might be useful at lowering speeds in a variety of driving situations such as work zones, curves, roundabouts, and toll plazas. Evaluations are required in order to determine the effectiveness of these various treatments at reducing speeds.

Research Objectives

Although there have been some limited evaluations of peripheral transverse markings in previous studies, no significant field evaluation has been performed and a recommended design for the markings has not been discussed. The goals of this study are to:

- Determine pavement marking treatments with a high probability of success based on previous research,
- Determine the effectiveness of the markings through an evaluation in the field at three different locations,
- Determine the effectiveness of the markings using varying characteristics in a driving simulator ,
- Evaluate variations of pavement marking spacing designs in a controlled research environment,
- Develop recommendations for optimal pavement marking design as a speed reduction countermeasure.

Research Contributions

The research contained in this dissertation has many unique contributions to the body of knowledge on research related to speed reductions. The author first began by investigating appropriate treatments in response to a request by a research advisory group to look for an appropriate use of pavement markings to reduce vehicle speeds (Chapter 2).

In the literature, transverse bars have been applied at "decreasing intervals", but no design recommendations are provided as to how to design the pavement markings for varying locations. The first major goal of this dissertation focuses on a methodology for the determination of appropriate marking spacing designs that take into account vehicle speed upstream as well as desired final speed at the end of the treatment section (Chapter 3).

Also after investigating past research, the concept of transverse peripheral lines has been tested in a driving simulator but has not been analyzed in the field. Therefore, the second major goal of the dissertation is to design and conduct a field study at three locations to examine the effects of peripheral transverse lines in the field (Chapter 4).

Several past research studies in the literature search discussed a concept of placing transverse bars closer together to achieve a reduction in speed, but the actual methods and theories behind them are not defined. Therefore, the third major goal of the dissertation was to design and conduct a simulator study to examine the effects of several designs of the peripheral transverse lines including constant spacing, exponential spacing, spacing at a rate of 2 bars per second, and spacing at a rate of 4 bars per second (Chapter 5).

Finally, there is no information available on the effective design spacing of peripheral transverse lines in the field and thus the fourth major goal of the dissertation is to design and conduct a controlled field study that investigates two spacing designs that are designed specifically for the location where the markings are applied (Chapter 6).

Dissertation Layout

This dissertation begins with this introductory section that explains the problem to be addressed and the research objectives. The second chapter provides a literature review that describes various previous research efforts that are related to the current research project. The third chapter provides the methodology that was used in the design of the pavement marking spacings. The fourth chapter is a research paper that describes the field study in detail and provides results of the field portion of the project. The fifth chapter is a research paper that provides the driving simulator evaluation and provides results of the study. The sixth chapter is a research paper that analyzes pavement marking pattern spacing in a controlled environment. The seventh chapter provides overall conclusions as well as recommendations for further research.

CHAPTER 2: LITERATURE REVIEW

Introduction

This paper examines research on the effectiveness of perceptual countermeasures to speeding. The introduction describes the purpose of this literature review, defines perceptual countermeasures to speeding, and outlines the limitations of conventional countermeasures to speeding. Next, the paper examines the concept behind perceptual countermeasures, particularly perceptual cues and manipulation through roadway design. The next portion of the paper discusses in detail the various strategies used as perceptual countermeasures. Finally, the paper concludes with recommendations for future research. Appendix A at the end of this paper contains tables summarizing research projects discussed in this literature review.

Purpose

The purpose of this literature review is to investigate research studies and field tests involving perceptual countermeasures to speeding. Primarily, this paper focuses on the applications and strategies used to keep motorists from speeding using various perceptual techniques. Based on the information that has been obtained from past research, gaps in the research will be discussed to define future research needs. In a TRB Report on Managing Speed (1998), the authors refer to perceptual countermeasures (such as patterned road surfaces, center and edgeline treatments, reductions in lane width, curvature enhancements, and increased delineation) as being low in cost and may be appropriate where more expensive treatments cannot be justified.

Definition

Although several definitions exist, a research report by Godley, Fildes, Triggs, and Brown (1999) provides a useful definition and describes perceptual counter-measures to speeding as "manipulations of the road scene presented to a driver that can influence his or her subsequent behavior [by using] relatively low cost additions or modifications to the road or the immediate roadside setting that can lead to a change in the way the driving environment is perceived by drivers." For the purpose of this report, the Godley et al. definition will be used.

Conventional Countermeasures to Speeding

Before discussing types of perceptual countermeasures to speeding, it is important to understand what conventional countermeasures have been used. A report written by Eric Meyer (2000) describes several conventional countermeasures, with particular attention to those used in work zone applications (see Figure 2-1). The most obvious of these are posted speeds. Posted speeds can be either regulatory signs or warning signs. Other conventional countermeasures are flagging and police traffic control. The use of flagging and police traffic control can be effective; however, both are very expensive and it is relatively impossible to have a large enough work force to cover every possible high-risk location. Regulatory signs, warning signs, and flagging control are all countermeasures to speeding that can be found in the Manual on Uniform Traffic Control Devices (MUTCD); however, it is difficult without enforcement to expect a large amount of compliance.

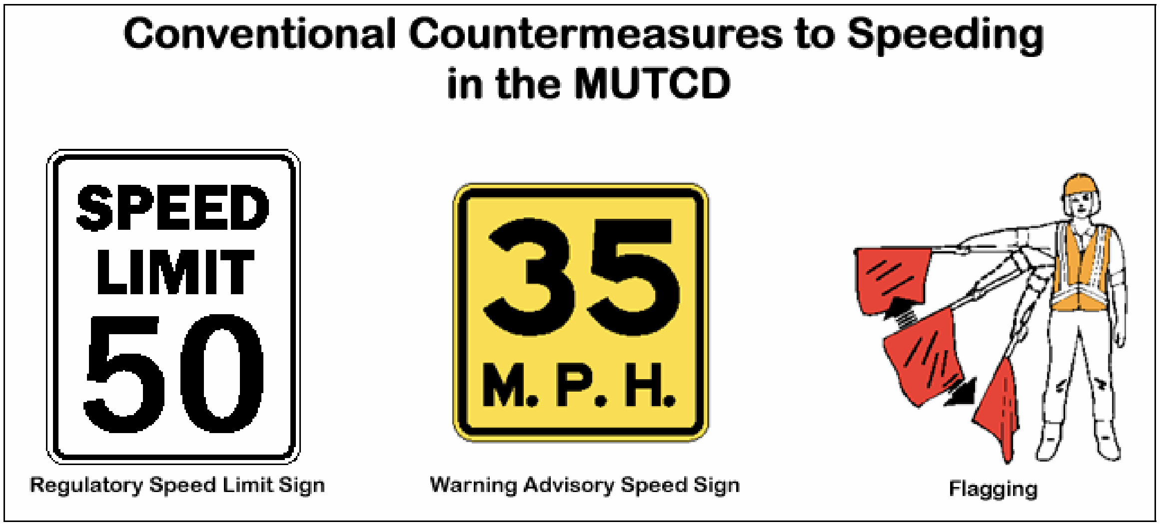


Figure 2-1: Conventional countermeasures to speeding (source: MUTCD).

Law enforcement is another countermeasure to speeding; however, similar to the use of flagging and police traffic control, it is very expensive. Changeable message signs can be used as well to reduce speeds, particularly in work zones; however, over the long term, the signs may cease to be effective. Radar drones can also be used to reduce speeds and have been shown to have a small effect on speeding.[3] The last countermeasure that Meyer discusses is the use of lane width restrictions. They have proven effective at reducing speed; however, there are several safety issues involved. When lane reductions are used, studies have shown that there tends to be an increase in speed variance as well as an increase in erratic maneuvers. Although law enforcement and some conventional countermeasures have proven to be somewhat successful in reducing speed, most of the countermeasures are very expensive and thus are not feasible for widespread use.

How Drivers Perceive Speed

Road Factors

In a report entitled *Down With Speed*, the New Zealand Accident Compensation Corporation and Land Transport Safety Authority (2000) discussed many roadway factors and their impact on speed. The report points out that psychological factors play a major role on the speed motorists select and that decisions depend on both sensory perception and cognitive processing. That is, motorists rely on the roadway environment in order to select an appropriate speed. The speed decision made is most likely related to the level of safety that a motorist feels while driving a particular roadway segment.

The first road factor that the report discusses is roadside development. If there is more development on the roadside, then motorists are more apt to reduce their speeds. For example, drivers traveling on rural roads are much more likely to drive faster than on urban roads with a lot of roadside development. In urban areas, roadside development usually consists of houses and buildings whereas in rural areas, roadside development typically consists of trees and other forms of vegetation.

The second road factor deals with the physical attributes of the road. Various attributes such as the number of lanes, lane width, pavement markings, geometry, and smoothness have generally been shown to play a role in a motorist's speed choice. Generally, motorists will travel at a much faster speed on four-lane divided highways as opposed to two-lane highways. Studies have shown that decreasing the lane width at a similar facility compared to one with a wider lane width will generally lower the average speeds. Pavement markings have been used on curves with varying widths to exaggerate the appearance of the sharpness of a curve as an attempt to get motorists to slow down. Another major physical attribute is roadway geometry. Motorists tend to drive slower on roads with horizontal and vertical curvature as opposed to a straight road on level terrain. Additionally, motorists will generally drive faster on a smooth roadway as opposed to a rough roadway surface.

The third road factor discussed in *Down with Speed* concerns traffic related characteristics. As traffic volume and density of a roadway increase, vehicle speed will decrease. Additionally, as motorists approach an intersection, there is generally a change in speed. The sight distance at the intersection is considered to be a major factor in determining the speed a motorist will choose to proceed through an intersection.

The final road factor discussed concerns the time of day and weather. In Sweden, for example, speeds tended to be higher at night than during the day, perhaps because of a decrease in congestion at night. Additionally, when roadway surfaces are wet or covered in snow, studies have shown that motorists are more apt to decrease their speed.

Perceptual Cues

In a report entitled *Driver Speed Estimation: What Road Designers Should Know,* Alison Smiley (1999) discussed the concept of perceptual cues for speed estimation. The report states that motorists primarily use peripheral vision for determining speed. If only the central field of view is used to determine speed, the ability to estimate speed is poor; alternatively, if only the peripheral view is used, then motorists better estimate their speed. Another major perceptual cue is eye height. When a motorist is closer to the road, angular velocities appear higher and so sensations of faster speeds are stronger. Smiley cites the example that a sports car feels faster at a given speed than a truck at the same speed simply because it is closer to the roadway. Noise level also is an important perceptual cue to speed, but technology may be reducing its influence. For example, by making cars quieter and building roads with smoother pavements, a motorist's sensitivity to his or her speed will probably decrease.

Environmentally Adapted and Self-Explaining Roads

The concept of achieving a reduction in speed due to the roadway environment is known as an environmentally adapted road (Kallberg et al 1998). In a report entitled *Recommendations for Speed Management Strategies and Policies*, an environmentally adapted road is described by Kallberg et al. as "reshaping the environment in a way that the visual impression, together with the changed design of the road, makes the driver lower his speed." Examples would include village gateways, rumble strips, and changes to the road surface. The effectiveness of these treatments on reducing speed has been significant; however, generally there are high installation costs involved with changing the environment surrounding a road.

Self-explaining roads are defined by Kallberg et al. as "roads with a design that evokes correct expectations from road users, which in turn leads to correct choices of speed." Generally, there is less speed variation when self-explaining roads are developed. Safety is also improved because motorists know what to expect from the particular class of highway judging from the experience of similar roads.

Strategies

This portion of the paper discusses various design strategies that have been tested and studied to provide perceptual cues to reduce a motorist's speed. Various traffic calming strategies such as speed humps, roundabouts, and chicanes have been shown to be very effective in reducing speeds. However, the strategies in this paper focus on other roadway elements that do not alter the horizontal or vertical characteristics of the roadway.

Roadway Width

In a report titled *The Effects of Road Design on Speed Behavior*, Martens, Comte, and Kaptein (1997) state that roadway width is one of the strategies that can be used to affect a motorist's speed. The authors discuss three roadway width components that must be considered: lane width, width of pavement, and lateral clearance. These characteristics are illustrated in Figure 2-2.

As lane width decreases, driving speeds tend to decrease because of the effort required to steer and maintain position in the lane. For every 1 m (3.3 ft) reduction in lane width beyond 4 m (13.1 ft), Yagar and Van Aerde (1984) found a reduction in speed of 5.7 km/h (3.5 mi/h). In another study performed by Vey and Ferreri (1968), two similar bridges in Philadelphia were analyzed in which one bridge had 3.0 m (9.8 ft) wide lanes and the other bridge had 3.4 m (11.1 ft) wide lanes. They found greater speed, and less headway for the bridge with wider lanes.

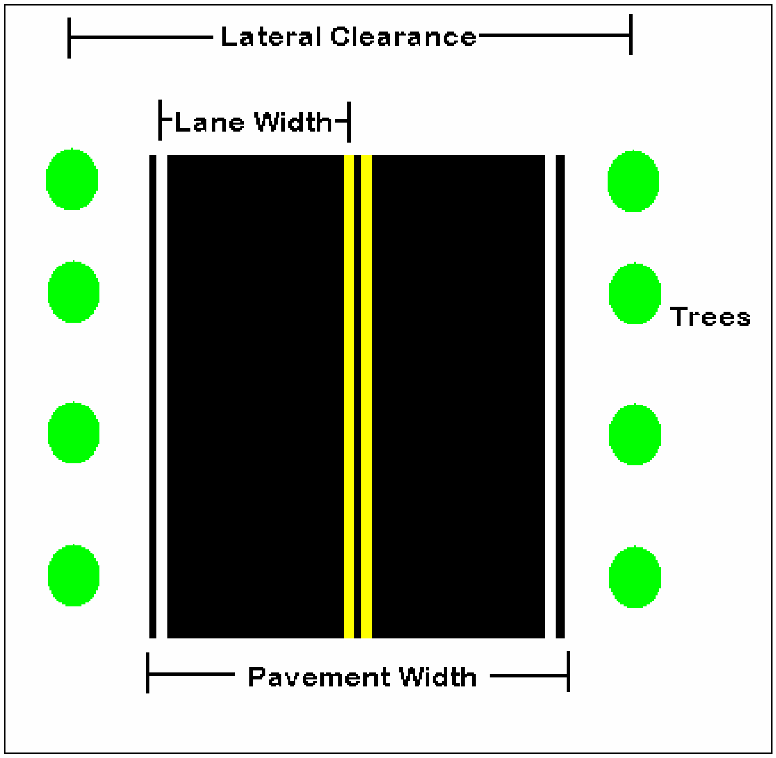


Figure 2-2: Roadway width characteristics.

Pavement width covers the length across both travel lanes as well as the shoulders on both sides. The additional space on the shoulder gives some extra room for lateral displacement or lane recovery and this generally leads to higher speeds (Martens et al 1997). Studies were performed by both Smaalen (1987) and Kolsrud (1985) which demonstrated that speed and pavement width were directly proportional and although the speed limit was the same, there was an increase in driving speed.

The third roadway width component is lateral clearance, or the space available between obstacles on both sides of the road. In a study performed by Van der Heijden (1978), it was found that a reduction of lateral clearance from 30 m (98.4 ft) to 15 m (49.2 ft) decreased speed by only 3 percent but when reduced to 7.5 m (24.6 ft), a 16 percent reduction occurred.

Longitudinal Pavement Markings

Longitudinal pavement markings consist of markings such as centerlines and edge lines placed along the roadway surface. In a study performed by Lum (1984), two residential streets test sites in Orlando, Florida (Plaza Terrace and South Lake Orlando Parkway) were evaluated to observe the effects of using pavement markings to decrease the effective width of the roadway on vehicle speeds. Both locations started with a 152 mm (6 in) wide broken centerline. Each stripe was 3 m (9.8 ft) in length with 9 m (29.5 ft) spacing. At the Plaza Terrace test site, 152 mm (6 in) white solid edge lines were added. Additionally, raised pavement markers were installed at both ends of each segment of the broken centerline. At the South Lake Orlando Parkway test site, a double white solid edge line spaced 0.5 m (1.6 ft) apart was added. Red and white raised pavement markers were installed along the edge of the edge line nearest the roadway. Additionally, a standard broken yellow centerline with red and white raised pavement markers installed at both ends of each segment. After the revised striping, the effective lane width at both locations was 2.7 m (8.9 ft).

Data were collected prior to treatment installation, again immediately after installation, and approximately two weeks later. Each data set consisted of 1-hour sessions in the morning afternoon and night for two days. Between 60 and 100 speed measurements were collected for each session. Thirty-six comparisons were made between the before treatment, immediately after treatment, and two weeks after treatment of which 23 had an increase in mean speed, 2 had no change, and 11 had a decrease. The conclusion was that there was no effect on the mean speed or on the distribution of speeds before and after the treatments were placed. It should be noted that only two treatment sites were used, and that traffic patterns or volumes were not included. Thus, these findings may not generalize to other sites.

As part of a simulator study conducted by Jamson, Pyne, and Carsten (1999), the effects of various longitudinal pavement markings were tested. The longitudinal pavement marking patterns tested included various centerline and edge line hatching patterns, including a hatched chicane, broken centerlines with the space between lines becoming progressively closer together. Treatments that were shown to significantly reduce speeds are listed in Table 2-1.

Table 2-1. Significant speed reducing treatments.

Left Curves	Mean speed km/h (mi/h)	85th Percentile Speed km/h (mi/h)	SD of speed km/h (mi/h)
Control	70.6 (43.86)	90.2 (56.04)	13.3 (8.25)
Central hatched area	66.7 (41.45)	83.7 (51.98)	12.6 (7.81)
5 ft Road edge hatching	67.1 (41.74)	79.7 (49.53)	11.3 (7.04)
Village treatments	**Position in village**	**Mean speed km/h (mi/h)**	**Control speed km/h (mi/h)**
Central hatching without narrowing sign	Middle	50.6 (31.42)	52.1 (32.43)
Central hatching with narrowing sign	Exit	53.2 (33.07)	55.8 (34.71)

Transverse Pavement Markings

Transverse pavement markings are placed on the roadway perpendicular to the direction of travel. Typically, transverse markings are placed on the roadway at progressively closer distances apart creating the illusion of acceleration. The two major types of transverse pavement markings used to reduce traffic speeds are transverse bars and transverse chevrons.

Transverse Bars

As a strategy of reducing traffic speeds, transverse bars (also known as optical speed bars) have been placed at some locations. One of the first studies of transverse bars was performed by Denton (1980). A transverse bar pattern was applied to the approach to the Newbridge Roundabout located in Midlothian, Scotland. The pattern consisted of 0.6 m (2 ft) wide yellow stripes stretching from edge line to edge line on the approach side of a divided roadway. Ninety stripes were applied on the roadway at progressively closer spacing from 6 m (20 ft) to a minimum of 3 m (10 ft).

The pattern had a significant effect on both 85th percentile and mean speeds (see Table 2-2 and Table 2-3). Additionally, there were 14 crashes during the 12 months prior to the installation, and 2 during the 16 months after.

The report does not mention the number or types of vehicles recorded. However, data were collected over a 3-week period before the transverse bars were installed, and another 3-week period after installation. In light of this, the sample size is probably adequate. Additionally, the author alludes to a possible novelty effect due to what he describes as a "small but significant mean increase in speed…some months later". Denton discounts this and cites the continued effectiveness of the pattern over a number of years, but no empirical support of this is provided in the report.

Table 2-2. Mean speeds before and after with percent reduction.

	7-9am km/h (mi/h)	2-4pm km/h (mi/h)	6-8pm km/h (mi/h)	Overall Mean km/h (mi/h)
Before	59.1 (36.7)	57.8 (35.9)	54.9 (34.1)	57.0 (35.4)
After	42.2 (26.2)	45.2 (28.1)	44.7 (27.8)	44.1 (27.4)
Percent reduction	28.60%	21.70%	18.50%	22.6%

Table 2-3. 85th percentile speeds before and after with percent reduction.

	7-9am km/h (mi/h)	2-4pm km/h (mi/h)	6-8pm km/h (mi/h)	Overall Mean km/h (mi/h)
Before	77.4 (48.1)	75.9 (47.2)	72.4 (45.0)	75.1 (46.7)
After	50.8 (31.6)	54.1 (33.6)	53.7 (33.4)	52.8 (32.8)
Percent reduction	34.30%	28.80%	25.80%	29.80%

A study on transverse bars was also performed by Agent (1980) in which the bars were placed upstream of a sharp curve on US Highway 60 in Meade County, Kentucky with high accident rates. Speed was listed as a factor in 75 percent of the crashes at this location. The strips were installed at progressively decreasing distances so a vehicle decelerating normally would cross a strip every 0.5 seconds. The width of the strips was also decreased to a minimum width of 0.6 m (2 ft). A total of 30 strips were installed for a distance of 247 m (810 ft) ahead of the beginning of the curve.

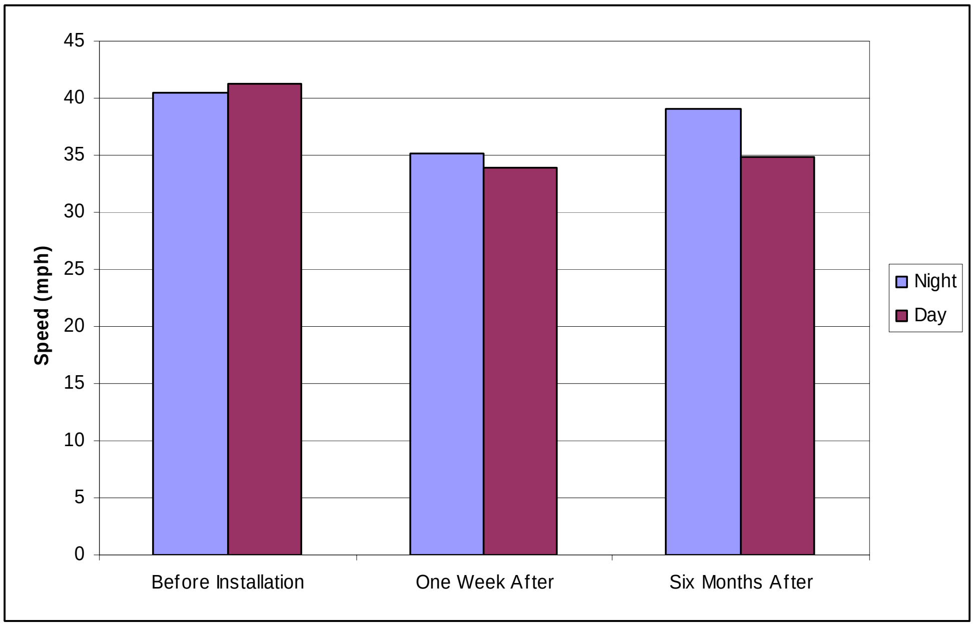


Figure 2-3: Observed speeds at beginning of curve.

One measure of effectiveness used in the study was the speed of the motorist at the beginning of the curve. The mean observed speeds at the beginning of the curve is shown in Figure 2-3. As motorists became familiar with the changes, there was an increase in the mean speeds from one week after the installation to six months after the installation. Interestingly, there was a larger long-term effect during the daytime condition compared to nighttime condition.

The second measure of effectiveness was crash history. Crash rates for the six years preceding the installation of the transverse bars were compared to the crash rate for the year after installation. The author found a 61 percent decrease in crashes. Given that the before and after periods were of substantially different lengths, this crash rate decrease may not be entirely accurate.

A study conducted by Hungerford and Rockwell (1980) tested different delineation systems to modify motorists behavior on high accident rural horizontal curves. The authors performed before, after, and final comparisons of the following delineation systems: raised pavement markers, transverse stripes, standard delineators in different configurations, flexible delineator posts in a standard configuration, and chevron signs in a standard configuration. The after measurements were performed within 24 hours of delineator installation; the before measurements served as a control, while the final measurements were collected between two to four weeks after installation. Vehicle velocities were measured at the approach to the curves, and at the curve tangents. The method of evaluation was the difference in velocity between the two points. Velocity data for approximately 50 vehicles was collected at each test curve (see Table 2-4). The results show that at night, transverse stripes reduced vehicle velocities. However, because novelty was the probably key factor, the speed effect degraded significantly. The daytime effect was negligible.

Table 2-4. Speed reduction results from Hungerford and Rockwell.

	Day			Night		
	All km/h (mi/h)	Upper 25% km/h (mi/h)	Lower 75% km/h (mi/h)	All km/h (mi/h)	Upper 25% km/h (mi/h)	Lower 75% km/h (mi/h)
Before	1.5 (0.94)	6.5 (4.06)	--	1.1 (0.68)	3.2 (2.00)	.51 (0.32)
After	0.7 (0.44)	7.2 (4.46)	--	2.8 (1.74)	4.4 (2.73)	1.7 (1.03)
Final	1.7 (1.03)	7.3 (4.56)	--	0.8 (0.51)	--	-1.9 (-1.2)

In addition to concerns about a novelty effect in the Hungerford and Rockwell study, there are also concerns about the sample size because only about data were collected on about 50 vehicles per site. Further, data pertaining to the lower 75% of the speed distribution is missing. It should also be noted that all of the treatments were installed at different curves, and hence the roadway segments both leading into and exiting are inconsistent. Furthermore, no control sites were used for weather or traffic volume.

Maroney and Dewar (1987) performed a study of transverse pavement markings as part of a project to modify speeding behavior of motorists. The roadway chosen was a straight single-lane freeway off-ramp 770 m (2,526 ft) long with a posted advisory speed of 50 km/h (30 mi/h). Ninety fluorescent white lines were painted transversely on the ramp over a 404 m (1,325 ft) distance. Each line was 60 cm (23.6 in) wide and 4 m (13.1 ft) long. The distance between the lines gradually decreased from 7.7 m (25.3 ft) at the beginning of the treatment area to 2.75 m (9 ft) at the end. The lines began 100 m (328 ft) from the beginning of the ramp and ended 400 m (1,312 ft) from the end.

A total of 247,036 vehicle speeds were recorded during the baseline period and the experimental period. There were two methods of evaluation in the study: mean speed and the percentage of vehicles traveling faster than 80 km/h (50 mi/h), which was 30 km/h (19 mi/h) above the advised speed. Results showed significant decreases for both measures as well as a decrease in speed variability (see Table 2-5). However, the decreases began diminishing within one week (see Table 2-6) suggesting the treatment only created a temporary novelty effect.

Table 2-5. Results immediately after treatment installation.

	Mean Speed km/h (mi/h)	Standard Deviation km/h (mi/h)	Percent >80 km/h	Standard Deviation of percentages km/h (mi/h)
Before	64.46 (40.1)	2.96 (1.8)	5.45	3.78 (2.3)
After	61.44 (38.2)	2.81 (1.7)	4.06	3.07 (1.9)

Table 2-6. Long-term results after treatment installation.

Week	Hours of Data	Mean Speed km/h (mi/h)	Percent >80 km/h
First	148	60.43 (37.6)	3.19%
Second	130	61.89 (38.5)	4.55%
Third	138	62.09 (38.6)	4.50%
Total	416	61.44 (38.2)	4.06%

A simulator study conducted by Jamson, Pyne, and Carsten (1999) investigated various traffic calming treatments installed on rural 2-lane roads. Three situations were tested: treatments to reduce entry speeds at sharp curves (left and right), and treatments to reduce entry speeds through small villages. The treatments were as follows:

- Road markings creating an illusion of narrowing.
- Transverse lines with a reduction in spacing creating an illusion of acceleration.
- Various signs on posts and/or painted on road surface.
- Narrowing of the roadway by removing lane space from the edge and center of the road.
- Various centerline and edge line markings.

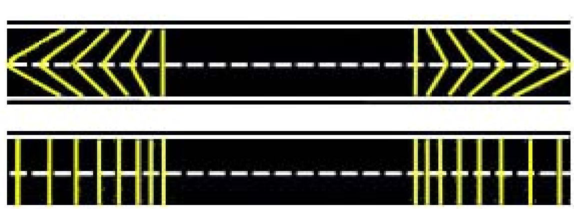
The study was performed in two phases. Phase one assessed treatments applied to a road section individually, while phase two assessed combinations of treatments. The road section used for the sharp curves consisted of an 800 m (2,625 ft) tangent followed by a 200 m (656 ft) long circular curve with a 300 m (984 ft) radius either to the left or the right. Each road was 1 km (3,280 ft) in length. Treatment sections were ordered randomly and placed end-to-end creating 32 km (19.9 mi) long scenarios. The road sections used for the villages consisted of a 400 m (1,312 ft) tangent, followed by a 200 m (656 ft) curve with a 800 m (2,625 ft) radius either to the left or right, followed by another 400 m (1,312 ft) tangent before a 400 m (1,312 ft) “built-up” village. Each road section was 1.4 km (0.87 mi) in length. Treatment sections were ordered randomly and placed end-to-end creating 28 km (17 mi) long scenarios.

For phase one, 35 participants were used: 18 drove the tangent roadway sections, and 17 drove the curve sections. For phase two, 18 participants from phase one were used to test for novelty effects of repeated exposure to the treatments, and test the treatments when used in combination. Phase two participants drove both the curve and village sections. Both samples were balanced for age, gender, and annual miles driven.

The effects of the treatments were evaluated three ways: 1) mean speed, 2) speed variance, and 3) 85th percentile speed. Listed in Table 2-7 are the transverse lines shown to produce significant reductions in all three of the evaluation methods. The difference between a standard transverse line treatment and Wundt illusion treatment is shown in Figure 2-4. As can be seen in the table, transverse lines applied to the curve midpoint outperformed the other transverse line configurations in all three methods of evaluation. Additionally, this treatment outperformed all seventeen traffic calming treatments tested, at both right and left curves as well as when installed at village entrances. However, when applied at the village center or exit, transverse bars had no effect.

Table 2-7. Individual transverse line treatments that significantly reduced vehicle speeds at left curves, right curves, and villages.

Left hand curve treatments	Mean speed km/h (mi/h)	85th percentile speed km/h (mi/h)	Standard deviation of speed km/h (mi/h)
Control (curve with no treatment)	70.6 (43.86)	90.2 (56.04)	13.3 (8.25)
Transverse lines to curve midpoint	64.7 (40.19)	78.7 (48.92)	12.6 (7.73)
Transverse lines to curve entry point	65.2 (40.53)	79.7 (49.54)	12.6 (7.86)
Central Transverse lines	65.7 (40.85)	84.1 (52.28)	13.1 (8.16)
Wundt narrowing Illusion	66.3 (41.17)	81 (50.36)	13.2 (8.24)
Right hand curve treatments	Mean speed km/h (mi/h)	85th percentile speed km/h (mi/h)	Standard deviation of speed km/h (mi/h)
Control	69.7 (43.3)	81.6 (50.7)	10.4 (6.48)
Transverse lines to curve midpoint	64.6 (40.15)	75.9 (47.19)	11.7 (7.27)



Wundt narrowing illusion

Transverse lines

Figure 2-4: Transverse lines.

In phase one of the Jamson, Pyne, and Carsten study, all treatments produced reductions in both mean speed, speed variation in both village and sharp bend situations. The authors note that treatments that worked well individually (in phase one) lost some effectiveness when used in combination (in phase two). The authors explain this by stating that with exposure, motorists become desensitized to the effects of traffic calming treatments.

As with any simulation research, field validation is critical for interpreting the results. The authors claim there is a "close correlation" in both absolute and relative terms between speed in their simulator and real driving situations. The authors also comment that the simulated road signs did not model well and this may have affected the test results for these signs. Also worth mentioning is the absence of a motion base in the simulator. It has been suggested that at least part of the speed calming effect of transverse bars is due to the tactile or auditory sensation of driving across the paint much like rumble strips. Since the simulator used in this study was fixed base, the tactile sensation was removed, leaving the auditory and visual sensations as possible mechanisms for the speed reductions.

Godley et al (1997) had 24 participants drive an advanced simulator through 3 transverse line pavement treatments. The treatments were installed at the approach to a yield controlled intersection situated on a two-lane rural road. The three treatments evaluated were: full lane width transverse lines spaced at decreasing distances apart, full lane width transverse lines spaced at a constant distance apart. The third treatment consisted of peripheral transverse lines spaced also at decreasing distances (lines protruding 60 cm (24 in) from the edge line without paint in the center). A control intersection approach was also used. Treatments were 404 m (1,325 ft) long with 90 lines, ending 35 m (115 ft) before the intersection. The distances between the lines ranged from 7.7 m (25 ft) to 2.75 m (9 ft). The distance between lines for the transverse pattern using a constant distance between lines was 4.5 m (15 ft). The treatments used yellow painted lines, 0.6 m (2 ft) wide, situated in the participants driving lane only.

Speed data were collected beginning 500 m (1,640 ft) preceding the 35 m (115 ft) non-treatment area before the intersection. This area was divided into five 100 m (328 ft) sections. The first section began before the treatment area, with the remaining four within the treatment area. For each section a single mean was calculated for each participant. Data analysis relevant to this discussion consisted of three contrasts. The first contrast compared the experimental control with the three transverse line treatments to investigate their effects. The second contrasted the two transverse line treatments with the peripheral transverse treatment. The final contrast compared the transverse treatment using decreased spacing to the treatment using constant spacing.

The authors averaged the means across the total measurement area of the three treatments roads and compared the results to the control road. The three treatment road mean speeds were significantly slower than the control road from 73.5 km/h (45.7 mi/h) to 81.9 km/h (51 mi/h). However, driving speeds during the 100 m (328 ft) pretreatment area were not significantly different from one another. It was only during the remaining 400 m (1,312 ft) treatment area that speeds became significantly different. For the second comparison, driving speeds of the two full lane width treatments were not significantly different from the peripheral treatment site. However, driving speeds were slower during the first 100 m (328 ft) of the full transverse lines (92 km/h or 57.2 mi/h) compared to the same area of the peripheral transverse lines (98 km/h or 60.9 mi/h). For the third comparison, there was a small but nonsignificant difference between the decreasing spaced and constant spaced transverse lines.

In summary, all three transverse line treatments led to slower driving than the control, but only within the treatment area. Speed reductions in the areas prior to the transverse lines and immediately after they were reached, or both would indicate that the lines had an alerting effect. There were small speed reductions in this area but not significant reductions. The authors state that possibly a larger sample might have resulted in statistically significant results.

As previously discussed, the validity of simulator data should be established with field research, and this is particularly true for speed data. No validation data for this simulator is currently available. A second drawback of this and other simulator-based studies of perceptual countermeasures to speeding is the fact that novelty effects cannot be readily tested.

Retting, McGee, and Farmer (2000) conducted a study of the effect of longitudinal pavement markings on vehicle speed on urban freeway exit ramps. The treatments consisted of a gradual inward tapering of the existing edge line or exit gore markings to create the illusion of lane narrowing. Also, raised pavement markings were installed adjacent to the markings. The ramps were not uniform in geometric design or layout of pavement markings. The study was performed at four exit ramps located in New York state, and Virginia. Four similar ramps along the same freeways were used as control sites for the study, and a before and after design was used. Data were collected six weeks before and two weeks after installation of the markings. The methods of evaluation were mean vehicle speeds, 90th percentile speeds, and percentages of vehicles exceeding the posted advisory speeds by more than 16 km/h (10 mi/h). Speeds were measured approximately 152 m (500 ft) before the ramp, and at a point before the curvature of the exit. The total number of observations was 84,188 passenger vehicles, and 3,557 large trucks.

Results indicate a general reduction of vehicle speeds after the installation of the markings. Overall, mean passenger vehicle speeds were reduced significantly at three of the four exit ramps. There was no change at Virginia Ramp B. The percentage of passenger vehicles exceeding the posted advisory speed by more than 16 km/h (10 mi/h) decreased from 83 to 66 percent at the New York ramp, from 40 to 21 percent at Virginia Ramp A, and from 27 to 21 percent at Virginia Ramp C. No significant changes were found at Virginia Ramp B. The 90th percentile speeds were lowered at three of the four ramps, albeit, not significantly. Overall, mean large truck speeds were reduced significantly at three of the four ramps. Due to an unexpected decrease in the number of large trucks at Virginia Ramp B no data were reported for this site. The percentage of large trucks exceeding the posted advisory speed by more than 8 km/h (5 mi/h) decreased from 77 to 55 percent at the New York Ramp, from 35 to 18 percent at Virginia Ramp A, and from 49 to 30 percent at Virginia Ramp C.

The study was limited in that only four ramps were studied, as well as the inability to separate short-term or novelty effects from long-term effects. However, the study used appropriate experimental controls. For instance, the before and after data collected upstream of the study exits showed freeway conditions were equal before and after installation of the markings.

The Kansas Department of Transportation and the University of Kansas conducted a study to evaluate the effectiveness of transverse pavement markings on freeway work zone vehicle speeds (Meyer 2001). A rural section of I-70 west of Topeka, KS with an average annual daily traffic (AADT) count of 18,000 vehicles per day was chosen. The speed limit on the section of highway was typically 113 km/h (70 mi/h) but was reduced to 97 km/h (60 mi/h) during the construction. Three patterns were used on the roadway segment: primary pattern, leading pattern, and work zone pattern. The leading pattern was located upstream of the primary pattern to separate warning and perceptual effects. The work zone pattern was located downstream of the primary pattern to keep drivers from returning to their normal speed after the primary pattern. The work zone was approximately 8 km (5 mi) long, and the data collection area approximately 2.2 km (1.4 mi) in length.

The leading pattern consisted of 20 bars with a constant width of 105 cm (42 in) spaced 16 m (52 ft) apart for a span of 332 m (1,090 ft). The primary pattern consists of 29 bars with varying widths from 105 cm (42 in) to 60 cm (24 in) spaced at varying distances from 16 m (52 ft) to 9 m (29 ft). The work zone pattern consists of 4 sets of 6 bars with 152 m (500 ft) between each set for a span of 747 m (2,450 ft). Each bar was 60 cm (24 in) wide with a spacing of 6 m (20 ft). The research revealed that optical speed bars reduced mean speeds, 85^{th} percentile speeds, and speed variations. The data also showed that both warning effects and perceptual effects existed. There was a reduction in speeds at the first portion of the primary pattern, but this trend disappeared by the second portion of the pattern when the spacing of the bars was fairly uniform. The work zone pattern did not perform well at maintaining the speed reductions. Although there was a reduction in speeds with a 95% significance level, the magnitude of the reduction was fairly small. Meyer recommends further research to design optical speed bars that increase the magnitude of the reduction before widespread use of the technique. There are some factors that limit the interpretation of Meyer's findings. For example, only daytime results are reported, and no control condition was used. Furthermore, the author only reports speed profiles of vehicles traveling through the data collection area. There was no data collected before the treatment was installed to compare results to. Consequently, the speed reductions reported cannot be reliably attributed to the treatments.

Transverse Chevrons

Transverse chevrons are similar to transverse bars; however, a chevron pattern is used instead of bars. The design of transverse chevrons comes from Japan where several bridges with high accident rates were identified for possible transverse markings. The actual design is detailed in a paper by Ito (1995). Although the application of the markings has been used in Japan, there are no published studies that have evaluated the effectiveness of the markings with respect to speed.

Rumble Strips

A rumble strip is a marking or other road treatment that is placed in the lateral direction on the roadway to produce noise and vibrations, which increase the sense of speed. In a report by Kallberg et al. (1998), rumble strips are said to be effective at approaches to intersections as a speed reduction measure. It is also stated that noisy or rough road surfaces such as tile or stone can have similar effects of reducing speeds.

Zaidel, Hakkert, and Barkan (1986), conducted a field study comparing rumble strips to transverse pavement markings. A pattern of 38 strips with progressively closer spacing was installed at the two minor approaches to a four-way stop controlled low-volume rural intersection. Strips were 60 cm (2 ft) wide and installed beginning 269 m (883 ft) upstream of the intersection and ending 17.4 m (55 ft) from the stop bar. A similar pattern of rumble strips, 12 to 15 mm (1/2 to 5/8 in) high, was applied to the opposite leg. During the crossover phase a modified shorter pattern of rumble strips [150 m to 10 m (492 ft to 33 ft)] was used. Both rumble strip patterns resulted in a 2-Hz rate of vibration. Both rumble strips, and transverse bars were painted yellow with reflective glass beads added. Special advanced warning signs were added to the normal sequence of signs on each approach.

A before, after, and crossover design was used. The after period was one month after installation, and one year after installation. Normally using a crossover design would result in removing one experimental treatment and replacing it with the second treatment, and vice versa. However, the authors, citing the poor performance of the transverse pavement markings, decided to use a modified rumble strip pattern instead of the transverse pavement markings.

Data were collected for 2,500 vehicles over a four-day period (Monday through Thursday, 8:30 am to 6:00 pm), at both approach legs simultaneously. Measurement was performed at 8 locations beginning 420 m (1,378 ft), and ending 15 m (55 ft) from the stop bar. The methods of evaluation were: stopping behavior, speed, and deceleration.

Results for the transverse bars condition showed that approach speeds just before the beginning of the treatment area did not change—if there is an alerting mechanism to transverse bars there should have been a reduction in speed. However, from the point the treatment area begins to the final data collection point near the stop bar a significant reduction was found. There were no significant changes in maximum or average deceleration patterns. During both the before and after periods, average deceleration ranged from 0.20 m/s^2 farthest from the intersection up to 1.6 m/s^2 nearest the intersection. Stopping behavior was found to be high both before treatment and after. Before treatment, 79 percent stopped, 11 percent made a rolling stop, and 10 percent did not stop. After treatment, 85 percent stopped, 7 percent made a rolling stop, and 8 percent did not stop.

Results for the rumble strips showed approach speeds just before the beginning of the treatment area were lowered significantly. When measured across the entire approach area a significant reduction in speed of 40 percent was found. During the before period, most of the deceleration occurred beginning at approximately 150 m (492 ft) and continued to the intersection. After rumble strip installation, most deceleration took place over the first 100 m (328 ft) of the treatment area. Stopping behavior was found to be 82 percent before treatment installation, and no significant changes were found.

On the approach where transverse markings were used the researchers decided to replace the treatment with a modified rumble strip pattern. The pattern was installed beginning 150 m (492 ft) upstream of the stop bar, and ended 10 m (33 ft) from the stop bar. The treatment resulted in a significant reduction in speed beginning approximately 60 m (197 ft) to 100 m (328 ft) before the treatment and continuing to the stop bar. No deceleration data were reported, but stopping compliance increased to 95 percent, a slight improvement over the transverse markings. Treatment effects were reevaluated one year after installation. The authors reported no significant drop-off in performance for either treatment.

Conclusions and Recommendations

Speeding is one of the major factors that result in fatal crashes in the United States as well as the rest of the world. Getting motorists to slow down is not a trivial task, and understanding the way motorists perceive speed is the first step in tackling this large problem. Unfortunately state departments of transportation have limited funds to place conventional countermeasures at every possible safety hazard—low cost methods are required instead. Many of the countermeasures presented in this literature review such as longitudinal pavement markings, transverse pavement markings, and rumble strips are inexpensive compared to other countermeasures involving traffic calming devices. These countermeasures when used appropriately and at critical safety hazard locations have the opportunity to decrease speed and as a result, decrease the number of fatal crashes.

Research shows that some perceptual countermeasures have promise as effective speed control methods; however, there are gaps in the research that should be addressed. Transverse pavement markings were found to be effective in initially reducing mean speeds, 85^{th} percentile speeds, and speed variance in several studies (e.g., Denton, Agent, Hungerford and Rockwell; Meyer; Zaidel et al.; Godley et al.), but questions remain about whether transverse pavement markings produce long-term effects. Some studies showed increases in speed upon retesting (Agent; Hungerford and Rockwell) while other studies did not test for long-term effects (Denton, Zaidel et al.; and Godley et al.). Another area that merits research concerns the effectiveness of transverse markings on residential streets.

Longitudinal pavement markings were found to be effective on freeway exit ramps (Retting, McGee, and Farmer) with a significant reduction in mean speeds as well as the percentage of vehicles traveling more than 10 mi/h over the advisory speed limit. Longitudinal pavement markings were also found to be effective in the driving simulator at significantly reducing mean and 85th percentile speeds (Jamson, Pyne, and Carsten). One study was performed in the field at a residential location with no reduction in speed and an increase in speed two weeks later with 50 percent of the observations (Lum). Other studies using text and symbol markings on the pavement in the field (Retting and Farmer) as well as in the simulator (Jamson, Pyne, and Carsten) also showed significant reductions in speed.

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CHAPTER 3: PAVEMENT MARKING DESIGN METHODOLOGY

Several factors were considered when determining the design of the transverse pavement markings. When synthesizing the literature on driver speed choice, it became apparent that two factors could potentially be incorporated into the design of transverse pavement markings. First, several research studies described in Chapter 2 (Martens et al 1997, Vey and Ferreri 1968, and Yagar and Van Aerde 1984) showed that reductions in lane width resulted in a reduction of vehicle speeds. Second, although not explicitly termed as "vection", several research studies used the concept of vection in placing transverse bars on approaches to curves in the roadway to reduce vehicle speeds (Agent 1980, Denton 1980, Godley et al 1999, Ito 1995, and Meyer 2001). Vection is defined as the perception of self-motion induced by visual stimuli.

Peripheral transverse bars provide several benefits. First, peripheral transverse bars do not require as much material and thus are cheaper to install and maintain when compared to other markings that extend over the full width of the travel lane. Second, there is also a safety concern of placing pavement markings in the wheel paths of vehicles due to the potentially slick surface that can result from wet pavement conditions.

For this study, it is hypothesized that markings that are placed on the edge of the travel lanes will result in a roadway that appears to have a reduced lane width without actually reducing the width of the pavement which may result in a reduction in driver speed. The Highway Capacity Manual contains adjustments for Free Flow Speed based on lane width. For freeway and multilane segments, the adjustments are 0.0, 1.9, and 6.6 miles per hour for 12, 11, and 10 feet, respectively[1]. Although it is not anticipated that the peripheral markings will have the same effect as reduced lane width, it is hypothesized that there will be some effect. Additionally, it is hypothesized that through vection, transverse bars spaced closer together at a constant speed would give the driver the sensation that they are actually traveling faster and thus result in a decrease in speed.

A standard lane width is generally designed to be 12 feet wide whereas a standard truck width is 102 inches (8.5 feet) wide. Thus, markings were designed to be 18 inches wide which would reduce the effective "visual" lane width to 9 feet and still allow for a 0.5-foot cushion. Therefore, the wheel paths of the vehicles would avoid the peripheral transverse lines if the vehicle were to travel down the center of the lane. The markings were also designed to be 1 foot long in order to be visible on the roadway. Initially, markings of 4 inches were tested in the field but the markings were not visible whereas the 1 foot markings were visible to motorists. The marking spacings chosen for this chapter is based on 4 bars per second which was found based on studies in the field and on the Virginia Tech Smart Road to be the optimal design for the pavement markings (refer to Chapter 4 and Chapter 6).

The transverse pavement marking pattern designs used in previous research have been placed at either constant intervals or in intervals with decreasing spacing without

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[1] Source: *Highway Capacity Manual 2000*. Transportation Research Board. Washington, DC, 2000. page 21-5.

accounting for the initial and final desired speed. Therefore, two different treatment patterns were developed that take into account driver deceleration, initial speed on the approach to the reduction, as well as the final speed required in the reduction area. The computations in this chapter are based on a constant deceleration level. An analysis of the speed over distance from the curve using the Smart Road Study data in Chapter 6 resulted in a relatively linear relationship with an average R^2 value through the treatment section of 0.92. This deceleration profile may not be realistic in all situations, but various geometric characteristics could result in possibly varying deceleration profiles and thus a constant deceleration is reasonable for these calculations.

The first step in the process is to determine the initial speed on the roadway. The initial speed could potentially be the posted speed limit, the facility free-flow speed, the mean speed, the 85^{th} percentile speed, or other any other speed estimate that a practitioner believes should be used as the appropriate initial speed. In many cases, the posted speed limit is the most available and will generally be used for this type of application.

The next step in the process is to select the desired speed (for the particular reduction scenario). This may be a lower posted speed limit, an advisory speed for a curve, or potentially designed for a speed of practically zero on the approach to a stop sign.

The final step in the process is to determine a required deceleration level for the treatment area. In many cases, the required deceleration level will be dictated by adjacent geometric elements. The lower the deceleration level, the larger the treatment section has to be to achieve the desired speed reduction. For example, on multilane roadways with a curve, drivers are generally given much more time to reduce speed in advance of the curve whereas on some exit ramps where deceleration ramps are short, a more rapid deceleration would be required. The Traffic Engineering Handbook (1999) states that rates up to 10 ft/s^2 (3 m/s^2) are considered comfortable.[2] Several factors contribute to the chosen deceleration level but primarily, the space available on the approach to the condition will determine the required deceleration level. If space is available, it is recommended that the smallest possible deceleration is chosen. Although any value greater than zero and less than 10 ft/s^2 (3 m/s^2) would be acceptable, this chapter uses values of 1.0, 2.0, and 3.0 m/s^2 (3.3, 6.7, and 10 ft/s^2) which would be approximately equal to 0.1g, 0.2g, and 0.3g to simplify the design for the practitioner.

After discussing the placement of the transverse markings with the Traffic Control Devices Pooled Fund Study research panel, it was determined that in general the markings should be placed up to the point of curvature if used on a horizontal curve. The concept is that drivers will have already needed to slow down to the desired speed in order to comfortably negotiate the curve. Markings can be placed in the curve, but the spacings should be constant after achieving the reduction at the point of curvature.

The determination of marking spacing begins with the differential equation

[2] Source: Pline, James (editor). *Traffic Engineering Handbook*. Institute of Transportation Engineers, 1999. page 68.

$$\frac{dv}{dt} = a \qquad (1).$$

Where v is the vehicle speed (m/s), a is the vehicle acceleration (m/s^2), and t is the solution time step (s). Assuming a constant acceleration level the differential equation can be solved by integrating Equation 1 and separating variables as

$$\int_{v_t}^{v_{t+\Delta t}} dv = \int_{t}^{t+\Delta t} a dt \ . \qquad (2),$$

Where Δt is the analysis time step. Equation 2 can be solved to derive

$$v_{t+\Delta t} - v_t = a\Delta t \qquad (3).$$

Since Δt represents the analysis time step (s), it can be related to the number of bars (n) and the bar frequency (f) in bars per second using the formula:

$$\Delta t = \frac{n}{f} \qquad (4).$$

Substituting Equation 4 into Equation 3 results in the formula:

$$v_{t+\Delta t} - v_t = a\frac{n}{f} \qquad (5).$$

By rearranging the terms of Equation 5 the speed Δt seconds later can be computed as

$$v_{t+\Delta t} = v_t + a\frac{n}{f} \ . \qquad (6)$$

Given that the acceleration level is assumed to remain constant for the entire deceleration maneuver. Equation 6 can be generalized as

$$v_t = v_0 + a\frac{n}{f} \ . \qquad (7)$$

When calculating the desired marking placement, the position can be derived from the differential equation:

$$\frac{dx}{dt} = v_0 + a\Delta t \ . \qquad (8)$$

Where x is the distance in meters from the beginning of the treatment area (located at x_0 feet) and v_0 is the initial speed entering the treatment. The equation can be solved by multiplying dt on both sides and integrating the function:

$$\int_0^t dx = \int_0^t (at + v_0) dt \qquad (9),$$

Resulting in:

$$x_t = \frac{1}{2}at^2 + v_0 t + x_0 \qquad (10).$$

Replacing Equation 4 into Equation 9 results in:

$$x_t = \frac{1}{2}a\left(\frac{n}{f}\right)^2 + v_0\left(\frac{n}{f}\right) + x_0 \qquad (11).$$

To simplify the process, Appendix A contains tables so that practitioners can effectively design marking spacing for a wide variety of conditions. Note that due to rounding for practical applications and for standardization in lookup tables, the values given in the equation may slightly vary from the values in the table. The tables are found first in order of decelerations at 1.0, 2.0, and 3.0 m/s^2 (3.3, 6.7, and 10 ft/s^2). For installation purposes, the distances are given from the end of the treatment area in feet. Then, the tables are sorted in order of increasing desired speeds (the speed desired at the end of the treatment area). The tables can therefore be used to determine marking spacing requirements for any particular initial speed. Desired speeds of anywhere from 5 miles per hour to 55 miles per hour may be used with initial speeds ranging from 10 miles per hour to 65 miles per hour.

For example, if the decision were made to reduce speeds from 55 mi/h to 35 mi/h on the approach to a curve and it was determined that limited space was available so a deceleration of 10 ft/s^2 was required, then Table A-29 would be used which shows marking patterns for a desired speed of 35 mi/h. Since the initial speed is 55 mi/h, bars X_0 through X_{12} would be used on the approach to the curve where X_0 is placed at the end of the treatment area and X_{12} is placed 196 feet upstream.

To calculate the distance by hand using Equation 11, the value of x at the 12th bar would be:

$$x_{12} = \frac{1}{2}(-10)\left(\frac{12}{4}\right)^2 + (80.85)\left(\frac{12}{4}\right) = 197.5 \text{ feet},$$

where a = -10ft/s^2, n = 12 bars, f = 4 bars per second, and v_0 = 80.85 ft/s^2 (55 mi/h).

CHAPTER 4:

DESIGN AND EVALUATION OF PERIPHERAL TRANSVERSE BARS TO REDUCE VEHICLE SPEEDS

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DESIGN AND EVALUATION OF PERIPHERAL TRANSVERSE BARS TO REDUCE VEHICLE SPEEDS

Authors:

Bryan J. Katz
Science Applications International Corporation
6300 Georgetown Pike, F-215   McLean, VA 22101
Phone: (202) 493-3388   Fax: (202) 493-3390
E-mail: Bryan.Katz@fhwa.dot.gov

Dana E. Duke
Science Applications International Corporation
6300 Georgetown Pike, F-215   McLean, VA 22101
Phone: (202) 493-3377   Fax: (202) 493-3390
E-mail: Dana.Duke@fhwa.dot.gov

Hesham A. Rakha
Virginia Polytechnic Institute and State University
301 Patton Hall   Blacksburg, VA 24061
Phone: (540) 231-1505   Fax: (540) 231-7532
E-mail: hrakha@vt.edu

Abstract

Speeding is considered to be a contributing factor in crashes and therefore is a very important safety issue. Because higher vehicle speeds result in more severe crashes, if vehicle speeds can be reduced in dangerous road sections, then presumably safety can be improved. One speed reduction method that has shown promise in past research is to use pavement marking patterns to give drivers the perception that they are traveling faster than they really are. This illusion is created by making the travel lanes appear narrow or adding optical patterns to the roadway surface.

The present research project examined whether perceptual countermeasures such as pavement marking patterns have the potential to reduce vehicle speeds. Sites were chosen in New York, Mississippi, and Texas. Speed measures were taken to evaluate the effectiveness of the markings before installation and four months after the installation to examine long-term effects at each site.

The markings resulted in a decrease in overall vehicle speeds with total vehicles as well as specific classifications of vehicles. There were also reductions in speed with vehicles traveling with headways greater than four seconds. Speed reductions were found to be higher at the New York site and Mississippi site, which were interstate and arterial roadways whereas in Texas where the markings were placed on a local road, the effects were not as large.

Introduction

In the United States, speeding is considered to be a contributing factor in about 30 percent of fatal crashes (1). In an attempt to reduce speeds on roadway segments where speed is considered to be a safety concern, various pavement marking patterns that create the appearance of narrowing and/or increasing speed have been considered as a relatively low-cost countermeasure. Perceptual countermeasures are one potential method of influencing motorists to slow down, and ultimately, to save lives. These perceptual techniques might be useful at lowering speeds in a variety of driving situations such as work zones, curves, roundabouts, and toll plazas. Other similar treatments include the use of other text and symbol pavement markings that get the attention of motorists.

Although the perceptual countermeasures are not widely used in the United States, some treatment alternatives have undergone experimentation in the field as well as in simulators with varying results. Further evaluation of marking pattern alternatives is needed to determine which patterns are best at encouraging drivers to maintain safe and appropriate speeds. The Traffic Control Devices Pooled Fund Study panel recognized the potential of these low-cost pavement marking improvements and chose this topic for investigation. This paper describes a field study performed as part of the investigation at three field locations in New York, Mississippi, and Texas where perceptual countermeasures involving markings were evaluated. The goals of this study are to:

- Determine a low-cost pavement marking treatment with a high probability of success based on previous research,
- Determine the effectiveness of the marking through a field evaluation at three different locations, and
- Provide recommendations for pavement marking use as a speed reduction device for possible inclusion in the Manual on Uniform Traffic Control Devices (MUTCD).

Previous Research

Both longitudinal as well as transverse pavement markings have been used to influence drivers' perceptions of their roadway environment. Longitudinal markings consist of either centerlines or edge lines and can be used to reduce lane widths. Research performed by Yagar and Van Aerde (2) found a reduction in speed as lane width decreases. However, several studies (3, 4) did not show any decrease in speeds when lane widths were decreased using pavement markings. Both studies only investigated the effects of using pavement markings alone to reduce speed without any forms of hatching or other markings on the shoulder which may have contributed to that outcome. Another study by Retting et al (5) looked into the effects of speeds on markings used to narrow freeway exit ramps to reduce speeds. Results indicated that the added markings were effective in reducing speeds by approximately 1 mi/h (1.6 km/h) on average, but the study used diagonal lines next to the edge lines rather than simply edge lines alone.

Transverse pavement markings, a series of lines or bars (typically white) which are perpendicular to the path of travel and are placed across the road like rumble strips, are the most commonly used form of pavement markings in speed reduction. Transverse pavement markings typically take the form of either transverse bars or transverse chevrons and are placed closer to each other to give the perception that the driver is speeding up as a driver drives down the roadway. In a Kansas study (6), transverse bars were placed in a work zone in which three patterns were used. The first pattern was a "leading pattern" with constant widths and constant spacing to warn drivers of the upcoming work zone. The second pattern or "primary pattern" consisted of bars with varying widths and varying distances which led up to the work zone. The actual "work zone pattern" consisted of four sets of six bars spaced every 500 feet (153 meters). The results showed a decrease in speeds at a 95% confidence level; however, the magnitudes of the speed reductions were fairly small. An earlier study (7) was performed on a sharp curve with a high accident rate in Kentucky. In six years, there were 48 accidents at the location and speed was considered as a contributing factor in 36 of the 48. There was a reduction in speeds six months after the installation compared to before the installation; however, the long-term effects during nighttime were much smaller than the long-term effects during daylight hours.

A more recent study by Drakopoulas and Vergou (8) evaluated converging chevron pavement marking patterns in Wisconsin. These markings were placed on Interstate 94 on a freeway exit ramp at the Mitchell Interchange in Milwaukee, Wisconsin. The mean speed of the exit ramp was determined to be 70 mi/h (113 km/h) before the installation and 53 mi/h (85 km/h) twenty months after the installation for an overall reduction of 17 mi/h (27 km/h).

Another study by Godley, Triggs, and Fildes (9) evaluated transverse lines as well as peripheral transverse lines versus a control section of roadway in a driving simulator. Transverse lines are stripes that are placed across the entire travel lane whereas the peripheral transverse lines are placed only on the edges of the travel lane. The study showed that driving speeds were only slower for the transverse lines (as compared to the peripheral transverse lines) for the initial section of the treatment but that overall, the peripheral lines performed the same and in some cases better than the regular transverse lines.

Research Method

Pavement Marking Selection

After analyzing the perceptual countermeasure field and simulator literature, it was determined that peripheral transverse lines have potential to encourage slower driving speeds. New York, Mississippi, and Texas Departments of Transportation also agreed that these markings would be the best alternative for their sites because: 1) Peripheral transverse lines are very easy to install and maintain; 2) They are not located in the wheel path of a vehicle and thus do not provide a slick surface under wet conditions on a road segment that already has safety concerns; and 3) Since only a small amount of pavement marking material is needed, the treatment is very cost effective.

Research Approach

The underlying approach to this study was to determine possible pavement marking alternatives that seem to have promise in reducing vehicle speeds and implementing one of those alternatives in the field. Three field locations were chosen in which before and after speed data were collected. To avoid the need for a multi-year accident analysis study for determining safety effects, this method assumes that speed is a surrogate safety measure and it will be assumed that a higher safety rating is achieved if vehicle speeds are reduced. Data were collected at a common site upstream during all data collection periods to check for environmental or seasonal differences. Additionally, data were collected just prior to entering the curve to determine the reduction in speeds. There were two data collection periods reported in this study. The first was prior to the installation of the markings. The second data collection period took place approximately four months after the installation.

Data Collection

Traffic data collection devices are used in this study to collect characteristics such as time, speed, volume, vehicle headway, and vehicle classification. Additionally, weather data as well as pavement condition (e.g., wet, dry) were noted and data were only used for periods with dry roadway conditions. Data were collected at a point just upstream of the treatment area (shown in Figure 4-1) as well as at the point of curvature of the curve. The traffic data collection devices were verified with radar or laser speed gun periodically for accuracy. A laptop computer was used to verify the data periodically as well to download the data. In summary, the following equipment was used in the course of data collection:

- Traffic Speed Measuring Devices (Jamar Traffic Counters)
- Laser Speed Gun
- Laptop Computer (for downloading data)

Data Analysis

The data collected from the traffic data collection devices were examined by individual vehicle speeds to determine characteristics of each vehicle traveling through the site. Several data analyses were performed to determine the effectiveness of the pavement markings. For each speed analysis, the mean, median, variance, and 85th percentile speeds were observed. The following analyses were performed:

- Effects of the pavement markings on speed for all vehicles,

- Effects of the pavement markings on speed of vehicles by vehicle classification, and
- Effect of the pavement markings on speed by vehicles with varying headways.

All data were included in the analysis regardless of the effects of speed by varying headways because although the leading vehicle will effect the speeds of the entire platoon, the magnitude of vehicles reducing speed is still critical. In many cases, crashes may occur with a vehicle that is not in the lead of a platoon.

In addition to the overall speed comparisons, it was also necessary to correct for environmental differences. Environmental effects were treated by observing the differences in the control location upstream and applying that difference to the treatment location. For example, if the control site showed an increase in speed between the before and after periods, then the treatment site took this difference into consideration in the analysis. Effectively, the overall speed difference at the treatment location was taken to be the quantity of the speed after the installation minus the speed before the installation minus the quantity of the speed after the installation at the control site minus the speed before the installation at the control site.

Site Selection and Pavement Marking Installation

Three sites, where speeding has been cited as a safety problem, were chosen for the installation of the experimental markings. The markings were designed individually for each site such that a comfortable deceleration could be made to go from the initial speed to the final speed at the curve. Thus, the overall design was slightly different for each site. The first site was Interstate 690 in Syracuse, New York at the exit ramp for the New York State Thruway (see Figure 4-1). The portion of Interstate 90 marked on the figure represents the access ramp and toll plaza for the exit to and from Interstate 690. The speed limit on the freeway is 65 mi/h (105 km/h) and the posted advisory speed on the ramp is 30 mi/h (48 km/h). There are two thru lanes at the location with one exit only lane where the ramp is located. There is also a bridge abutment very close to the ramp and the abutment causes a very limited sight distance of the sharp curve on the ramp; it is hard to see how severe the curve actually is until the driver is too close. Therefore, drivers travel too fast approaching the ramp and decelerate at a very rapid rate when approaching the gore area. The treatment as installed used 12 inch (30.5 cm) wide pavement markings extending 18 inches (45.7 cm) into the roadway spaced increasingly closer together and placed perpendicular to the travel lane on both the left and right edges of the travel lane (see Figure 4-2).

The second site was on a two lane rural roadway in Flowood, Mississippi near Jackson, Mississippi (see Figure 4-1). The speed limit on the tangent section is 45 mi/h (72 km/h) and the advisory speed for the curve is 40 mi/h (64 km/h). Figure 4-2 shows the marking treatment with 12 inch wide (30.5 cm), 18 inch long (45.7 cm) pavement markings spaced increasingly closer together and placed perpendicular to the travel lane on both the left and right edges of the travel lane.

The third installation was on a two lane rural highway in Waller, Texas near Houston, Texas (see Figure 4-1). The speed limit on the tangent section is 65 mi/h (105 km/h) and the advisory speed for the curve is 40 mi/h (64 km/h). A similar treatment was placed in Houston as was placed in Jackson; however, the need to reduce travel speeds from 65 to 40 miles per hour as opposed to from 45 to 40 miles per hour meant that more markings needed to be placed at the Houston site. Figure 4-2 shows the marking treatment as installed.

Results

Effects of Pavement Markings on Speed of All Vehicles

In order to determine the appropriate statistical tests, it was necessary to determine if the data could be approximated with a normal distribution. Figure 4-1 shows the frequency distribution of the downstream speed data before installation of the markings. The sample sizes in this case were very large, and the Kolmogorov-Smirnov goodness-of-fit test indicated that the data was not normally distributed at the 0.05 level. An argument could be made that the data visually resembled a normal curve and that the nonsignificance is related to the very high sample size, so both a parametric ANOVA test and a nonparametric Kolomogorov-Smirnov (K-S) test was used for all data.

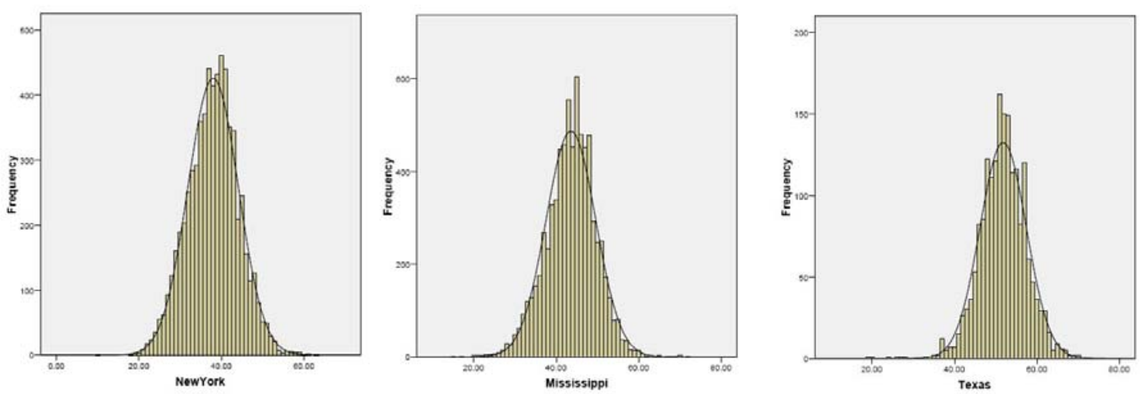

Figure 4-1: Frequency Distribution of Speed Data

For the Syracuse, New York site, the pavement markings appeared to have an effect on the speed of all types of vehicles when observing the before, after, and extended after data as shown in Table 4-1. Data collection occurred upstream of the treatment as well as downstream at the end of the treatment area, just prior to entering the curve (see Figure 3). In both the after data and the extended after data, there was approximately a 4 mph reduction (6 km/h) in the average speeds, a 4 mph reduction (6 km/h) in the median speed, and a 5 mph reduction (8 km/h) in the 85^{th} percentile speeds. The effects of the immediately after data are even stronger when noting that there was actually a 5.6 mph

(9.0 km/h) increase in the upstream counter. When correcting for possible environmental conditions such as weather or time of year trends that may have led to the increase, there was an actual adjusted decrease of 9.5 mph (15.3 km/h). Adjusted decreases were calculated as the quantity of the difference in speed from the after condition from the before condition upstream minus the quantity of the difference in speed from the after condition from the before condition. The net decrease; however, was 4 mph (6 km/h) in the extended after data. When testing for statistical significance between the before and after speeds downstream of the curve, the mean difference was significant at the .05 level using Analysis of Variance (ANOVA) and K-S.

For the Flowood, Mississippi test location, the pavement markings also had an effect on total vehicle speeds (shown in Table 4-2), but not as large as the effect in Syracuse. At this location, it turned out that the effects of the pavement markings on speed were slightly greater in the extended after period as opposed to the directly after period. It is anticipated that the increase in speed at the upstream location may have been caused by various environmental factors such as weather or time of year. After adjusting for these environmental conditions (i.e. accounting for the changes at the upstream control location), the adjusted decrease would be 4.6 mph (7.4 km/h). The total net decrease is 1.84 mph (2.96 km/h). When testing for statistical significance between the before and after speeds downstream of the curve, the mean difference was significant at the .05 level using ANOVA and K-S.

The Waller, Texas site provided some very interesting observations. Although drivers at the upstream location would not be able to view the markings, the data showed a decrease in speed in extended after periods for the upstream location (see Table 4-1). However, the speeds for vehicles downstream of the markings (at the curve) were all reasonably similar through all three periods. There was a slight reduction in average speed over the before period at the downstream data collection point but the magnitude is not as large as the reduction in average speed over the before period at the upstream data collection point. It is interesting to note that there was no statistical difference in the average speed at the .05 level downstream of the curve in the extended after period compared to the before period; however, when testing for statistical significance between the before and after speeds upstream of the curve, the mean difference was significant at the .05 level using ANOVA and K-S. One possible reason this occurrence took place was that drivers slowed down in advance of the curve but then determined that the curve was safe to negotiate at a faster speed. Unfortunately, speed profiles are not available in order to test this theory. The curve was slightly different from the other two curves in that drivers had the ability at this location to see the upcoming curve from a significant distance and thus the markings may not be appropriate at these locations. Additionally, the roadway was a low-volume roadway primarily driven by local drivers who were very familiar with the road and thus the drivers were most likely aware of the severity of the sharp curve.

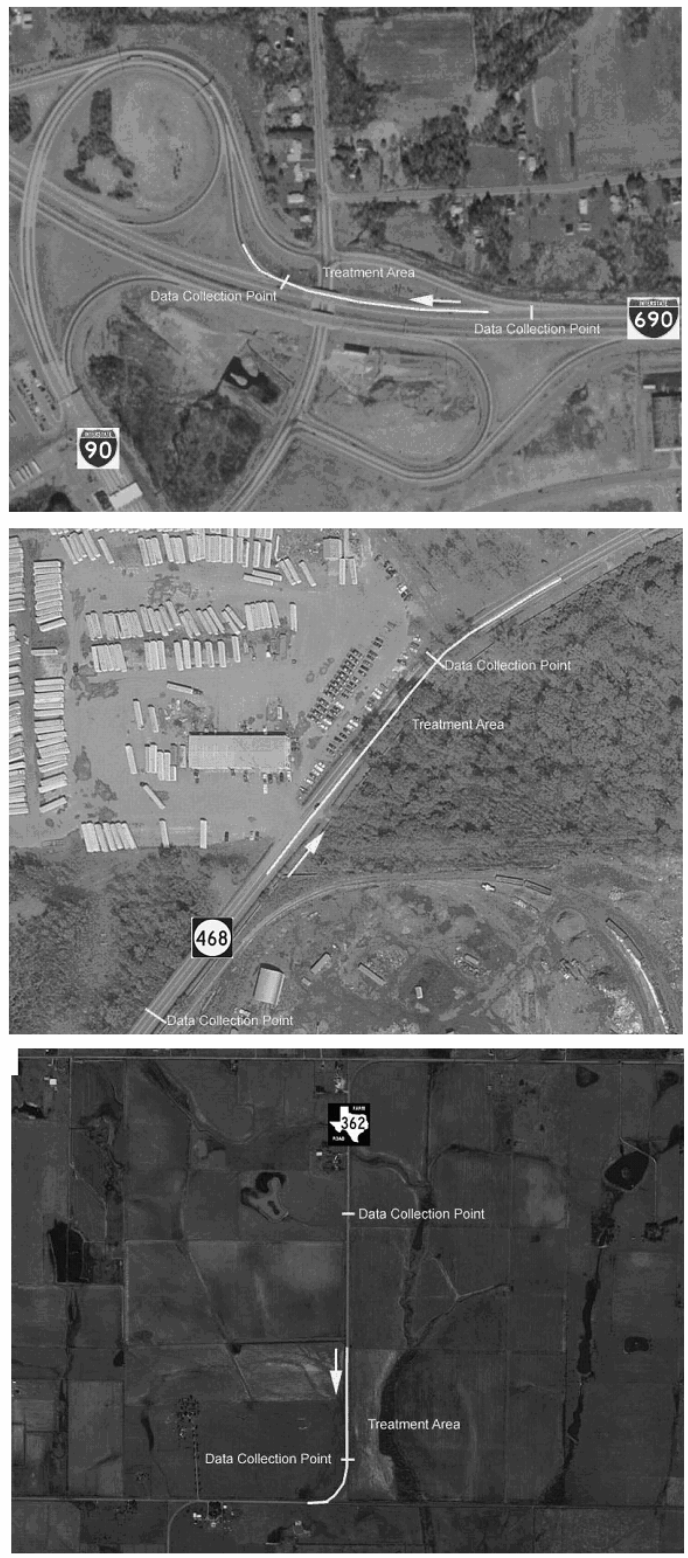

Figure 4-2: Data Collection Sites (New York, Mississippi, Texas – from top to bottom)

Figure 4-3: Peripheral Transverse Lines (New York [upper left], Mississippi [lower left], Texas [right])

Table 4-1: Effects of Pavement Markings on Speed for All Vehicles (in mph)

	New York		Mississippi		Texas	
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
Before						
Average	55.3	38.0	41.2	43.6	65.6	53.1
Standard Deviation	7.8	6.1	7.1	6.0	7.7	5.7
Median	56	38	42	44	65	53
85th Percentile	63	44	47	49	72	55
After						
Average	55.5	34.1	44.0	41.7	59.7	52.8
Standard Deviation	7.2	4.9	8.1	7.6	5.7	5.6
Median	56	34	45	43	60	53
85th Percentile	63	39	51	48	65	58
Reduction						
Average		3.9		1.9		0.3
Median		4		1		0
85th Percentile		5		1		-3

Note: Negative Value Signifies Increase in Speed

Effects of Pavement Markings on Speed of Vehicles by Vehicle Classification

The data for the effects of pavement markings on speed of vehicles by vehicle classification are shown in Table 4-2. As expected because of the need to navigate curves at a slower speed for safety reasons, vehicles with more than two axles tend to drive slower than vehicles with only two axles. However, the general trends of the reductions are consistent with what was seen in the analysis of all vehicles. The overall results show that the greatest effects were found in New York with a mild reduction in Mississippi and a reduction in speed upstream of the markings in Texas for both two axle vehicles and vehicles with more than two axles.

Table 4-2: Effects on Speed by Number of Axles (in mph)

	New York				Mississippi				Texas			
	2 Axles		>2 Axles		2 Axles		>2 Axles		2 Axles		>2 Axles	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
Before												
Average	57.2	39.6	48.6	32.8	41.5	43.8	38.4	40.9	65.8	53.7	43.9	50.1
Standard Deviation	7.0	5.5	6.4	4.9	7.1	6.0	6.7	5.8	7.9	5.6	5.9	5.4
Median	57	40	49	33	42	44	39	41	66	54	64	51
85th Percentile	64	45	55	38	48	50	45	47	73	59	69	56
After												
Average	57.0	35.2	49.4	30.0	44.4	42.1	40.2	38.1	60.2	53.3	57.5	50.0
Standard Deviation	6.7	4.6	5.8	3.9	8.0	7.4	8.5	8.4	5.7	5.5	5.2	5.7
Median	57	35	49	30	45	43	41	40	60	54	58	50
85th Percentile	63	40	55	34	52	48	48	45	66	59	62	56
Reduction												
Average		4.4		2.8		1.7		2.8		0.4		0.1
Median		5		3		1		1		0		1
85th Percentile		5		4		2		2		0		0

Effect of the Pavement Markings on Speed by Vehicles with Varying Headways

To determine whether or not the effects of other vehicles had an influence on driver speed choice, it is important to look at various gap sizes and their effects on speed. Speed comparisons were made using both 4 seconds and 10 seconds as cut points. For example, vehicles with headways of 4 seconds or less were compared to vehicles with headways longer than 4 seconds. The results of the analysis are shown below in

Table 4-3. Bold values indicate statistical significance of the means between the gap being "less than" or "greater than or equal to" each of the tested gap sizes indicating that vehicles with increased headway tend to have faster speeds. The analysis showed that for the most part, the mean speeds were significant at a cutoff with a gap size of four seconds. Therefore, a four second gap was used to perform an analysis similar to that performed in the first analysis in this section to determine the effect of the pavement markings on driver speed choice when negating the effects of platoons.

Table 4-3: Effects of Gap Size on Mean Speed (in mph)

	New York		*Mississippi*		*Texas*	
	Upstream	**Downstream**	**Upstream**	**Downstream**	**Upstream**	**Downstream**
Before						
Mean (Gap <4)	**53.98**	**37**	**39.73**	**42.16**	**63.17**	**51.44**
Mean (Gap >=4)	**55.71**	**38.35**	**42.6**	**45.01**	**65.9**	**53.38**
85^{th} Percentile (Gap >=4)	63	45	48	51	73	59
After						
Mean (Gap <4)	**54.3**	**33.22**	**42.26**	**40.84**	**58.57**	52.29
Mean (Gap >=4)	**55.93**	**34.45**	**45.74**	**42.65**	**59.87**	52.85
85^{th} Percentile (Gap >=4)	63	39	53	49	66	58
Reduction						
Avg. Reduction (Gap <4)		3.78		1.32		-0.85
Avg. Reduction (Gap >=4)		3.9		2.36		0.53
85^{th} Percentile Reduction (Gap >=4)		6		2		1

Notes: Bold values indicate significance between 'less than 4' or 'greater than or equal to 4' at .05 level
Negative values indicate an increase in speed

Upon performing an analysis including only vehicles with gap sizes of greater than four seconds, the results from the analysis with all vehicles look somewhat different. Similar to the analysis including all vehicles, there was a significant difference at the .05 level between the Before speeds at the curve and the After and Extended After speeds at the curve for the Syracuse, New York site and the Flowood, Mississippi site. There was also a significant difference in speeds upstream at the Waller, Texas site between the Before data collection period and the After and Extended After periods. There was a reduction in speed as well at the Waller, Texas site; however, the reduction was not statistically significant; however, there was a slight decrease in the average and 85^{th} percentile speeds, so there was a slight effect at the Texas site as well. Therefore, it is apparent that the gap size has an effect on vehicle speeds in the treatment area and when following vehicles are removed from the analysis, the pavement markings still show to be very effective in reducing vehicle speeds.

Conclusions and Recommendations

Overall with the exception of the Texas site, the pavement markings seemed to have an effect on overall vehicle speeds when comparing total vehicles, two axle vehicles, vehicles with more than two axles, and particularly with vehicles following further than four seconds behind the previous vehicle. There are several factors that may impact the magnitude of the effect, particularly driver familiarity with the road and geometric characteristics of the roadway. For example, at the New York site where the traffic is interstate traffic on a freeway the markings had more of an effect than at Texas where most of the traffic is most likely local and at Mississippi which is somewhere in between with traffic primarily traveling on a rural arterial between Jackson, Mississippi and its suburbs. Another major factor is the degree of curvature in the road. The Syracuse, New

York site requires the most rapid deceleration for the curve in the exit ramp and thus drivers are forced to slow down much faster than at the other two sites. The Jackson, Mississippi site does not require as much of a reduction in speed to safely navigate the curve. Another factor is the visibility of the pavement markings. The New York and Mississippi sites were very visible with a dark asphalt pavement with white markings whereas the Texas site had a lighter colored pavement and the markings were more difficult to see because of the color contrast.

The Waller, Texas site presented the most interesting case where although there was only a slight decrease in speed at the curve over the long term, the upstream data showed a significant decrease in speed for the after and extended after data. One possible reason is that since traffic is mostly local where drivers are familiar with the road, the travelers are aware that the markings are coming up and thus they are slowing down more gradually through the section prior to entering the curve. This may indicate that the transverse bars provided a warning for drivers familiar with the road.

Based on the results of this study and the given that other studies have shown to have seen an effect on pavement markings as a speed reduction technique, focus needs to be given to determine alternative pavement marking patterns to see if some have more of an effect than others. Overall, it appears that particularly for locations with unfamiliar drivers (such as at the Syracuse, New York site), the pavement markings have a larger effect on vehicle speeds. Conversely, in areas with mostly local drivers where the geometry of the roadway is well-known by most users and areas with high visibility of the upcoming geometric configuration, the results of the Texas site indicate that these locations may not be a good candidate for treatments. Therefore, this application may be applied to other similar sites or perhaps other settings that drivers encounter where reduced speeds are required.

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CHAPTER 5:

EVALUATION OF DESIGN ALTERNATIVES OF PERIPHERAL TRANSVERSE BARS TO REDUCE VEHICLE SPEEDS AND CENTER LINE ENCROACHMENT IN A DRIVING SIMULATOR

To Be Submitted for Publication

EVALUATION OF DESIGN ALTERNATIVES OF PERIPHERAL TRANSVERSE BARS TO REDUCE VEHICLE SPEEDS AND CENTER LINE ENCROACHMENT IN A DRIVING SIMULATOR

Authors:

Bryan J. Katz
Science Applications International Corporation
6300 Georgetown Pike, F-215   McLean, VA 22101
Phone: (202) 493-3388   Fax: (202) 493-3390
E-mail: Bryan.Katz@fhwa.dot.gov

John A. Molino
Science Applications International Corporation
6300 Georgetown Pike, F-215   McLean, VA 22101
Phone: (202) 493-3381   Fax: (202) 493-3390
E-mail: John.Molino@fhwa.dot.gov

Hesham A. Rakha
Virginia Polytechnic Institute and State University
301 Patton Hall   Blacksburg, VA 24061
Phone: (540) 231-1505   Fax: (540) 231-7532
E-mail: hrakha@vt.edu

Abstract

Speeding is considered to be a contributing factor in crashes and therefore is a very important safety issue. Because higher vehicle speeds result in more severe crashes, if vehicle speeds can be reduced in dangerous road sections, then presumably safety can be improved. One speed reduction method that has shown promise in past research is to use pavement marking patterns to give drivers the perception that they are traveling faster than they really are. This illusion is created by making the travel lanes appear narrow or adding optical patterns to the roadway surface.

A past research effort investigated perceptual countermeasures using pavement marking patterns in New York, Mississippi, and Texas. The study showed that placing the markings at 4 bars per second were effective in reducing vehicle speeds. The purpose of the current study is to investigate differences between four different pavement marking spacing designs (constant, exponential, 2 bars per second, and 4 bars per second) in a driving simulator. In addition, the study evaluates vehicle lane placement to determine whether or not the markings can cause drivers to have fewer encroachments toward the center line which could potentially have a safety benefit on two lane roads.

The study found no significant difference between the various treatments applied to the simulated roadway. However, an analysis of vehicle speeds at the end of the treatment area to see if they had reached the desired speeds showed that in all cases where a reduction was required without stopping, the observed speeds were within a 95% confidence interval of the desired speeds. An analysis of lane position was performed, and for the two bars per second and four bars per second design alternatives, the driver did travel significantly further away from the centerline. Additional research in the field may quantify the magnitude of the effect as well as possible safety implications in reducing crashes on two lane roads.

Introduction

Highway safety analysts estimate that speeding is considered to be a contributing factor in about 30 percent of fatal crashes (1). Many safety improvements have been investigated as possible speed reduction measures from conventional signing and enforcement practices to traffic calming measures and innovative traffic control device designs. In an attempt to reduce speeds on roadway segments where speed is considered to be a safety concern, various pavement marking patterns that create the appearance of narrowing and/or increasing speed have been considered as a relatively low-cost countermeasure. Perceptual countermeasures are one potential method of influencing motorists to slow down, and ultimately, to save lives. These perceptual techniques might be useful at lowering speeds in a variety of driving situations such as work zones, curves, roundabouts, and toll plazas.

At its inaugural meeting in 2003, several federal, state, and local representatives of the Traffic Control Devices Pooled Fund Study determined that research was required to determine the effect that various pavement marking patterns would have on reducing vehicle speeds on curves. A research effort was conducted by Katz et al (2) to determine the effectiveness of peripheral transverse lines as a pavement marking pattern. The research showed that the markings resulted in a decrease in overall vehicle speeds among all vehicles as well as specific classifications of vehicles (i.e. trucks and cars as well as with varying headways). However, the study only investigated the design of pavement markings using a series of transverse bars placed at 4 bars per second.

Another study by Godley, Triggs, and Fildes (3) evaluated transverse lines as well as peripheral transverse lines versus a control section of roadway in a driving simulator. Transverse lines are stripes that are placed across the entire travel lane whereas the peripheral transverse lines are placed only on the edges of the travel lane. The study showed that overall, peripheral lines performed the same and in some cases better than the regular transverse lines when spaced at exponentially decreasing distances on a roadway.

The current study investigates several alternative pavement marking pattern designs in the Highway Driving Simulator (HDS) at Turner-Fairbank Highway Research Center (TFHRC). These designs included the placement of pavement markings at constant distances, at exponentially decreasing distances, at a rate of 2 bars per second (bps), and at a rate of 4 bps. The previous study by Katz et al. showed that peripheral transverse pavement markings have the potential to reduce speeds in the field and thus the goal of this laboratory study is to determine how effective various design alternatives might be at reducing speeds.

Research Method

Research Approach

The current study involved the use of the Highway Driving Simulator (HDS) which was programmed to replicate Pennsylvania State Highway 851 in the rural area of Delta, PA in Southeastern Pennsylvania. The roadway contained several horizontal curves that were ideal for simulation of the peripheral transverse lines due to the severity of the curves. The horizontal and vertical alignments were programmed into the simulator along with traffic control devices, structures, and vegetation as located in the study area. In the study area, four curves and two tangent sections were treated with peripheral transverse lines including four different design patterns. The scenario was driven in three separate runs, both eastbound and westbound. First, the participant drove both directions of the roadway under baseline conditions. Second, the participant drove both directions of the roadway with one set of experimental treatments. Finally, the participant drove both directions of the roadway with a second set of experimental treatments. These trials were performed as part of a larger experiment looking at the effectiveness of low-cost safety improvements on two-lane rural roads.

Research Participants

Research participants were recruited from the McLean, Virginia, area from a list of interested participants from previous Federal Highway Administration studies and by word of mouth. Each research participant possessed and showed a valid U.S. driver's license and passed a locally administered vision test. The criterion for passing the vision test is at least 20-40 visual acuity in each eye (corrected, if necessary). The parent study from which this study was performed focused on visibility enhancements to curves. The authors assume that although the magnitude of driver speed may vary by the age of drivers, the overall trends should not be different. Eighteen research participants were recruited. The eighteen research participants were divided into two age groups of 9 participants each: younger drivers (age 18 to 25 years) and older drivers (age 60 years and above). Limited demographic information (e.g., age, gender, city of residence, driving experience, health, etc.) were collected. Each participant read detailed written instructions on what was required of her/him in the experiment. The experiment was conducted in a dark laboratory environment in which the research participant was dark adapted to the environment for at least 15 minutes before driving in the simulator. Red photographic lighting that does not interfere with dark adaptation was provided for moving about the laboratory room.

Experimental Variables

Although many variables were collected for the entire laboratory investigation in the HDS, the current study involved the use of the following independent variables:

1. Direction of travel (Eastbound versus Westbound)
2. Presence of experimental marking (none, constant, exponential, 2 bps, 4 bps)
3. Length of curve on the simulated roadway
4. Length of tangent section on the simulated roadway
5. Regulatory and advisory speed limits for each segment
6. Age of the research participants: younger drivers (age 18 to 25 years) or older drivers (age 60 years and above)

Vehicle speed along the simulated roadway was the dependent variable in this study and was collected at a rate of approximately 30 Hz.

Experimental Design

The experimental design included six treatment sections, two directions, and five pavement marking alternatives (including a baseline condition) as within subject factors in which every participant was presented each level of those factors. The treatments were counterbalanced to the extent possible so that participants would see a variety of treatments on each test section, not necessarily the same treatment on every curve. However, a complete counterbalanced design was not possible due to design constraints of the driving simulator design for the remainder of a larger study as well as the fact that the roadway was driven as if it were actually in the field (i.e. each trial or roadway section could not be separated out to randomize the scenarios).

Pavement Marking Pattern Design

The treatment applied to the simulated roadway used 12 inch (30.5 cm) wide pavement markings extending 18 inches (45.7 cm) into the roadway perpendicular to the travel lane on both the left and right edges of the travel lane (see Figure 5-2). The constant and exponential spacing patterns were consistent with those used on the transverse bar spacings in the Godley et al study (3). The exponential pattern consisted of markings with decreased spacings between the markings through the treatment area, but did not have calculations based on initial and desired speed. The 2 bars per second and 4 bars per second patterns take into consideration vehicle final speed, vehicle initial speed, and a constant yet comfortable deceleration while taking into account the amount of roadway preceding the treatment area. The maximum deceleration as designed for this study was -6.8 ft/s^2 (-2.1 m/s^2) (approximately 0.2g) which in general would be considered a comfortable deceleration.

Roadway Parameters

The design used for the study is shown in Table 5-1. There were six different test sections including four curves and two tangents. Tangent 1 Eastbound concluded with a stop sign whereas Tangent 2 is a straight section with no advisory speed constraints (depicted by n/a in the table). The treatment used for each trial is shown in the table. Trial 1 was a baseline scenario with no treatments whereas Trial 2 and Trial 3 incorporated all four of the design alternatives. In the parent study from which this data was obtained, Trial 1 took place directly after a practice session at the beginning of the study on the first day whereas Trial 2 and Trial 3 were performed on the last day of three or four days in a six hour study.

Stimulus Generation

Stimulus generation is achieved in the HDS by means of a system of three projectors above the car cab and a wrap-around wide-angle screen in front of the car cab. Images of the roadway segments are projected on the curved screen. The horizontal field of view covers 120 degrees and the vertical field of view covers the entire windshield. The scenarios are presented and data are collected at a nominal update rate of 30 Hertz. The scenario scenes are rendered under nighttime lighting conditions, and a software headlight model generates dynamic headlight illumination of the scene. Examples of stimuli from the simulator are shown in Figure 5-1. The simulator car cab has limited motion consisting of three degrees of freedom: two rotational modes, pitch and roll, and one translational mode, heave (vertical motion). These movements are imparted to the simulator car cab by an electro-mechanical motion base controlled by appropriate vehicle dynamics software. The vehicle motion system employs both software and hardware safety clamps and interlocks to protect research participants from harm due to unexpected motion of the car cab. A sound system in the HDS laboratory generates engine and roadway sounds in the car cab.

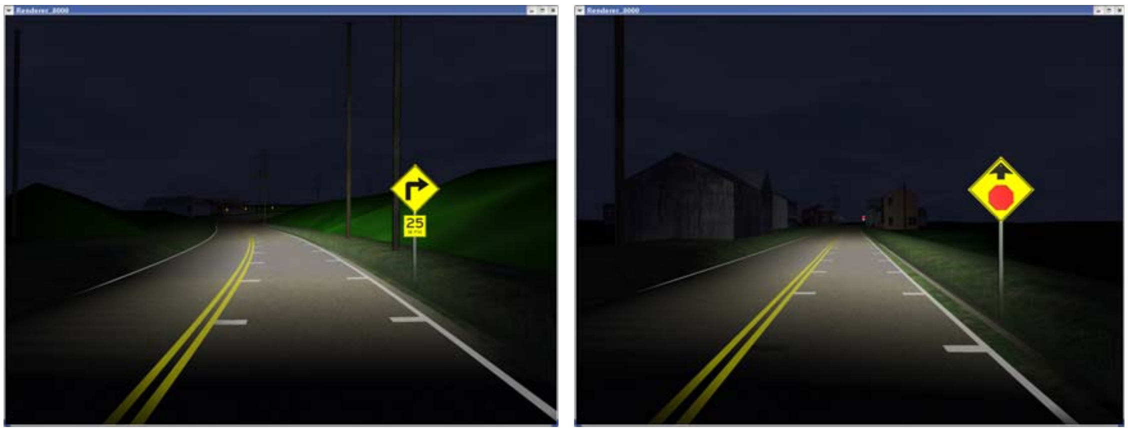

Figure 5-1: Screenshots of the Highway Driving Simulator on a curve section (left) and approach to a stop sign (right)

Data Analysis

Speed of the simulated vehicle was used to evaluate the impact of the alternative designs for the peripheral transverse line patterns. Driving speeds were collected continuously throughout the trial but the two critical points that were analyzed in this study are the speeds just prior to the marking treatment area and the speeds at the end of the marking treatment area. The various design alternatives were compared for their relative effectiveness in reducing vehicle speeds. Additionally, the lane positions at points both before the treatment and at the end of the treatment were analyzed to determine whether the pavement marking treatments reduced encroachment toward the centerline. The authors recognize that driving behavior in the simulator is different from actual driving behavior in the field. However, it is assumed that since the patterns were found to be effective in the field, the relative differences between treatments in the simulator can demonstrate the most effective treatments.

The statistical analysis for the experiment was directed at determining relative effectiveness between pavement marking treatments on both speed and lane position. Parametric statistical techniques were employed with an alpha significance level of $p = 0.05$. The statistical analysis utilized Repeated Measures analyses using a General Linear Model as employed by the software package SPSS. Post-hoc comparisons were employed to investigate specific effects as needed.

Table 5-1: Experimental Treatment Design

Section	Direction	Initial Speed mi/h (m/s)	Final Speed mi/h (m/s)	Trial 1	Trial 2	Trial 3	Simulator Distance (m)	Curve Radius (m)
Tangent 1	East West	45 (20) 45 (20)	0 (0) 35 (16)	Baseline Baseline	Exponential 4 bps	Constant 2 bps	6100-7095	n/a
Curve 1	East West	40 (18) 40 (18)	20 (9) 30 (13)	Baseline Baseline	Constant Constant	2 bps 2 bps	7350-7558	43
Curve 2	East West	40 (18) 40 (18)	30 (13) 20 (9)	Baseline Baseline	Constant 4 bps	4 bps 2 bps	7835-7963	232
Curve 3	East West	40 (18) 40 (18)	15 (7) 15 (7)	Baseline Baseline	2 bps 2 bps	Constant 4 bps	8125-8217	31
Tangent 2	East West	n/a n/a	n/a n/a	Baseline Baseline	Constant Exponential	Baseline Baseline	8400-8750	n/a
Curve 4	East West	40 (18) 40 (18)	25 (11) 25 (11)	Baseline Baseline	4 bps 4 bps	Constant 2 bps	8980-9065	86

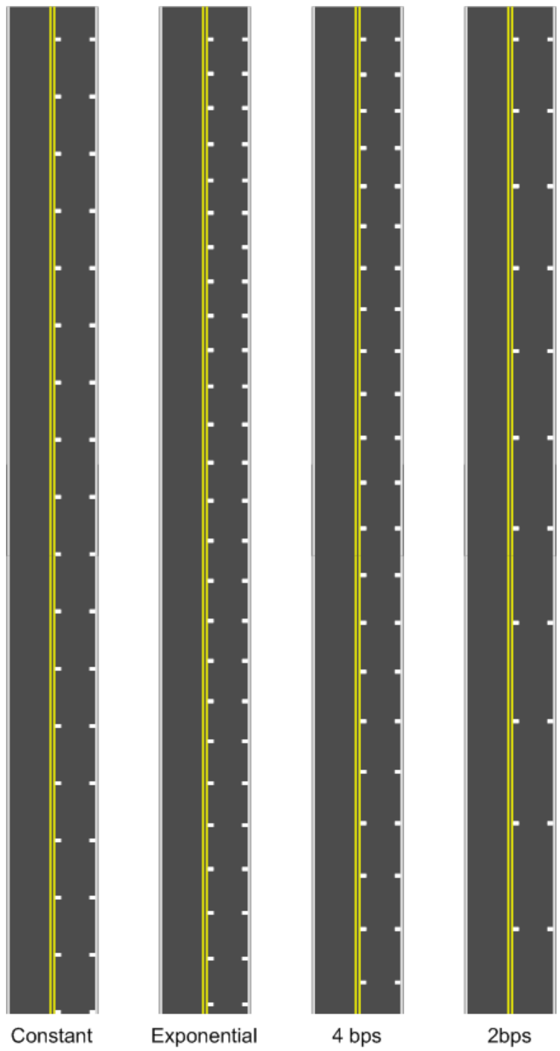

Figure 5-2: Examples of the peripheral transverse marking patterns

Results

Determination of Validity of Baseline Conditions

The simulator study was designed purposefully to have two baseline conditions. The first baseline condition was an overall baseline (with no treatments) and is referred to as Trial 1. The second set of baseline conditions were placed in the middle of Trial 3 on Tangent 2 to allow for analysis in the event that the initial baseline conditions vary from the results later on in the simulator study. As stated previously, Trial 1 was driven by the participants just after the practice trials and thus it is important to first determine whether Trial 1 will provide for an effective baseline condition. To do this, simulated vehicle speeds in Trial 1 were compared with the Baseline tangents used in Trial 3 on Tangent 2, both Eastbound and Westbound. The results showed that even without a treatment in place, the vehicle speeds were significantly different (p=0.001) and thus the baseline Trial 1 was not used in the remainder of the analyses. This significant difference indicated that there may have been some type of experience effect for research participants driving the simulator which caused them to be comfortable driving faster near the end of the study compared to the beginning.

Although the Trial 1 proposed baseline condition data were not useable, the simulator data were still appropriate to determine the effects between various treatments. It is important to recognize that previous research (2) indicated that peripheral transverse markings did have an effect in the field and assuming this, the simulator data could still provide useful information on the relative merits of alternative treatments.

Analysis of Vehicle Speed Data

Analysis of Speed Reduction

The simulated road segment used in this study consisted of two tangent sections and four curve sections that were given various treatments. Table 5-2 depicts the results of the analysis of speed reductions for each treatment. Condition 1 refers to the roadway condition that was experienced by the participant during the first run and Condition 2 refers to the roadway condition that was experienced on the second run. In each run, the driver drove both Eastbound and Westbound. Thus, for each roadway segment, there were four trials on each section (one in each of the two directions of travel and two repetitions for a total of four runs).

The percent reduction refers to the reduction in speed between the data point collected just prior to the roadway segment (before the marking pattern) and the data point collected at the end of the marking pattern. A negative value indicates an increase in speed which did occur on two of the roadway segments. Although there were some significant reductions in speed, the repeated measures analysis yielded only two cases where there were significant differences in reduction. One occurred on Tangent 2 when comparing the exponential marking pattern compared with the baseline pattern (p=0.02) and the other was on Curve 4 where the Constant spacing resulted in a larger speed reduction than 4 bars per second (p=0.01).

Table 5-2: Speed Reduction by Treatment Condition

Section	Direction	Condition 1	Percent Reduction	Condition 2	Percent Reduction	Significance
Tangent 1	East	Exponential	1.6%	Constant	2.9%	0.51
	West	4 bps	14.0%	2 bps	13.8%	0.65
Curve 1	East	Constant	19.7%	2 bps	19.3%	0.92
	West	Constant	74.2%	2 bps	71.6%	0.50
Curve 2	East	Constant	10.4%	4 bps	7.8%	0.28
	West	4 bps	13.4%	2 bps	9.9%	0.31
Curve 3	East	2 bps	30.3%	Constant	28.3%	0.51
	West	2 bps	-18.4%	4 bps	-12.0%	0.28
Tangent 2	East	Constant	-21.1%	Baseline	-20.2%	0.82
	West	***Exponential***	23.7%	***Baseline***	12.6%	***0.02***
Curve 4	East	***4 bps***	10.8%	***Constant***	17.1%	***0.01***
	West	4 bps	4.2%	2 bps	2.2%	0.40

NOTE: Values in bold and italics are significant at the α=0.05 level.

Although some significant differences were observed, there were several conflicts within the results when looking at cases in which the results were not significantly different. For example, although the constant spacing and 4 bars per second case were significant on the Westbound Curve 4, they were not significant on the Eastbound direction of Curve 2. Consequently, the results demonstrate that conclusions cannot be drawn as to whether a certain marking pattern will result in a larger reduction in speed over another marking pattern.

Analysis of Speed at End of Treatment

There are several appropriate methods to analyze the effect of the peripheral lines on speed. The first, as demonstrated above, is to look at the overall reductions in speed from the initial speed. The one flaw in the logic is that if drivers are traveling slower upstream due to other changes in previous treatment sections, the reduction in speed may have an effect on the following section. The overall goal of the markings is to have the vehicle speed at the end of the marking section equal the desired speed that the markings are set to achieve. This speed might be a design speed for a curve or a speed reduction on a tangent section leading to an intersection or small town where a reduced speed is required. This analysis investigated whether the final speed of the vehicle in the marking section is within a 95 percent confidence interval of the desired speed.

Table 5-3 shows the final speed by roadway section and condition. The final design speed indicates the speed that was used in the design of the markings. Tangent 2 shows a final speed of “n/a” (not applicable) for two reasons. First, the constant and exponential pavement marking design patterns do not vary based on speed and thus are not intended to be used with a design speed in mind. Additionally, the tangent section did not have any geometric constraints to require drivers to reduce speed, thus the only appropriate measure on this segment is overall speed reduction and not final speed.

The first observation that stands out when analyzing the data is that the speed variability was significantly high. All of the final desired speeds lied within the 95% confidence interval of the actual speeds, but that is only caused by the high level of variability in the speed measurements. The only exception was on Tangent 1 Eastbound on the approach to the stop sign where the final speed was not zero. The drivers were assumed to be traveling very slowly at the end of the treatment which was just prior to the stop bar. Thus the final desired speed at the stop bar was zero, but at the end of the treatment, it should be close to zero, not necessarily zero. The final speeds indicated that drivers most likely stopped farther ahead of the stop bar, closer to the actual intersection. In all other cases though, the final desired speed was within the confidence interval of the actual speeds.

Table 5-3: Final Speed by Section and Condition

Section	Direction	Final Desired Speed (m/s)	Condition 1	Condition 1 Final Speed (m/s)	Condition 1 Standard Deviation	Condition 1 95% Confidence Interval (m/s)	Condition 2	Condition 2 Final Speed (m/s)	Condition 2 Standard Deviation	Condition 2 95% Confidence Interval (m/s)
Tangent 1	East	0	Exponential	5.48	1.61	2.31-8.65	Constant	6.03	1.94	2.21-9.85
	West	16	4 bps	17.68	3.08	11.61-23.75	2 bps	18.18	2.92	12.43-23.93
Curve 1	East	9	Constant	13.24	3.29	6.76-19.72	2 bps	13.36	3.26	6.94-19.78
	West	13	Constant	13.34	3.09	7.25-19.43	2 bps	14.02	3.39	7.34-20.70
Curve 2	East	13	Constant	15.97	3.32	9.43-22.51	4 bps	17.03	3.69	9.76-24.30
	West	9	4 bps	10.21	3.06	4.18-16.24	2 bps	10.60	3.29	4.12-17.08
Curve 3	East	7	2 bps	11.33	2.66	6.09-16.57	Constant	11.79	2.93	6.02-17.56
	West	7	2 bps	11.08	3.83	3.53-18.63	4 bps	10.53	3.71	3.22-17.84
Tangent 2	East	n/a	Constant	16.68	3.03	10.71-22.65	Baseline	17.88	2.50	12.96-22.81
	West	n/a	Exponential	13.97	3.69	6.70-21.24	Baseline	15.94	4.04	7.98-23.90
Curve 4	East	11	4 bps	15.00	3.32	8.46-21.54	Constant	14.98	3.66	7.77-22.19
	West	11	4 bps	13.90	2.53	8.92-18.88	2 bps	14.14	3.03	8.17-20.11

Analysis of Lane Position

The next analysis involved the determination of a change in mean lane position due to the peripheral markings. It was hypothesized that a marking that was adjacent to the center line and edge line from both sides would visually reduce the width of the roadway and would result in drivers being more apt to center their vehicle in the travel lane. In this case, the lane position was calculated to be the distance between the left side of the vehicle and the center line. Table 5-4 shows the mean lane position by treatment both in advance of the treatment as well as inside the treatment area (at the end of the treatment). In the case of 2 bars per second and 4 bars per second, the mean lane position was significantly further away from the centerline. However, the results also showed that for the constant spacing treatment, the vehicles traveled significantly closer to the centerline (by 6 centimeters). It is important however to recognize that the differences in the significant means are between 6 centimeters and 17 centimeters. The width of the pavement marking was 46 centimeters, so the drivers still did not appear to avoid driving over the pavement markings; however, they may have caused the driver to move slightly more to the center of the road, particularly in the 2 bars per second and 4 bars per second designs.

Table 5-4: Mean Lane Position by Treatment

Condition	Mean Lane Position Prior to Treatment (cm)	Mean Lane Position In Treatment Area (cm)	Significance
2 Bars per Second	90	107	***<0.001***
4 Bars per Second	99	112	***<0.001***
Constant Spacing	111	105	***0.004***
Exponential Spacing	97	98	0.657

NOTE: Values in bold and italics are significant at the α=0.05 level.

Discussion of Variability in Simulator Results

There are several factors that may explain the results. First, there were only eighteen participants recruited for the experiment. The parent study from which the data were collected in this study was a psychophysical study with a corresponding field study that investigated the required brightness of longitudinal pavement markings. The required participant size for the study was only eighteen and additionally, the simulator was calibrated with scale factors based on field conditions. However, when looking at the very small changes in reduction in many cases where the p-values did not even come close to approaching significance, it may be concluded that participant size is not the overriding element resulting in the inconsistent results.

Second and perhaps more probable, drivers may not be getting the same exact sensations in the driving simulator that would be experienced in the field. In the parent study, it was determined that the variability in the simulator was much higher than the variability in the field (4) with the same number of participants. The results showed that for lane excursion, participants in the simulator portion of the study were thirteen times more likely than in the corresponding field study to traverse over the center line. Additionally, on average, the variability of speed ranges was 11 miles per hour (5 meters per second) higher in the simulator than in the field. This variability of 5 meters per second would count for an extremely large portion of the variability in the current study.

Conclusions and Recommendations

Four different alternative design patterns for peripheral transverse lines were evaluated (2 bars per second, 4 bars per second, constant, and exponential). The first step in the analysis was to test the validity of the baseline condition. In the parent study in which this investigation was conducted, each participant drove in the simulator for six hours over three or four days. The original baseline was conducted on the first day in the first run without treatments to correspond with the original field study. Although the design would have been more rigorous if the scheduling of the baseline trial was varied, the field conditions do not allow for a fully balanced design due to the required changes of pavement markings between participant trials. For example, if paint is applied to curves on the second day, it was not practical to remove the paint for participants on the fourth day. An additional baseline was maintained in one location on the current study to test for differences between the baselines. The speeds were found to be significantly different and thus the decision was made to not include the original baseline condition for comparison.

The second step in the analysis was to observe the effects of speed reduction between a segment just prior to the treatment and a location at the end of each treatment area. The results showed that there were no overall significant differences between the different treatments. Additional research may be useful in showing the speed profile of vehicles to determine whether the markings have an effect on vehicle speeds within each pavement marking treatment section. Additionally, a field study similar to the previous study (2) with more treatments at more locations may help to determine the effects of various marking pattern designs. The third portion of the analysis investigated vehicle speeds at the end of the treatment area to see if they had reached the desired speeds. In all cases where a reduction was required without stopping, the observed speeds were within a 95% confidence interval of the desired speeds. However, there was a large amount of variability that made the results insignificant.

An analysis of lane position was performed, and for the two bars per second and four bars per second design alternatives, the driver did travel significantly further away from the centerline. Additional research in the field may have a greater impact in showing the magnitude of the effect as well as possible safety implications in reducing crashes on two lane roads. The overall lesson learned in this study is that although the simulator can be a useful tool for evaluating speed and lane position, scale factors are required and the variability is significantly higher in the simulator than in the field. The previous study (2) showed that markings placed at 4 bars per second did result in a reduction in speed in the field. Therefore, a logical next step would be to perform additional field studies with goals similar to this simulator study to look at differences between design patterns in the field and to determine the magnitude of these differences.

Acknowledgements

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CHAPTER 6:

DETERMINATION OF EFFECTIVE DESIGN OF PERIPHERAL TRANSVERSE BARS TO REDUCE VEHICLE SPEEDS ON A CONTROLLED ROADWAY

To Be Submitted for Publication

DETERMINATION OF EFFECTIVE DESIGN OF PERIPHERAL TRANSVERSE BARS TO REDUCE VEHICLE SPEEDS ON A CONTROLLED ROADWAY

Authors:

Bryan J. Katz
Science Applications International Corporation
6300 Georgetown Pike, F-215 McLean, VA 22101
Phone: (202) 493-3388 Fax: (202) 493-3390
E-mail: Bryan.Katz@fhwa.dot.gov

Hesham A. Rakha
Virginia Polytechnic Institute and State University
301 Patton Hall Blacksburg, VA 24061
Phone: (540) 231-1505 Fax: (540) 231-7532
E-mail: hrakha@vt.edu

Abstract

Speeding is considered to be a contributing factor in crashes and therefore is a very important safety issue. Because higher vehicle speeds result in more severe crashes, if vehicle speeds can be reduced in dangerous road sections, then presumably safety can be improved. One speed reduction method that has shown promise in past research is to use pavement marking patterns to give drivers the perception that they are traveling faster than they really are. This illusion is created by making the travel lanes appear narrow or adding optical patterns to the roadway surface.

Previous research focused on using markings spaced at a frequency of four bars per second to reduce vehicle speeds in New York, Mississippi, and Texas with positive effects. There was a decrease in overall vehicle speeds on approaches to curves when analyzing all vehicles as well as specific classifications of vehicles. A driving simulator study was also performed to look at four different spacing patterns: constant, exponential, two bars per second, and four bars per second. However, the variability of driving speeds in the simulator was high and thus no conclusive evidence was made to support the idea that any marking pattern would perform more effectively.

The research effort described in this paper builds upon the previous two studies by investigating the optimal spacing pattern for peripheral transverse bars to reduce vehicle speeds in a controlled environment on the Virginia Tech Smart Road. Marking spacing patterns of two bars per second and four bars per second were applied to the roadway and compared to baseline conditions with no treatment applied. The primary measures that were investigated include: change in vehicle speed, vehicle speed profile with respect to distance, and brake pedal position with respect to distance. The results showed that the roadway geometry has a major effect on whether or not the pavement marking a marking spacing is effective. The treatment applied on the approach to a curve resembling a freeway exit ramp did have a 42% reduction in speed when a 4 bars per second pavement marking design was applied compared to the baseline.

Introduction

In the United States, speeding is considered to be a contributing factor in about 30 percent of fatal crashes (1). In an attempt to reduce speeds on roadway segments where speed is considered to be a safety concern, various pavement marking patterns that create the appearance of narrowing and/or increasing speed have been considered as a relatively low-cost countermeasure. Perceptual countermeasures are one potential method of influencing motorists to slow down, and ultimately, may save lives. These perceptual techniques might be useful at lowering speeds in a variety of driving situations such as work zones, curves, roundabouts, and toll plazas.

There has been some limited research in the past few years dealing with the application of perceptual countermeasures. One perceptual countermeasure that has been applied in the past few years is peripheral transverse bars to reduce vehicle speeds. Although evaluations have been performed to determine their effectiveness, there hasn't been a successful evaluation of appropriate design spacing requirements. Therefore, the goals of this study are to:

- Determine two potential pavement marking design spacings for evaluation,
- Apply these pavement markings in a controlled roadway environment,
- Evaluate the effectiveness of the markings using research participants, and
- Provide recommendations for marking spacing design for future implementations of the pavement markings.

Previous Research

Both longitudinal as well as transverse pavement markings have been used to influence drivers' perceptions of their roadway environment. Longitudinal markings consist of either centerlines or edge lines and can be used to reduce lane widths. Research performed by Yagar and Van Aerde (2) found a reduction in speed as lane width decreases. However, several studies (3, 4) did not show any decrease in speeds when lane widths were decreased using pavement markings. Both studies only investigated the effects of using pavement markings alone to reduce speed without any forms of hatching or other markings on the shoulder which may have contributed to that outcome. Another study by Retting et al. (5) looked into the effects of markings used to narrow freeway exit ramps in reducing vehicle speeds. Results indicated that the added markings were effective in reducing speeds by approximately 1 mi/h (1.6 km/h) on average, but the study used diagonal lines next to the edge lines rather than simply edge lines alone.

Transverse pavement markings, a series of lines or bars (typically white) which are perpendicular to the path of travel and are placed across the road like rumble strips, are the most commonly used form of pavement markings in speed reduction. Transverse pavement markings typically take the form of either transverse bars or transverse chevrons and are placed closer to each other to give the perception that the driver is speeding up as a driver drives down the roadway. In a Kansas study (6), transverse bars were placed in a work zone in which three patterns were used. The first pattern was a "leading pattern" with constant widths and constant spacing to warn drivers of the upcoming work zone. The second pattern or "primary pattern" consisted of bars with varying widths and varying distances which led up to the work zone. The actual "work zone pattern" consisted of four sets of six bars spaced every 500 feet (153 meters). The results showed a decrease in speeds at a 95% confidence level; however, the magnitudes of the speed reductions were fairly small. An earlier study (7) was performed on a sharp curve with a high accident rate in Kentucky. In six years, there were 48 accidents at the location and speed was considered as a contributing factor in 36 of the 48 accidents. There was a reduction in speeds six months after the installation compared to before the installation; however, the long-term effects during daytime hours were much smaller than the long-term effects during nighttime hours (3 mi/h or 5 km/h for daytime and 7 mi/h or 11 km/h at nighttime).

A more recent study by Drakopoulas and Vergou (8) evaluated converging chevron pavement marking patterns in Wisconsin. These markings were placed on Interstate 94 on a freeway exit ramp at the Mitchell Interchange in Milwaukee, Wisconsin. The mean speed of the exit ramp was determined to be 70 mi/h (113 km/h) before the installation and 53 mi/h (85 km/h) twenty months after the installation for an overall reduction of 17 mi/h (27 km/h).

Another study by Godley, Triggs, and Fildes (9) evaluated transverse lines as well as peripheral transverse lines versus a control section of roadway in a driving simulator. Transverse lines are stripes that are placed across the entire travel lane whereas the peripheral transverse lines are placed only on the edges of the travel lane. The study showed that driving speeds were only slower for the transverse lines (as compared to the peripheral transverse lines) for the initial section of treatment but that overall, the peripheral lines performed the same and in some cases better than the regular transverse lines at the beginning of the treatment area where the mean speed of transverse lines was 92 km/h or 57 mi/h and the mean speed of the peripheral transverse lines was 98 km/h or 61 mi/h at the beginning of the treatment

More recently, a study by Katz, Duke, and Rakha (10) evaluated peripheral transverse lines spaced at a frequency of 4 bars per second in New York, Mississippi, and Texas. The markings were applied on approaches to curves in both rural and urban environments on both multi-lane and two-lane roadways. The authors concluded that overall, the pavement markings reduced the adjusted speeds up to 9.5 mi/h (15.3 km/h) on overall vehicle speeds when comparing total vehicles, two axle vehicles, vehicles with more than two axles, and particularly with vehicles following further than four seconds behind the previous vehicle.

A follow-up study was performed by Katz, Molino, and Rakha (11) to investigate design alternatives for peripheral transverse lines to reduce speeds and reduce center line encroachment. The simulator compared baseline conditions to markings spaced at a constant interval, exponentially closer, at two bars per second, and at four bars per second. The peripheral transverse lines were effective in reducing centerline encroachment; however, the results were inconclusive as to which particular marking spacing pattern was most effective. There was a large amount of variability in driving speeds using the driving simulator which made it ineffective at comparing designs.

Research Method

The underlying approach to this study involved first, the determination of pavement marking spacing designs to evaluate. Once the markings were chosen, the markings were placed on the Virginia Tech Smart Road, a controlled test bed for performing research on research participants without the presence of other vehicles. Research participants were asked to drive the roadway which involved traveling over the marking patterns on the approaches to curves. The data were then analyzed to determine the effects of the marking patterns on vehicle speed.

Determination of Pavement Marking Spacing Designs

The research for this study took place in a controlled research environment using human subjects. Therefore, it would have been nearly impossible to test all variations of pavement marking patterns without significantly increasing the number of participants needed for the study. It was determined that two marking spacing patterns would be evaluated. The previous field research study (10) used a marking spacing pattern with a frequency of four bars per second and showed to have an effect on reducing speeds in the field. A frequency of two bars per second is easy to apply in a test environment since the markings would be placed in the same location of the four bars per second pattern but would only occur half as often. Therefore it was determined to test marking patterns with a frequency of two bars per second and four bars per second for thus study.

Research Facility

The test bed that was used for this study was located at the Virginia Department of Transportation's Smart Road facility, located at the Virginia Tech Transportation Institute (VTTI) in Blacksburg, Virginia. The Smart Road is a state-of-the-art facility built for full-scale research and evaluation of pavement and ITS systems, technologies, and products. The Smart Road is a 2.2 mile (3.5 kilometer) private highway that is limited to test vehicles. The entire length of the Smart Road was used for the data collection and includes curves at both ends of the roadway. The horizontal alignment in between the curves at the ends is fairly straight, and the vertical profile of this segment is a 3 percent slope.

A real-time Data Acquisition System (DAS) was installed in the Cadillac test vehicle which was concealed from the driver's view, in the car trunk. This DAS was developed and built by the Center for Technology Development at the Virginia Tech Transportation

Institute (VTTI) for collecting data for experiments such as this one. A notebook computer was connected to the DAS which controlled the sequence of test runs. The DAS is capable of collecting data at 0.1 s intervals. Among the almost 80 data streams recorded in real time, the proposed research will use the following data: longitudinal distance on the roadway, vehicle speed, and brake pedal position.

Pavement Marking Placement

Markings were placed on curves at both ends of the Smart Road. The treatment applied to the simulated roadway used 12 inch (30.5 cm) wide pavement markings extending 18 inches (45.7 cm) into the roadway perpendicular to the travel lane on both the left and right edges of the travel lane. On one end, the road terminates in a small cul-de-sac type of loop with a low design speed whereas on the other end, the road terminates on a freeway-style ramp that accommodates for faster traffic. The markings were designed to decrease speeds from 45 mi/h (72 km/h) to 35 mi/h (56 km/h) at a deceleration of 3.3 ft/s^2 (1.0 m/s^2) on the ramp and decrease speeds from 45 mi/h (72 km/h) to 25 mi/h (40 km/h) at a deceleration of 6.6 ft/s^2 (2.0 m/s^2) on the small loop. There were three conditions tested. The first condition was a baseline condition with no markings applied. The baseline condition in essence shows the effect of the curve alone on speed. The second condition was a treatment condition where markings were placed at 4 bars per second on the ramp and 2 bars per second on the small loop. The third condition was also a treatment condition where the treatments were reversed and the markings were placed at 2 bars per second on the ramp and 4 bars per second on the small loop. In both locations, two lead up bars were added across the travel lane to attract drivers' attention to the upcoming peripheral transverse markings. The markings were 9 feet (2.7 meters) long and 1 foot (30 centimeters) wide. The spacing of these markings was the same as the distance between the first two peripheral transverse lines at the beginning of the treatment area.

Research Participants

There were 26 participants originally recruited for this study. Of these 26, only 24 had valid data due to data errors. There were 13 females and 11 males ranging in age from 22 to 67 with a median age of 49. Participants consisted of licensed drivers who lived in the Blacksburg, Virginia area. These drivers were registered in a volunteer database maintained by VTTI. A vision test was administered to ensure that vision acuity was within the legal driving limit (corrected to 20/40). Participants were participating in another study on intersection safety at the Smart Road and once the data collection was completed, the participants were asked to drive the entire length of the road for the subject study. The participants were not told the purpose of the study and were simply instructed to drive the Smart Road as they would drive normally with a maximum speed of 45 mi/h (72 km/h). This deception was necessary to gain information on how people initially react to the markings.

Figure 6-1: Peripheral transverse bars applied to the Smart Road at the ramp (left) and at the small loop (right)

Data Analysis

Speed of the instrumented vehicle was used to evaluate the impact of the alternative designs for the peripheral transverse line patterns. Driving speeds were collected continuously throughout the trial but the two critical points that were analyzed in this study are the speeds 500 feet (152 meters) prior to the marking treatment area and the speeds at the end of the marking treatment area. The two design alternatives were compared for their relative effectiveness in reducing vehicle speeds. Additionally, the speed profiles and brake pedal position profiles were analyzed through the entire treatment area to determine overall driver behavior effects related to deceleration in the treatment area and not just at the onset of the curve itself.

The statistical analysis for the experiment was directed at determining relative effectiveness between pavement marking treatments on speed. Parametric statistical techniques were employed with an alpha significance level of $p = 0.05$. The statistical method used Repeated Measures analyses using a General Linear Model as employed by the software package SPSS. Post-hoc comparisons were employed to investigate specific effects as needed.

Results

Analysis of Driver Speed by Condition

Two curves were used in the analysis, one of which was an interstate-style ramp (hereafter referred to as Location 1) and the other as a small loop used as a turn around (hereafter referred to as Location 2). Both had very different characteristics one being that the small loop has an extremely long preview distance. Therefore, driver expectation of the navigation requirements is much different from a sharp curve in most situations, as illustrated in Figure 6-1.

Table 6-1 shows the results of the speed reductions with respect to location. The upstream speed was taken at a control location 500 feet prior to the beginning of the marking pattern to get a comparison of speeds where the treatment would have no effect. The speed at the end of treatment was taken just prior to the start of the curve at the end of the treatment area. The speed reduction and percent reduction is the difference between the speed at the end of the treatment and the upstream speed.

Table 6-1: Mean Speed Reductions (in mi/h) by Location

Condition	Location 1: Treatment at Ramp			
	Upstream Speed	Speed at End of Treatment	Speed Reduction	Percent Reduction
Baseline	42.7	34.1	8.5	20%
2 Bars per Second	43.6	33.7	9.9	23%
4 Bars per Second	43.0	**30.8**	**12.3**	**28%**

Condition	Location 2: Treatment at Small Loop			
	Upstream Speed	Speed at End of Treatment	Speed Reduction	Percent Reduction
Baseline	43.9	30.8	13.1	30%
2 Bars per Second	43.6	28.4	15.2	35%
4 Bars per Second	43.6	31.4	12.2	28%

NOTE: Bold values indicate a significant difference from the baseline condition

Although there were decreases in speed, the reduction in speeds at Location 2 was not statistically significant compared to the baseline. However, the decrease in speed with the 4 bars per second condition at Location 1 was significantly different from the baseline condition ($p = 0.048$) and also significantly different from the 2 bars per second condition ($p = 0.030$).

Table 6-2 shows the percent of speed reduction compared to the baseline. For example, at Location 1 with the 4 bars per second condition, the decrease in speed was 45% ((12.3-8.5) / 8.5) greater than the reduction in the baseline condition (the condition in which the speed reduction was only due to geometry alone, not due to a treatment). Conversely, speeds increased by 2% at Location 2 with the 4 bars per second compared to the baseline (although the difference is not significant).

Table 6-2: Percent of Mean Speed Reduction Compared to the Baseline

Condition	Location 1	Location 2
2 Bars per Second	13%	17%
4 Bars per Second	42%	-6%

The results make sense when putting the treatments in context of actual driving situations. At Location 2, the driver can see the curve in the distance and thus there is no need for cues a reduce speed given that drivers can determine in advance the necessary speeds to travel the curve at a comfortable rate. Therefore this scenario is not an appropriate location for the treatment. On the contrary, at Location 1, the entire curve cannot be seen on the approach to the curve which would be typical for a driver to encounter in an actual field environment.

Analysis of Speed Profiles

An analysis was performed to look at the difference in speed profiles in advance of and along the treatment section. The profile is taken to be the average speed of all participants at any given point. The average speed profile by distance for Location 1 is shown in Figure 6-2 and the profile for Location 2 is shown in Figure 6-4. The plots can also be compared with the design speeds for each of the curves through the treatment area. At both Location 1 and Location 2, the change in speed designed was not attained; however, the magnitude of the final speed in Location 1 of the 4 bars per second treatment was less than that of the design speed. The 95th Percentile range for Locations 1 and 2 can be found in Figure 6-3 and Figure 6-8, respectively. For Location 1 in all three conditions, it is interesting to note that upstream of the intersection, the speeds are very close across all treatments, but as the driver approaches the treatment (signified by the vertical line in the chart), the speeds begin to deviate with the participants who were exposed to the 2 bar per second treatment driving slower than the baseline treatment and the participants exposed to the 4 bar per second treatment decelerating more rapidly than either the baseline or the 2 bar per second condition. The deviation occurred approximately 200 feet from the treatment, which would be approximately the distance away from the beginning of the treatment that the treatment would have appeared in a driver's view.

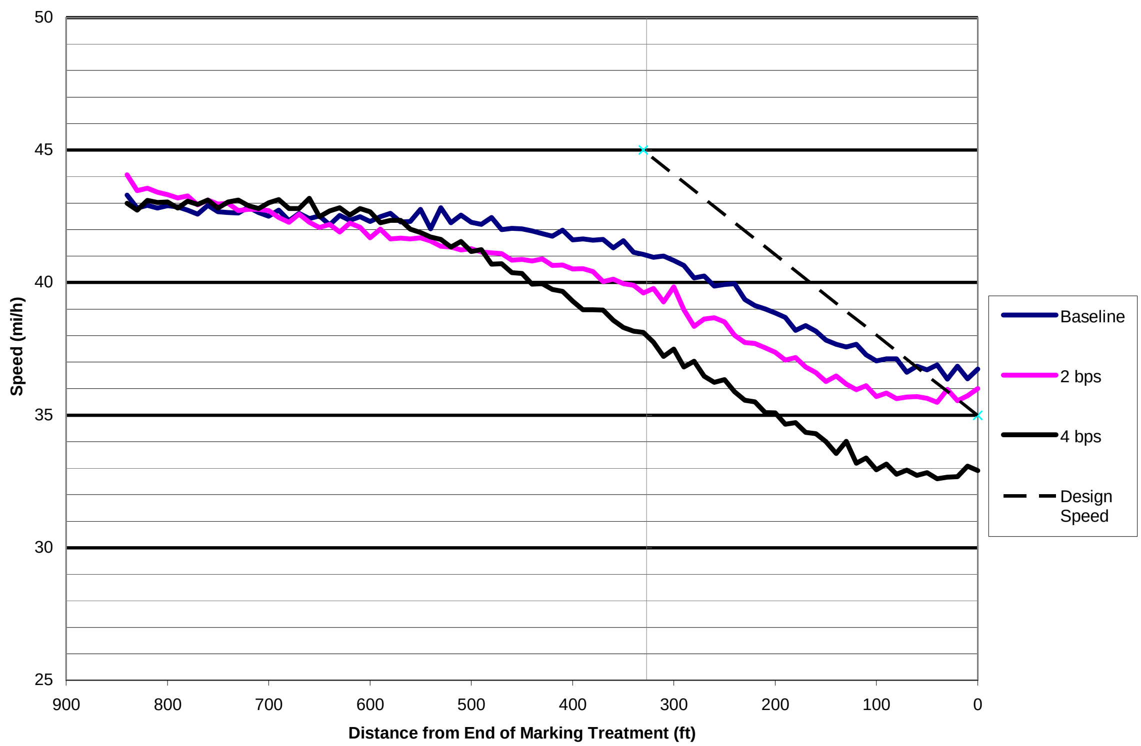

Figure 6-2: Average Speed Profile by Distance for Location 1

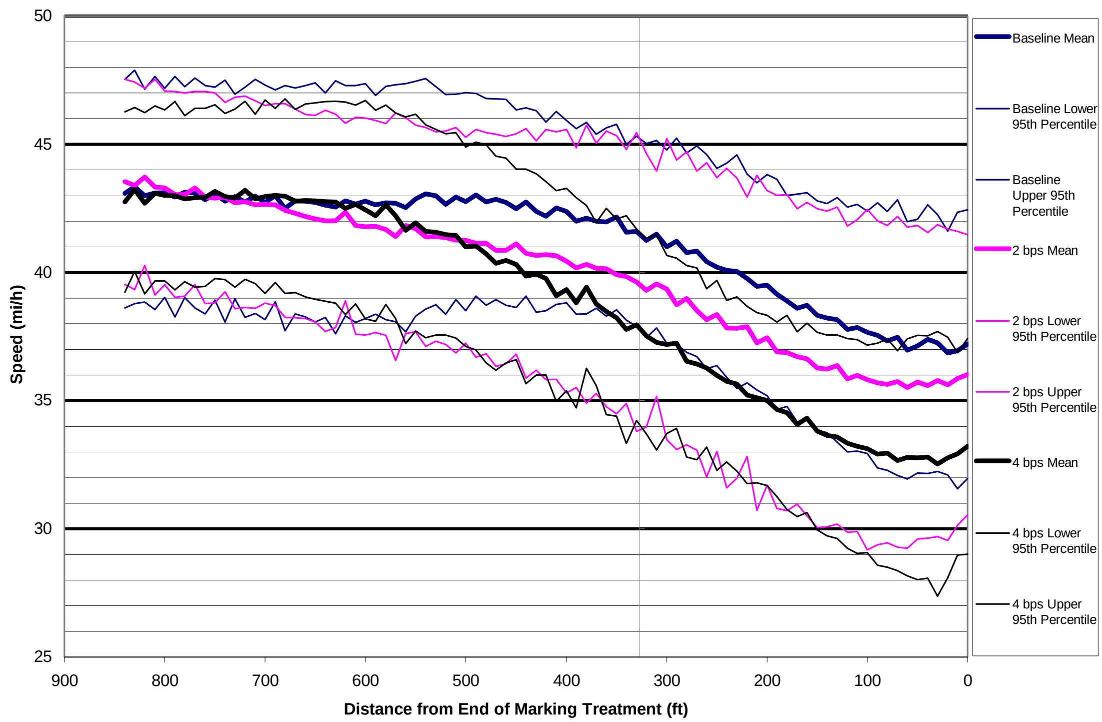

Figure 6-3: Mean and 95th Percentile Speed Profile by Distance for Location 1

At Location 2 where there were no effects of the pavement marking treatments, speeds are fairly similar across all treatments through the entire approach distance with a slight (but insignificant) reduction with the 2 bars per second condition. At this location, the curve can be seen from a significant distance (more than 800 feet from the end of the treatment), and thus driver behavior was not affected by the type of treatment.

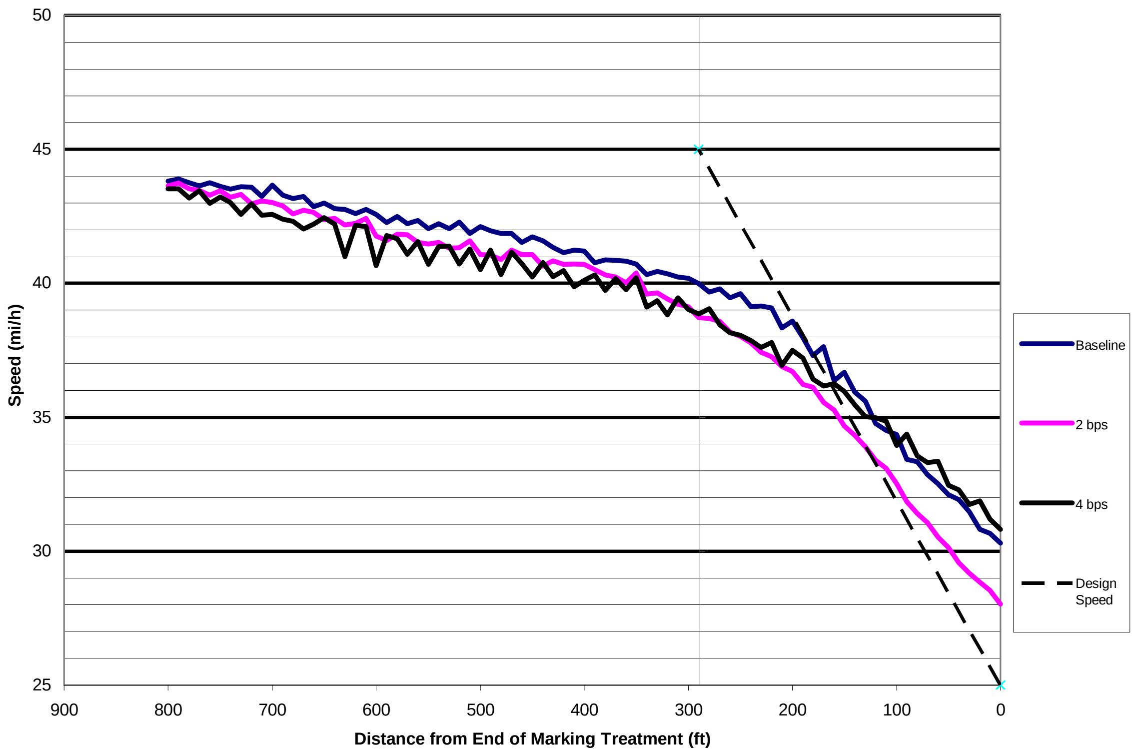

Figure 6-4: Average Speed Profile by Distance for Location 2

The overall assumption for deceleration on the approach to curves was that the deceleration was constant through the treatment area. On the upper ramp, the data were examined against a constant deceleration to determine whether the assumption was reasonable. The values for the ideal speed (given constant deceleration) at each distance were calculated and linear regression was performed to see how closely the mean values correlated with the ideal values. For the baseline condition, 4 bars per second treatment, and 2 bars per second treatment, the R^2 values were 0.953, 0.927, and 0.890, respectively. Therefore, the assumption the decelerations are constant was reasonable at this location.

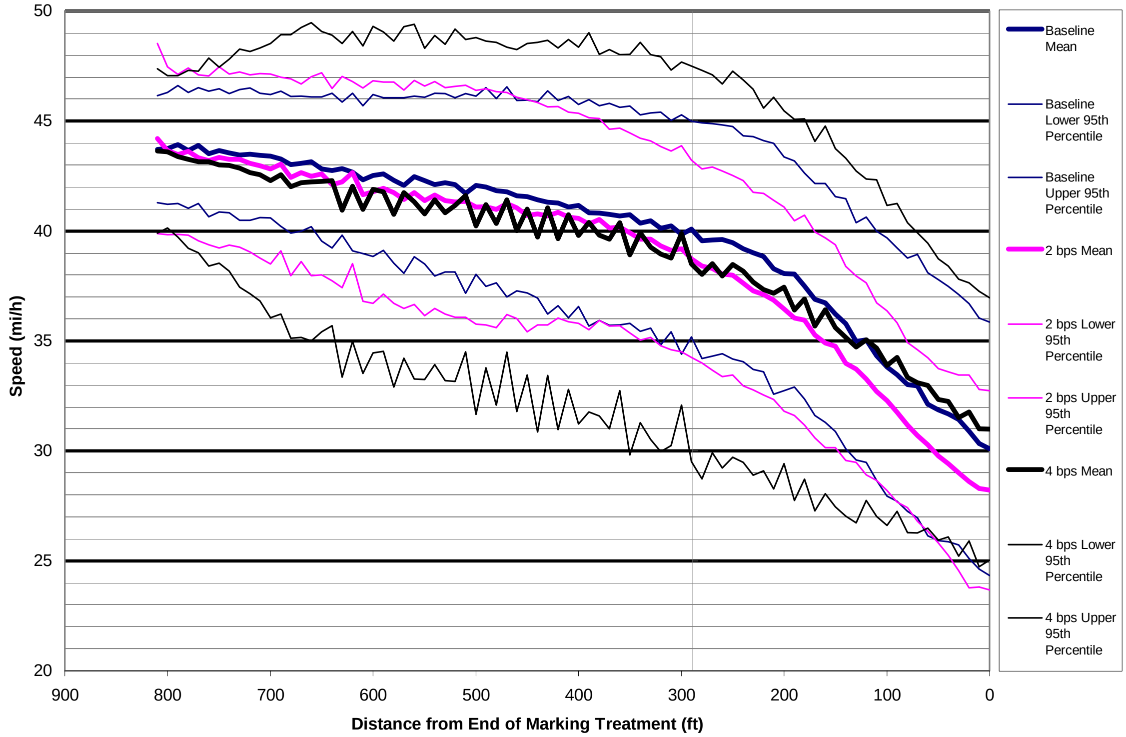

Figure 6-5: Mean and 95th Percentile Speed Profile by Distance for Location 2

An additional analysis performed using the driver speed profiles included looking at the acceleration noise which describes the smoothness of traffic flow for the distance leading up to and including the curve as shown in Figure 6-2 and Figure 6-4. For the upper ramp, acceleration noise was 6.1, 7.4, and 9.7 ft/s^2 and the lower loop resulted in noise values of 4.8, 6.8, and 6.7 ft/s^2 for the baseline, 2 bars per second, and 4 bars per second treatments, respectively. It is interesting to note that the noise was higher for the treatment sections compared to the baseline. A plot showing the cumulative plots for acceleration noise on the upper ramp and lower loops are shown in Figure 6-6 and Figure 6-7, respectively. For the upper ramp, the 4 bars per second treatment has slightly more variation whereas the baseline and 2 bars per second treatment have similar trends. For the lower loop, the 2 bars per second treatment and 4 bars per second treatments have more variation in acceleration noise than the baseline. A Kolmogorov-Smirnov test was performed on all the cumulative plots and due to the small sample size, there were no significant differences at the 0.05 level.

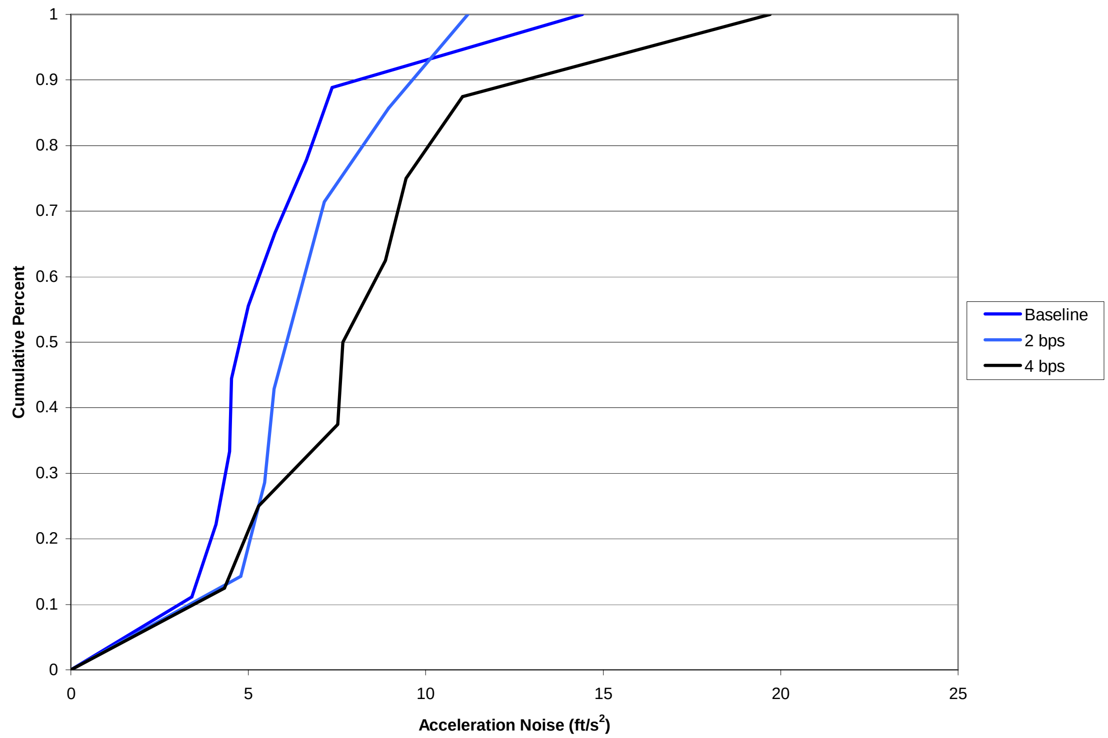

Figure 6-6: Cumulative Percentage of Acceleration Noise for Location 1

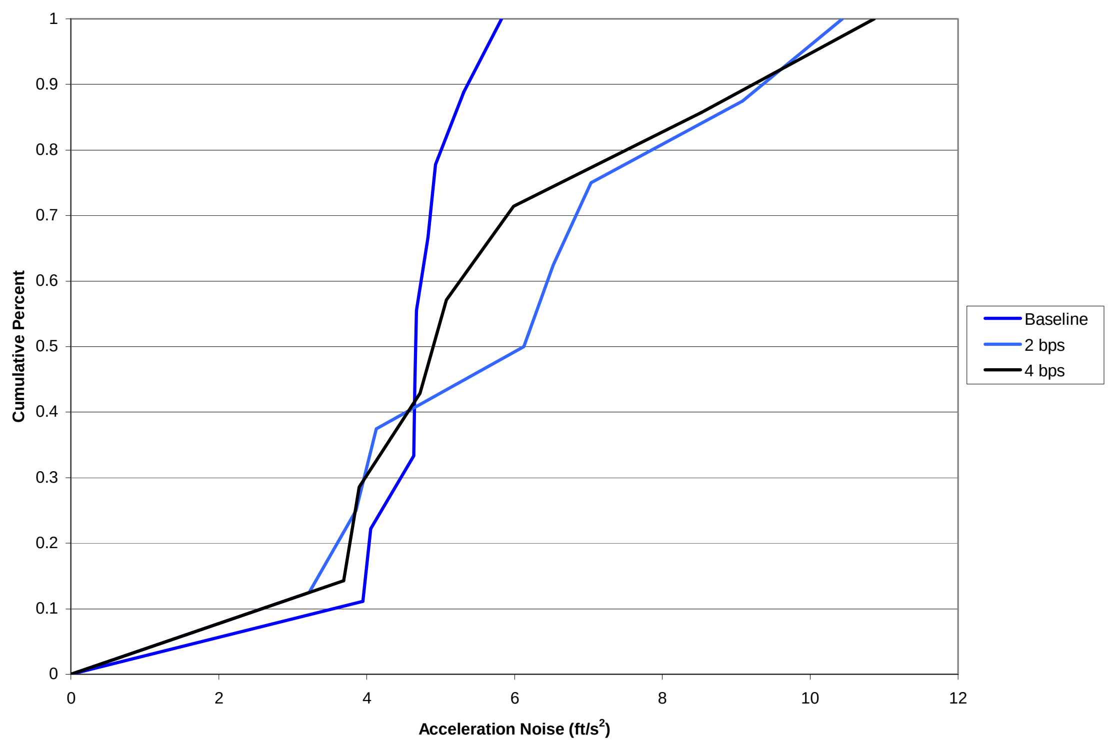

Figure 6-7: Cumulative Percentage of Acceleration Noise for Location 2

Analysis of Driver Braking Behavior

Driver braking data were also used to determine the impact of the pavement marking treatments on driver behavior. Brake pedal position by distance is shown for Location 1 in Figure 6-8 and for Location 2 in Figure 6-9. The results clearly show the impact that the markings have on driver braking. At Location 1, brake pedal position was constant among all groups up until approximately 600 feet prior to the curve which would be approximately the point in which drivers would begin to see the pavement marking treatment. At 600 feet, participants who were exposed to the 4 bars per second treatment began to brake, and in general, applied the brakes at a greater magnitude than the other conditions through the entire treatment area. The participants who did not experience any of the treatments did not begin to apply the brakes until approximately 500 feet prior to the curve. The participants who were exposed to the 2 bars per second treatment however, did not brake until 400 feet prior to the curve.

The results can be explained by the fact that pavement markings can have two main effects when placed in advance of a curve. On the one hand, a curve that is given more visibility through added pavement markings can cause drivers to travel faster because the driver is comfortable with the environment. On the other hand, pavement markings that give a clear meaning that an approaching curve is dangerous and does give adequate cues that a reduction in speed is required could result in a driver choosing to reduce speed in advance of the curve. At 4 bars per second, the intended message was more obvious to the driver and therefore caused a significant reduction in speed. It is therefore important to note that adequate spacing is required to have an effect if the desire is to have drivers apply the brake at a further distance from the curve.

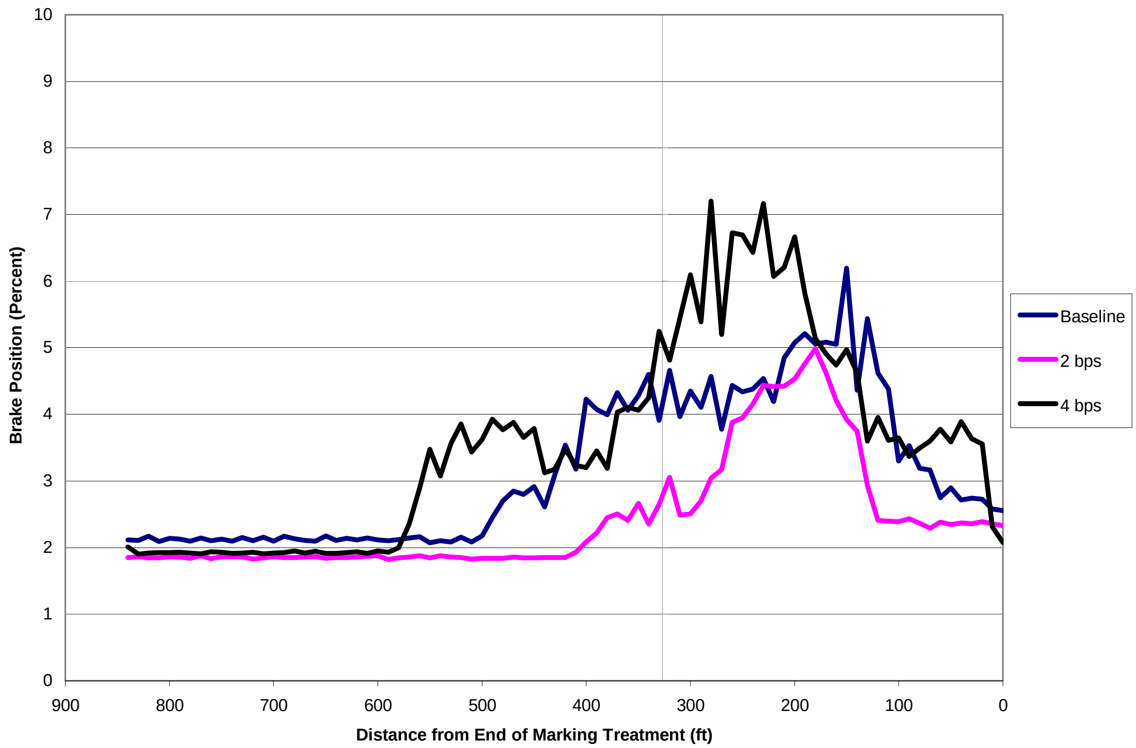

Figure 6-8: Brake Position by Distance for Location 1

As expected at Location 2, driver braking behavior was fairly erratic because the driver had an extremely large preview distance of the upcoming curve. The magnitude of the braking behavior is different between the two locations because Location 1 was located on an incline whereas Location 2 was located on a decline, thus the percent of braking required to slow the vehicle was much higher for Location 2. It is interesting to note however, that participants who were exposed to the 4 bars per second markings were likely to begin to apply the brakes early and the magnitude of the braking was less while inside the treatment area.

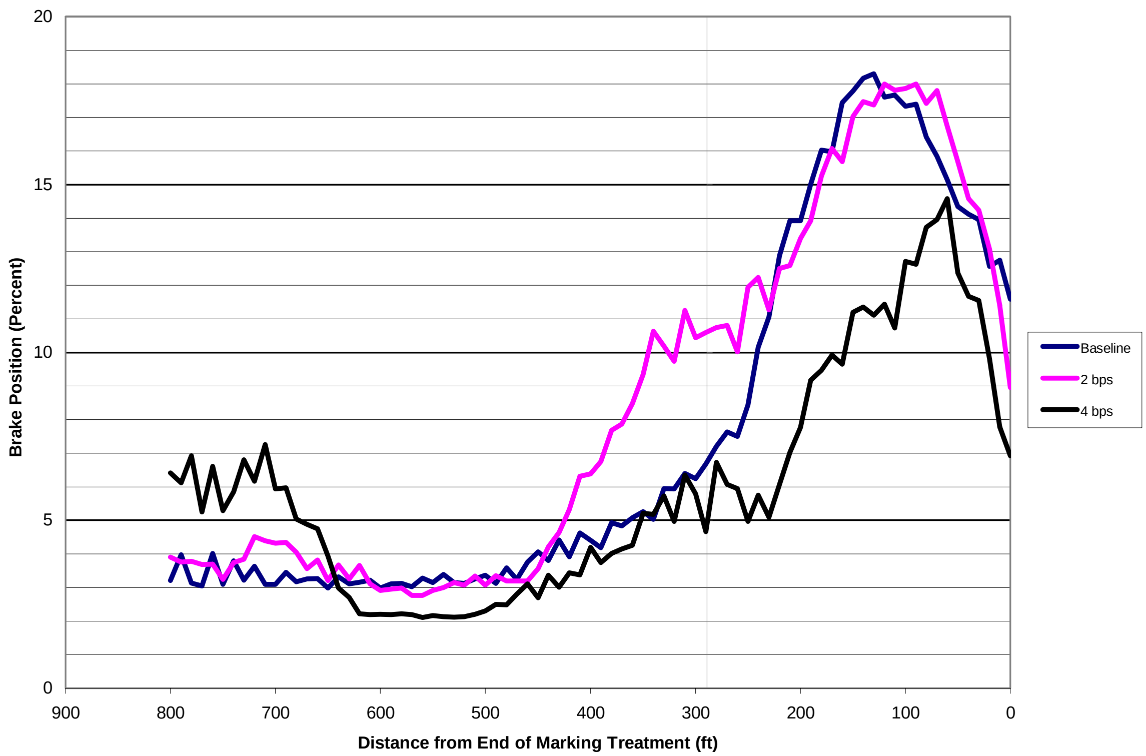

Figure 6-9: Brake Position by Distance for Location 2

Conclusions and Recommendations

Two design patterns for peripheral transverse lines were evaluated in this controlled field study. Peripheral transverse pavement markings were spaced at 2 bars per second and 4 bars per second on the approaches to two curves at different locations. One curve was representative of a freeway ramp whereas the other curve could be viewed in its entirety at distance and therefore proved to not be an appropriate curve for applying a peripheral transverse pavement marking treatment. When looking at the results of the freeway ramp, peripheral transverse lines spaced at 4 bars per second resulted in a significant decrease in speed at the entrance to the curve compared to both 2 bars per second and the baseline condition with no markings applied. In addition, the speed profile of drivers who experienced the curve with the 4 bars per second markings were more apt to reduce their speed upon viewing the treatment and traveled slower throughout the treatment area than drivers who experienced the other two conditions. At the freeway ramp approach, drivers also applied the brakes at a greater distance than the other two conditions.

As with all situations in which treatments are applied to the roadway, it is important to recognize whether or not the treatment is appropriate. In the case of this study, when a curve could be seen in its entirety at a significant distance away, the treatment was not effective. However, in the case where a sharp curve is encountered on a roadway and drivers require additional information to know the reduction in speed that is required and are forced to use other cues to determine speed selection, peripheral transverse lines may be effective.

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CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This research effort was the culmination of three independent research efforts with the focus of determining the design as well as the effectiveness of using peripheral transverse lines to reduce vehicle speeds. The first portion of the study was done on three actual roadways in New York, Mississippi, and Texas. The results from the study showed that in New York and Mississippi, peripheral transverse lines were effective at reducing speeds in locations without large preview distances of the entire curve (reductions of up to 59% compared to the baseline in the short term and 24% in the long term). The study, however, only examined one peripheral transverse marking design – a design with a pattern frequency of four bars per second. The second portion of the study was done in a driving simulator on a two lane rural road. The goal of this second study was to determine whether certain marking designs were more effective than others. Unfortunately, due to variability in the simulator, the conclusion could not be made; however, the markings did show a potential to reduce lane excursions over the center line on a two lane road. Although the finding was interesting and further illustrates the potential impact that the markings can have on safety, the original question of effective pattern design was not addressed. The final portion of the study was performed on the Virginia Tech Smart Road in which markings were both placed at a pattern frequency of two bars per second as well as four bars per second. From this final study, the four bars per second condition proved to be more effective at reducing speeds than the two bars per second condition and the baseline condition and resulted in reductions up to 42% over the baseline.

All three studies illustrated the importance of proper installation of the peripheral transverse lines as they will not be effective in every situation. The Texas data provide an example when drivers are primarily all local drivers on extremely rural high speed and high visibility roads in which case markings are not effective. However, in New York where there is a large amount of out-of-town travelers and large amounts of unfamiliar truck traffic, the markings worked extremely well. The driving simulator study took place on roadways with a large amount of horizontal curvature and the curves continued throughout the entire test run. Therefore, driver expectation of sharp curves was already at a heightened state and so the opportunity was not as readily available to find significant differences in speed reductions. The Smart Road study had two curves, one being a freeway exit ramp and the other as a small loop which is unrealistic in a normal roadway environment. Drivers adjusted their behavior in the presence of the markings on the ramp whereas the markings had no effect on the approach to the small loop since drivers could see in advance exactly what to expect.

Another important lesson learned from the three independent studies is that various research tools all have differing capabilities and in some cases where research may be appropriate in a controlled environment, it may not be appropriate for a driving simulator. Driver speed choice for example can portray challenges when analyzed in a driving simulator. The sensations of speed that are generated through roadway roughness, roadway noise, and a realistic peripheral view are much harder to generate in a simulated environment.

One of the differences in analyzing speed data across different research environments relates to variability. One measure to analyze the variability across the various research environments is to look at the average coefficient of variation which is determined from the ratio of the mean to the standard deviation. All data points at the end of the treatment area were analyzed to determine the mean and standard deviation. All treatment conditions were examined as shown in the formula:

$$CV_{env} = \frac{\sum_{i=1}^{n} \frac{\sigma}{\mu}}{n}$$

where CV_{env} is the coefficient of variation for a particular research environment, n is the number of conditions and σ and μ are the standard deviation and mean, respectively for each condition.

The coefficient of variation was 14% in the field, 8% on the Smart Road, and 25% in the simulator. It is hypothesized that the variability in the field is higher than the Smart Road since there is a mix of vehicle types as well as varying vehicle interactions which would have an impact on speed. Both the Smart Road drivers and simulator drivers all drove the same vehicle throughout the test run but the variability was more than three times greater in the simulator than on the smart road.

One concern of the analysis of the CV for the simulator study is that unlike the other two studies, only older and younger participants are used. To determine how the overall CV relates to that of each population, an analysis of the Smart Road data can be performed. When performing an analysis of the coefficient of variation by age for participants in the Smart Road Study, the CV was 6.5% for participants 25 years of age and younger, 8.3% between 26 and 59 years of age, and 9.3% for participants 60 years of age and older. The overall coefficient of variation for the Smart Road population was 8% which is greater than that of the older population and less than that of the younger population. Therefore, using the same assumption, although the simulator study only included the younger and older age groups, the overall CV of the entire group of participants if middle-aged participants were used would be between that of the younger and older population given the results of the Smart Road study. Therefore, the results of the three environments should be comparable.

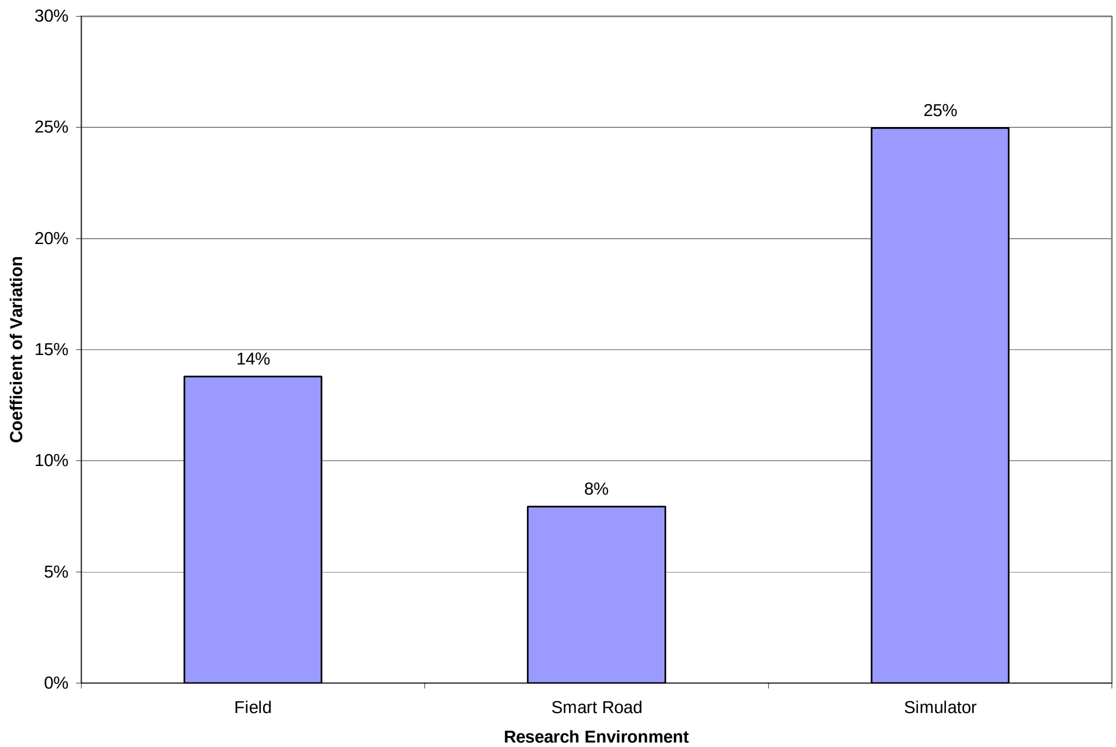

Figure 7-1: Coefficient of Variation in Speed Data by Research Environment

The variation data can also provide very useful information in order to determine the requirements for analyzing speed in the field, on the Smart Road, and in a simulator. A power analysis was performed using a two-tail test with a 95% confidence interval (α = 0.05) and adjusting for the incorrect assumption that there is no difference when a real difference exists (β = 0.50). As an example, to realize a change in speed of 1 mi/h, there would need to be 140 traffic observations in a field study, 24 research participants for a Smart Road study, and 180 research participants for a simulator study.

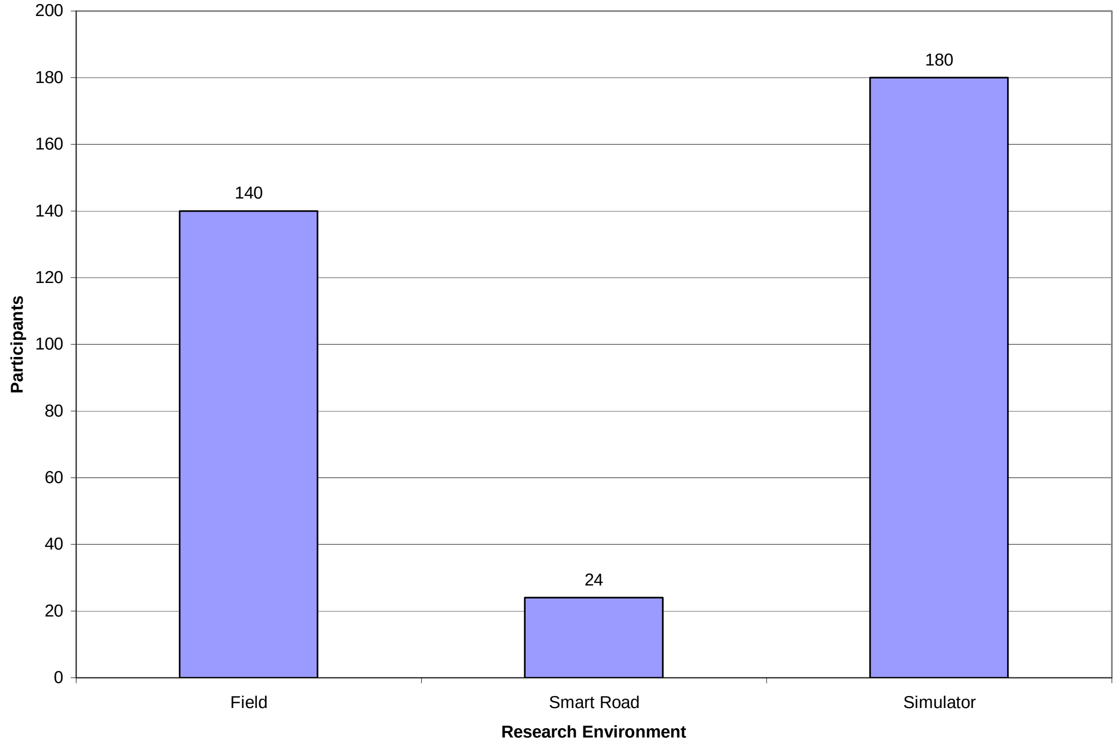

Figure 7-2: Number of Participants Required for a 1 mi/h Realized Change in Speed by Research Environment

It is important to recognize that this statement in variance is true when analyzing vehicle speeds and not necessarily other investigations that may be done in a field, on a controlled road, or in a driving simulator. There are several types of studies that potentially would work better in a simulated environment whereas for some other studies, a field evaluation would be the best. An experimental device for example may be better tested in a controlled environment to reduce the chance of safety implications and also to have staff on hand to troubleshoot devices. If a concept of a roadway was designed but was not constructed, simulation would prove to be a useful tool in order to evaluate potential problems both in design considerations as well as possible driver behavior issues. Table 7-1 provides a table of sample Pros and Cons for conducting research in various research environments. The table is not comprehensive, but through experience on the three studies, there are several observations that have been made.

Table 7-1: Considerations (Pros and Cons) for Various Research Environments

	Observational Field Studies	Controlled Research Facility Studies	Simulator Research Studies
Drivers	In general, drivers are unaware they are being evaluated and thus would not alter driving behavior	Research participants are aware that they are being tested and might alter their behavior	Research participants are aware that they are being tested and might alter their behavior
Data Collection	Collection of data can be very difficult and expensive if the infrastructure needs to be installed to monitor traffic data	Data collection is fairly easy in a controlled facility as individual vehicles and the infrastructure can be instrumented	In general, collecting data is extremely simple as the driving simulator is already computerized and capable of collecting large amounts of data
Experimentation of High Risk Devices	High risk experimental devices generally cannot be placed on the road due to safety implications	Some higher risk experimental devices that cannot be placed on a highway can be placed in a controlled setting	High risk experimental devices that cannot be placed on a highway can be placed in a simulator
Development of Varying Scenarios	Evaluations of concepts under varying roadway geometries is limited to the characteristics of the roadway being observed	Evaluations of concepts under varying roadway geometries is limited to the characteristics of the controlled facility itself	Driving situations in areas that are in concept or not yet constructed can be easily modeled for visualization purposes and perhaps for obtaining driver behavior data in the simulator
Interaction With Drivers	Aside from intercept surveys, it is difficult to obtain driver opinions or comments	Driver understanding and response to various devices can be obtained through interaction with the participant and thus focused information can be gathered	Driver understanding and response to various devices can be obtained through interaction with the participant and thus focused information can be gathered
Realism	The driver is experiencing the actual environment in an actual vehicle	The driver is experiencing the actual environment in an actual vehicle	Simulators are not capable of producing all of the required elements that are necessary to the driving task. Care must be taken to ensure that the measure being evaluated is appropriate for simulator use depending on the fidelity of the simulator
Weather	Data collection may delayed if adverse weather conditions exist	If weather-making capabilities are available, various weather can be generated	Weather is not a factor in the simulator; however, it is very difficult to simulate weather if required

Recommendations

This research took an extremely detailed look at peripheral transverse lines as a method of reducing speed given various spacing patterns. Other types of perceptual countermeasures should be investigated to determine their effectiveness on speed reductions. Additionally, this investigation used transverse bars of standard widths (18 inches) in all scenarios; however, perhaps the bars should be designed with increasing widths through the treatment area. Another aspect that may be investigated would be to attempt varying angles of the peripheral transverse lines to create an additional illusion of roadway narrowing.

Although the peripheral transverse lines were used in various geometric configurations in this study, only a comprehensive set of applications will provide more insight on the situations where the lines are predicted to have a benefit versus when they are not. For example, this study did not look into the application of peripheral transverse lines on tangent sections in detail and thus further research could be performed there to see what the effects would be on the approaches to speed reduction zones on main roads through rural towns, on approaches to toll plazas, or other similar treatments on tangent sections. Additionally, even on sections of roadway with curves such as those performed in this study, the driver and roadway characteristics of a given roadway section may lead to varying results of success using peripheral transverse markings. Roadway sections with long preview distances to curves was one geometric characteristic that was shown in this study to not be an appropriate location for the treatment but there may be others.

Future applications of the peripheral transverse lines should examine overall speed profiles, similar to the method that the analysis was performed in the Smart Road study. It is important to determine speeds upstream as well as at the initial portion of the curve, but further analysis of speed profiles would aid in an optimal spacing pattern based on actual roadway conditions. It is hypothesized that various geometric characteristics would result in a range of speed profiles, but in the future, generalizations may be possible on optimal deceleration curves for particular scenarios.

Additional Field Applications

The design used for the transverse marking spacings since its implementation in the field in 2003 has obtained a large amount of interest. To date, additional installations using marking designs based on the field study are known to have been implemented in Virginia, Wisconsin, Oregon, and an additional site in Texas. Also, departments of transportation in Canada, Pennsylvania, and Minnesota have also requested design information for upcoming roadway implementation.

APPENDIX A: PAVEMENT MARKING DESIGN TABLES

Table A-1: Desired Speed of 5 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	7.4	5
X_1	1.8	8.2	6
X_2	3.9	9.0	6
X_3	6.1	9.8	7
X_4	8.6	10.7	7
X_5	11.3	11.5	8
X_6	14.1	12.3	8
X_7	17.2	13.1	9
X_8	20.5	14.0	9
X_9	24.0	14.8	10
X_{10}	27.7	15.6	11
X_{11}	31.6	16.4	11
X_{12}	35.7	17.3	12
X_{13}	40.0	18.1	12
X_{14}	44.5	18.9	13
X_{15}	49.2	19.7	13
X_{16}	54.2	20.6	14
X_{17}	59.3	21.4	15
X_{18}	64.6	22.2	15
X_{19}	70.2	23.0	16
X_{20}	75.9	23.9	16
X_{21}	81.9	24.7	17
X_{22}	88.1	25.5	17
X_{23}	94.4	26.3	18
X_{24}	101.0	27.2	18
X_{25}	107.8	28.0	19
X_{26}	114.8	28.8	20
X_{27}	122.0	29.6	20
X_{28}	129.4	30.5	21
X_{29}	137.0	31.3	21
X_{30}	144.8	32.1	22
X_{31}	152.9	32.9	22
X_{32}	161.1	33.8	23
X_{33}	169.5	34.6	24
X_{34}	178.2	35.4	24
X_{35}	187.0	36.2	25
X_{36}	196.1	37.1	25
X_{37}	205.4	37.9	26
X_{38}	214.8	38.7	26
X_{39}	224.5	39.5	27
X_{40}	234.4	40.4	27
X_{41}	244.5	41.2	28
X_{42}	254.8	42.0	29
X_{43}	265.3	42.8	29
X_{44}	276.0	43.7	30
X_{45}	286.9	44.5	30
X_{46}	298.0	45.3	31
X_{47}	309.3	46.1	31
X_{48}	320.9	47.0	32
X_{49}	332.6	47.8	33
X_{50}	344.5	48.6	33
X_{51}	356.7	49.4	34
X_{52}	369.0	50.3	34
X_{53}	381.6	51.1	35
X_{54}	394.4	51.9	35
X_{55}	407.3	52.7	36
X_{56}	420.5	53.6	36
X_{57}	433.9	54.4	37
X_{58}	447.5	55.2	38
X_{59}	461.3	56.0	38
X_{60}	475.3	56.9	39
X_{61}	489.5	57.7	39
X_{62}	503.9	58.5	40
X_{63}	518.6	59.3	40
X_{64}	533.4	60.2	41
X_{65}	548.4	61.0	41
X_{66}	563.7	61.8	42
X_{67}	579.1	62.6	43
X_{68}	594.8	63.5	43
X_{69}	610.7	64.3	44
X_{70}	626.7	65.1	44
X_{71}	643.0	65.9	45
X_{72}	659.5	66.8	45
X_{73}	676.2	67.6	46
X_{74}	693.1	68.4	47
X_{75}	710.2	69.2	47
X_{76}	727.5	70.1	48
X_{77}	745.0	70.9	48
X_{78}	762.7	71.7	49
X_{79}	780.6	72.5	49
X_{80}	798.8	73.4	50
X_{81}	817.1	74.2	50
X_{82}	835.6	75.0	51
X_{83}	854.4	75.8	52
X_{84}	873.3	76.7	52
X_{85}	892.5	77.5	53
X_{86}	911.9	78.3	53
X_{87}	931.4	79.1	54
X_{88}	951.2	80.0	54
X_{89}	971.2	80.8	55
X_{90}	991.4	81.6	56
X_{91}	1011.8	82.4	56
X_{92}	1032.4	83.3	57
X_{93}	1053.2	84.1	57
X_{94}	1074.2	84.9	58
X_{95}	1095.5	85.7	58
X_{96}	1116.9	86.6	59
X_{97}	1138.5	87.4	59
X_{98}	1160.4	88.2	60
X_{99}	1182.4	89.0	61
X_{100}	1204.7	89.9	61
X_{101}	1227.2	90.7	62
X_{102}	1249.8	91.5	62
X_{103}	1272.7	92.3	63
X_{104}	1295.8	93.2	63
X_{105}	1319.1	94.0	64
X_{106}	1342.6	94.8	64
X_{107}	1366.3	95.6	65

Table A-2: Desired Speed of 10 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_{0}	0.0	14.7	10
X_{1}	3.7	15.5	11
X_{2}	7.6	16.4	11
X_{3}	11.6	17.2	12
X_{4}	15.9	18.0	12
X_{5}	20.4	18.8	13
X_{6}	25.1	19.7	13
X_{7}	30.1	20.5	14
X_{8}	35.2	21.3	14
X_{9}	40.5	22.1	15
X_{10}	46.0	23.0	16
X_{11}	51.8	23.8	16
X_{12}	57.7	24.6	17
X_{13}	63.9	25.4	17
X_{14}	70.2	26.3	18
X_{15}	76.8	27.1	18
X_{16}	83.6	27.9	19
X_{17}	90.5	28.7	20
X_{18}	97.7	29.6	20
X_{19}	105.1	30.4	21
X_{20}	112.7	31.2	21
X_{21}	120.5	32.0	22
X_{22}	128.5	32.9	22
X_{23}	136.7	33.7	23
X_{24}	145.1	34.5	23
X_{25}	153.8	35.3	24
X_{26}	162.6	36.2	25
X_{27}	171.6	37.0	25
X_{28}	180.9	37.8	26
X_{29}	190.3	38.6	26
X_{30}	200.0	39.5	27
X_{31}	209.8	40.3	27
X_{32}	219.9	41.1	28
X_{33}	230.2	41.9	29
X_{34}	240.7	42.8	29
X_{35}	251.3	43.6	30
X_{36}	262.2	44.4	30
X_{37}	273.3	45.2	31
X_{38}	284.6	46.1	31
X_{39}	296.2	46.9	32
X_{40}	307.9	47.7	32
X_{41}	319.8	48.5	33
X_{42}	331.9	49.4	34
X_{43}	344.3	50.2	34
X_{44}	356.8	51.0	35
X_{45}	369.6	51.8	35
X_{46}	382.5	52.7	36
X_{47}	395.7	53.5	36
X_{48}	409.1	54.3	37
X_{49}	422.6	55.1	38
X_{50}	436.4	56.0	38
X_{51}	450.4	56.8	39
X_{52}	464.6	57.6	39
X_{53}	479.0	58.4	40
X_{54}	493.6	59.3	40
X_{55}	508.4	60.1	41
X_{56}	523.4	60.9	41
X_{57}	538.7	61.7	42
X_{58}	554.1	62.6	43
X_{59}	569.7	63.4	43
X_{60}	585.6	64.2	44
X_{61}	601.6	65.0	44
X_{62}	617.9	65.9	45
X_{63}	634.3	66.7	45
X_{64}	651.0	67.5	46
X_{65}	667.9	68.3	46
X_{66}	685.0	69.2	47
X_{67}	702.2	70.0	48
X_{68}	719.7	70.8	48
X_{69}	737.4	71.6	49
X_{70}	755.3	72.5	49
X_{71}	773.5	73.3	50
X_{72}	791.8	74.1	50
X_{73}	810.3	74.9	51
X_{74}	829.0	75.8	52
X_{75}	848.0	76.6	52
X_{76}	867.1	77.4	53
X_{77}	886.5	78.2	53
X_{78}	906.0	79.1	54
X_{79}	925.8	79.9	54
X_{80}	945.8	80.7	55
X_{81}	965.9	81.5	55
X_{82}	986.3	82.4	56
X_{83}	1006.9	83.2	57
X_{84}	1027.7	84.0	57
X_{85}	1048.7	84.8	58
X_{86}	1069.9	85.7	58
X_{87}	1091.3	86.5	59
X_{88}	1112.9	87.3	59
X_{89}	1134.8	88.1	60
X_{90}	1156.8	89.0	61
X_{91}	1179.0	89.8	61
X_{92}	1201.5	90.6	62
X_{93}	1224.1	91.4	62
X_{94}	1247.0	92.3	63
X_{95}	1270.0	93.1	63
X_{96}	1293.3	93.9	64
X_{97}	1316.8	94.7	64
X_{98}	1340.5	95.6	65

Table A-3: Desired Speed of 15 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	22.1	15
X_1	5.5	22.9	16
X_2	11.2	23.7	16
X_3	17.2	24.5	17
X_4	23.3	25.4	17
X_5	29.6	26.2	18
X_6	36.2	27.0	18
X_7	42.9	27.8	19
X_8	49.9	28.7	19
X_9	57.0	29.5	20
X_{10}	64.4	30.3	21
X_{11}	72.0	31.1	21
X_{12}	79.8	32.0	22
X_{13}	87.8	32.8	22
X_{14}	95.9	33.6	23
X_{15}	104.3	34.4	23
X_{16}	113.0	35.3	24
X_{17}	121.8	36.1	25
X_{18}	130.8	36.9	25
X_{19}	140.0	37.7	26
X_{20}	149.4	38.6	26
X_{21}	159.1	39.4	27
X_{22}	168.9	40.2	27
X_{23}	179.0	41.0	28
X_{24}	189.2	41.9	28
X_{25}	199.7	42.7	29
X_{26}	210.4	43.5	30
X_{27}	221.2	44.3	30
X_{28}	232.3	45.2	31
X_{29}	243.6	46.0	31
X_{30}	255.1	46.8	32
X_{31}	266.8	47.6	32
X_{32}	278.7	48.5	33
X_{33}	290.8	49.3	34
X_{34}	303.1	50.1	34
X_{35}	315.7	50.9	35
X_{36}	328.4	51.8	35
X_{37}	341.3	52.6	36
X_{38}	354.5	53.4	36
X_{39}	367.8	54.2	37
X_{40}	381.4	55.1	37
X_{41}	395.1	55.9	38
X_{42}	409.1	56.7	39
X_{43}	423.3	57.5	39
X_{44}	437.7	58.4	40
X_{45}	452.3	59.2	40
X_{46}	467.0	60.0	41
X_{47}	482.0	60.8	41
X_{48}	497.3	61.7	42
X_{49}	512.7	62.5	43
X_{50}	528.3	63.3	43
X_{51}	544.1	64.1	44
X_{52}	560.1	65.0	44
X_{53}	576.4	65.8	45
X_{54}	592.8	66.6	45
X_{55}	609.5	67.4	46
X_{56}	626.3	68.3	46
X_{57}	643.4	69.1	47
X_{58}	660.7	69.9	48
X_{59}	678.1	70.7	48
X_{60}	695.8	71.6	49
X_{61}	713.7	72.4	49
X_{62}	731.8	73.2	50
X_{63}	750.1	74.0	50
X_{64}	768.6	74.9	51
X_{65}	787.3	75.7	51
X_{66}	806.2	76.5	52
X_{67}	825.4	77.3	53
X_{68}	844.7	78.2	53
X_{69}	864.2	79.0	54
X_{70}	884.0	79.8	54
X_{71}	903.9	80.6	55
X_{72}	924.1	81.5	55
X_{73}	944.4	82.3	56
X_{74}	965.0	83.1	57
X_{75}	985.8	83.9	57
X_{76}	1006.8	84.8	58
X_{77}	1028.0	85.6	58
X_{78}	1049.3	86.4	59
X_{79}	1070.9	87.2	59
X_{80}	1092.8	88.1	60
X_{81}	1114.8	88.9	60
X_{82}	1137.0	89.7	61
X_{83}	1159.4	90.5	62
X_{84}	1182.0	91.4	62
X_{85}	1204.9	92.2	63
X_{86}	1227.9	93.0	63
X_{87}	1251.2	93.8	64
X_{88}	1274.6	94.7	64
X_{89}	1298.3	95.5	65

Table A-4: Desired Speed of 20 mi/h with 3.3 ft/s2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	29.4	20
X_1	7.4	30.2	21
X_2	14.9	31.1	21
X_3	22.7	31.9	22
X_4	30.6	32.7	22
X_5	38.8	33.5	23
X_6	47.2	34.4	23
X_7	55.8	35.2	24
X_8	64.6	36.0	24
X_9	73.6	36.8	25
X_{10}	82.8	37.7	26
X_{11}	92.2	38.5	26
X_{12}	101.8	39.3	27
X_{13}	111.6	40.1	27
X_{14}	121.7	41.0	28
X_{15}	131.9	41.8	28
X_{16}	142.4	42.6	29
X_{17}	153.0	43.4	30
X_{18}	163.9	44.3	30
X_{19}	174.9	45.1	31
X_{20}	186.2	45.9	31
X_{21}	197.7	46.7	32
X_{22}	209.3	47.6	32
X_{23}	221.2	48.4	33
X_{24}	233.3	49.2	33
X_{25}	245.6	50.0	34
X_{26}	258.1	50.9	35
X_{27}	270.8	51.7	35
X_{28}	283.8	52.5	36
X_{29}	296.9	53.3	36
X_{30}	310.2	54.2	37
X_{31}	323.8	55.0	37
X_{32}	337.5	55.8	38
X_{33}	351.5	56.6	39
X_{34}	365.6	57.5	39
X_{35}	380.0	58.3	40
X_{36}	394.5	59.1	40
X_{37}	409.3	59.9	41
X_{38}	424.3	60.8	41
X_{39}	439.5	61.6	42
X_{40}	454.9	62.4	42
X_{41}	470.5	63.2	43
X_{42}	486.3	64.1	44
X_{43}	502.3	64.9	44
X_{44}	518.5	65.7	45
X_{45}	534.9	66.5	45
X_{46}	551.6	67.4	46
X_{47}	568.4	68.2	46
X_{48}	585.5	69.0	47
X_{49}	602.7	69.8	48
X_{50}	620.2	70.7	48
X_{51}	637.8	71.5	49
X_{52}	655.7	72.3	49
X_{53}	673.8	73.1	50

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_{54}	692.0	74.0	50
X_{55}	710.5	74.8	51
X_{56}	729.2	75.6	51
X_{57}	748.1	76.4	52
X_{58}	767.2	77.3	53
X_{59}	786.5	78.1	53
X_{60}	806.1	78.9	54
X_{61}	825.8	79.7	54
X_{62}	845.7	80.6	55
X_{63}	865.9	81.4	55
X_{64}	886.2	82.2	56
X_{65}	906.8	83.0	56
X_{66}	927.5	83.9	57
X_{67}	948.5	84.7	58
X_{68}	969.6	85.5	58
X_{69}	991.0	86.3	59
X_{70}	1012.6	87.2	59
X_{71}	1034.4	88.0	60
X_{72}	1056.4	88.8	60
X_{73}	1078.6	89.6	61
X_{74}	1101.0	90.5	62
X_{75}	1123.6	91.3	62
X_{76}	1146.4	92.1	63
X_{77}	1169.4	92.9	63
X_{78}	1192.7	93.8	64
X_{79}	1216.1	94.6	64
X_{80}	1239.8	95.4	65

Table A-5: Desired Speed of 25 mi/h with 3.3 ft/s2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_{0}	0.0	36.8	25
X_{1}	9.2	37.6	26
X_{2}	18.6	38.4	26
X_{3}	28.2	39.2	27
X_{4}	38.0	40.1	27
X_{5}	48.0	40.9	28
X_{6}	58.2	41.7	28
X_{7}	68.6	42.5	29
X_{8}	79.3	43.4	29
X_{9}	90.1	44.2	30
X_{10}	101.2	45.0	31
X_{11}	112.4	45.8	31
X_{12}	123.9	46.7	32
X_{13}	135.5	47.5	32
X_{14}	147.4	48.3	33
X_{15}	159.5	49.1	33
X_{16}	171.8	50.0	34
X_{17}	184.2	50.8	35
X_{18}	196.9	51.6	35
X_{19}	209.8	52.4	36
X_{20}	222.9	53.3	36
X_{21}	236.3	54.1	37
X_{22}	249.8	54.9	37
X_{23}	263.5	55.7	38
X_{24}	277.4	56.6	38
X_{25}	291.6	57.4	39
X_{26}	305.9	58.2	40
X_{27}	320.5	59.0	40
X_{28}	335.2	59.9	41
X_{29}	350.2	60.7	41
X_{30}	365.3	61.5	42
X_{31}	380.7	62.3	42
X_{32}	396.3	63.2	43
X_{33}	412.1	64.0	44
X_{34}	428.1	64.8	44
X_{35}	444.3	65.6	45
X_{36}	460.7	66.5	45
X_{37}	477.3	67.3	46
X_{38}	494.1	68.1	46
X_{39}	511.1	68.9	47
X_{40}	528.4	69.8	47
X_{41}	545.8	70.6	48
X_{42}	563.5	71.4	49
X_{43}	581.3	72.2	49
X_{44}	599.4	73.1	50
X_{45}	617.6	73.9	50
X_{46}	636.1	74.7	51
X_{47}	654.8	75.5	51
X_{48}	673.7	76.4	52
X_{49}	692.7	77.2	53
X_{50}	712.0	78.0	53
X_{51}	731.5	78.8	54
X_{52}	751.2	79.7	54
X_{53}	771.2	80.5	55
X_{54}	791.3	81.3	55
X_{55}	811.6	82.1	56
X_{56}	832.1	83.0	56
X_{57}	852.9	83.8	57
X_{58}	873.8	84.6	58
X_{59}	895.0	85.4	58
X_{60}	916.3	86.3	59
X_{61}	937.9	87.1	59
X_{62}	959.6	87.9	60
X_{63}	981.6	88.7	60
X_{64}	1003.8	89.6	61
X_{65}	1026.2	90.4	61
X_{66}	1048.8	91.2	62
X_{67}	1071.6	92.0	63
X_{68}	1094.6	92.9	63
X_{69}	1117.8	93.7	64
X_{70}	1141.2	94.5	64
X_{71}	1164.8	95.3	65

Table A-6: Desired Speed of 30 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	44.1	30
X_1	11.0	44.9	31
X_2	22.3	45.8	31
X_3	33.7	46.6	32
X_4	45.3	47.4	32
X_5	57.2	48.2	33
X_6	69.2	49.1	33
X_7	81.5	49.9	34
X_8	94.0	50.7	34
X_9	106.7	51.5	35
X_{10}	119.5	52.4	36
X_{11}	132.6	53.2	36
X_{12}	145.9	54.0	37
X_{13}	159.4	54.8	37
X_{14}	173.1	55.7	38
X_{15}	187.0	56.5	38
X_{16}	201.2	57.3	39
X_{17}	215.5	58.1	40
X_{18}	230.0	59.0	40
X_{19}	244.7	59.8	41
X_{20}	259.7	60.6	41
X_{21}	274.8	61.4	42
X_{22}	290.2	62.3	42
X_{23}	305.8	63.1	43
X_{24}	321.5	63.9	43
X_{25}	337.5	64.7	44
X_{26}	353.7	65.6	45
X_{27}	370.1	66.4	45
X_{28}	386.7	67.2	46
X_{29}	403.5	68.0	46
X_{30}	420.5	68.9	47
X_{31}	437.7	69.7	47
X_{32}	455.1	70.5	48
X_{33}	472.7	71.3	49
X_{34}	490.6	72.2	49
X_{35}	508.6	73.0	50
X_{36}	526.8	73.8	50
X_{37}	545.3	74.6	51
X_{38}	563.9	75.5	51
X_{39}	582.8	76.3	52
X_{40}	601.9	77.1	52
X_{41}	621.2	77.9	53
X_{42}	640.6	78.8	54
X_{43}	660.3	79.6	54
X_{44}	680.2	80.4	55
X_{45}	700.3	81.2	55
X_{46}	720.6	82.1	56
X_{47}	741.1	82.9	56
X_{48}	761.9	83.7	57
X_{49}	782.8	84.5	58
X_{50}	803.9	85.4	58
X_{51}	825.2	86.2	59
X_{52}	846.8	87.0	59
X_{53}	868.5	87.8	60
X_{54}	890.5	88.7	60
X_{55}	912.7	89.5	61
X_{56}	935.0	90.3	61
X_{57}	957.6	91.1	62
X_{58}	980.4	92.0	63
X_{59}	1003.4	92.8	63
X_{60}	1026.6	93.6	64
X_{61}	1050.0	94.4	64
X_{62}	1073.6	95.3	65

Table A-7: Desired Speed of 35 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	51.5	35
X_1	12.9	52.3	36
X_2	25.9	53.1	36
X_3	39.2	53.9	37
X_4	52.7	54.8	37
X_5	66.4	55.6	38
X_6	80.3	56.4	38
X_7	94.4	57.2	39
X_8	108.7	58.1	39
X_9	123.2	58.9	40
X_{10}	137.9	59.7	41
X_{11}	152.8	60.5	41
X_{12}	168.0	61.4	42
X_{13}	183.3	62.2	42
X_{14}	198.8	63.0	43
X_{15}	214.6	63.8	43
X_{16}	230.6	64.7	44
X_{17}	246.7	65.5	45
X_{18}	263.1	66.3	45
X_{19}	279.7	67.1	46
X_{20}	296.4	68.0	46
X_{21}	313.4	68.8	47
X_{22}	330.6	69.6	47
X_{23}	348.0	70.4	48
X_{24}	365.6	71.3	48
X_{25}	383.4	72.1	49
X_{26}	401.5	72.9	50
X_{27}	419.7	73.7	50
X_{28}	438.1	74.6	51
X_{29}	456.8	75.4	51
X_{30}	475.6	76.2	52
X_{31}	494.6	77.0	52
X_{32}	513.9	77.9	53
X_{33}	533.4	78.7	54
X_{34}	553.0	79.5	54
X_{35}	572.9	80.3	55
X_{36}	593.0	81.2	55
X_{37}	613.3	82.0	56
X_{38}	633.8	82.8	56
X_{39}	654.5	83.6	57
X_{40}	675.4	84.5	57
X_{41}	696.5	85.3	58
X_{42}	717.8	86.1	59
X_{43}	739.3	86.9	59
X_{44}	761.1	87.8	60
X_{45}	783.0	88.6	60
X_{46}	805.1	89.4	61
X_{47}	827.5	90.2	61
X_{48}	850.1	91.1	62
X_{49}	872.8	91.9	63
X_{50}	895.8	92.7	63
X_{51}	919.0	93.5	64
X_{52}	942.3	94.4	64
X_{53}	965.9	95.2	65

Table A-8: Desired Speed of 40 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	58.8	40
X_1	14.7	59.6	41
X_2	29.6	60.5	41
X_3	44.7	61.3	42
X_4	60.0	62.1	42
X_5	75.6	62.9	43
X_6	91.3	63.8	43
X_7	107.2	64.6	44
X_8	123.4	65.4	44
X_9	139.7	66.2	45
X_{10}	156.3	67.1	46
X_{11}	173.0	67.9	46
X_{12}	190.0	68.7	47
X_{13}	207.2	69.5	47
X_{14}	224.6	70.4	48
X_{15}	242.2	71.2	48
X_{16}	260.0	72.0	49
X_{17}	278.0	72.8	50
X_{18}	296.2	73.7	50
X_{19}	314.6	74.5	51
X_{20}	333.2	75.3	51
X_{21}	352.0	76.1	52
X_{22}	371.0	77.0	52
X_{23}	390.3	77.8	53
X_{24}	409.7	78.6	53
X_{25}	429.4	79.4	54
X_{26}	449.2	80.3	55
X_{27}	469.3	81.1	55
X_{28}	489.6	81.9	56
X_{29}	510.0	82.7	56
X_{30}	530.7	83.6	57
X_{31}	551.6	84.4	57
X_{32}	572.7	85.2	58
X_{33}	594.0	86.0	59
X_{34}	615.5	86.9	59
X_{35}	637.2	87.7	60
X_{36}	659.1	88.5	60
X_{37}	681.3	89.3	61
X_{38}	703.6	90.2	61
X_{39}	726.1	91.0	62
X_{40}	748.9	91.8	62
X_{41}	771.8	92.6	63
X_{42}	795.0	93.5	64
X_{43}	818.3	94.3	64
X_{44}	841.9	95.1	65

Table A-9: Desired Speed of 45 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed ft/s	Speed mi/h
X_0	0.0	66.2	45
X_1	16.5	67.0	46
X_2	33.3	67.8	46
X_3	50.2	68.6	47
X_4	67.4	69.5	47
X_5	84.8	70.3	48
X_6	102.3	71.1	48
X_7	120.1	71.9	49
X_8	138.1	72.8	49
X_9	156.3	73.6	50
X_{10}	174.7	74.4	51
X_{11}	193.3	75.2	51
X_{12}	212.1	76.1	52
X_{13}	231.1	76.9	52
X_{14}	250.3	77.7	53
X_{15}	269.7	78.5	53
X_{16}	289.4	79.4	54
X_{17}	309.2	80.2	55
X_{18}	329.2	81.0	55
X_{19}	349.5	81.8	56
X_{20}	369.9	82.7	56
X_{21}	390.6	83.5	57
X_{22}	411.5	84.3	57
X_{23}	432.5	85.1	58
X_{24}	453.8	86.0	58
X_{25}	475.3	86.8	59
X_{26}	497.0	87.6	60
X_{27}	518.9	88.4	60
X_{28}	541.0	89.3	61
X_{29}	563.3	90.1	61
X_{30}	585.8	90.9	62
X_{31}	608.6	91.7	62
X_{32}	631.5	92.6	63
X_{33}	654.6	93.4	64
X_{34}	678.0	94.2	64
X_{35}	701.5	95.0	65

Table A-10: Desired Speed of 50 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	73.5	50
X_1	18.4	74.3	51
X_2	37.0	75.2	51
X_3	55.7	76.0	52
X_4	74.7	76.8	52
X_5	93.9	77.6	53
X_6	113.3	78.5	53
X_7	133.0	79.3	54
X_8	152.8	80.1	54
X_9	172.8	80.9	55
X_{10}	193.0	81.8	56
X_{11}	213.5	82.6	56
X_{12}	234.1	83.4	57
X_{13}	255.0	84.2	57
X_{14}	276.0	85.1	58
X_{15}	297.3	85.9	58
X_{16}	318.8	86.7	59
X_{17}	340.4	87.5	60
X_{18}	362.3	88.4	60
X_{19}	384.4	89.2	61
X_{20}	406.7	90.0	61
X_{21}	429.2	90.8	62
X_{22}	451.9	91.7	62
X_{23}	474.8	92.5	63
X_{24}	497.9	93.3	63
X_{25}	521.3	94.1	64
X_{26}	544.8	95.0	65

Table A-11: Desired Speed of 55 mi/h with 3.3 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	80.9	55
X_1	20.2	81.7	56
X_2	40.6	82.5	56
X_3	61.3	83.3	57
X_4	82.1	84.2	57
X_5	103.1	85.0	58
X_6	124.4	85.8	58
X_7	145.8	86.6	59
X_8	167.5	87.5	59
X_9	189.3	88.3	60
X_{10}	211.4	89.1	61
X_{11}	233.7	89.9	61
X_{12}	256.2	90.8	62
X_{13}	278.9	91.6	62
X_{14}	301.7	92.4	63
X_{15}	324.8	93.2	63
X_{16}	348.2	94.1	64
X_{17}	371.7	94.9	65

Table A-12: Desired Speed of 5 mi/h with 6.7 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	7.4	5
X_1	1.8	9.0	6
X_2	4.1	10.7	7
X_3	6.8	12.4	8
X_4	9.9	14.1	10
X_5	13.4	15.7	11
X_6	17.3	17.4	12
X_7	21.7	19.1	13
X_8	26.4	20.8	14
X_9	31.6	22.4	15
X_{10}	37.2	24.1	16
X_{11}	43.2	25.8	18
X_{12}	49.7	27.5	19
X_{13}	56.6	29.1	20
X_{14}	63.8	30.8	21
X_{15}	71.5	32.5	22
X_{16}	79.7	34.2	23
X_{17}	88.2	35.8	24
X_{18}	97.1	37.5	26
X_{19}	106.5	39.2	27
X_{20}	116.3	40.9	28
X_{21}	126.5	42.5	29
X_{22}	137.2	44.2	30
X_{23}	148.2	45.9	31
X_{24}	159.7	47.6	32
X_{25}	171.6	49.2	33
X_{26}	183.9	50.9	35
X_{27}	196.6	52.6	36
X_{28}	209.7	54.3	37
X_{29}	223.3	55.9	38
X_{30}	237.3	57.6	39
X_{31}	251.7	59.3	40
X_{32}	266.5	61.0	41
X_{33}	281.7	62.6	43
X_{34}	297.4	64.3	44
X_{35}	313.5	66.0	45
X_{36}	330.0	67.6	46
X_{37}	346.9	69.3	47
X_{38}	364.2	71.0	48
X_{39}	382.0	72.7	49
X_{40}	400.1	74.3	51
X_{41}	418.7	76.0	52
X_{42}	437.7	77.7	53
X_{43}	457.1	79.4	54
X_{44}	477.0	81.0	55
X_{45}	497.3	82.7	56
X_{46}	517.9	84.4	57
X_{47}	539.0	86.1	59
X_{48}	560.6	87.7	60
X_{49}	582.5	89.4	61
X_{50}	604.8	91.1	62
X_{51}	627.6	92.8	63
X_{52}	650.8	94.4	64
X_{53}	674.4	96.1	65

Table A-13: Desired Speed of 10 mi/h with 6.7 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	14.7	10
X_1	3.7	16.4	11
X_2	7.8	18.1	12
X_3	12.3	19.7	13
X_4	17.2	21.4	15
X_5	22.6	23.1	16
X_6	28.3	24.8	17
X_7	34.5	26.4	18
X_8	41.1	28.1	19
X_9	48.2	29.8	20
X_{10}	55.6	31.5	21
X_{11}	63.5	33.1	23
X_{12}	71.7	34.8	24
X_{13}	80.4	36.5	25
X_{14}	89.6	38.2	26
X_{15}	99.1	39.8	27
X_{16}	109.1	41.5	28
X_{17}	119.4	43.2	29
X_{18}	130.2	44.9	31
X_{19}	141.4	46.5	32
X_{20}	153.1	48.2	33
X_{21}	165.1	49.9	34
X_{22}	177.6	51.6	35
X_{23}	190.5	53.2	36
X_{24}	203.8	54.9	37
X_{25}	217.5	56.6	38
X_{26}	231.6	58.3	40
X_{27}	246.2	59.9	41
X_{28}	261.2	61.6	42
X_{29}	276.6	63.3	43
X_{30}	292.4	65.0	44
X_{31}	308.6	66.6	45
X_{32}	325.3	68.3	46
X_{33}	342.4	70.0	48
X_{34}	359.9	71.6	49
X_{35}	377.8	73.3	50
X_{36}	396.1	75.0	51
X_{37}	414.9	76.7	52
X_{38}	434.0	78.3	53
X_{39}	453.6	80.0	54
X_{40}	473.6	81.7	56
X_{41}	494.1	83.4	57
X_{42}	514.9	85.0	58
X_{43}	536.2	86.7	59
X_{44}	557.8	88.4	60
X_{45}	579.9	90.1	61
X_{46}	602.5	91.7	62
X_{47}	625.4	93.4	64
X_{48}	648.8	95.1	65

Table A-14: Desired Speed of 15 mi/h with 6.7 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed ft/s	Speed mi/h
X_0	0.0	22.1	15
X_1	5.5	23.7	16
X_2	11.4	25.4	17
X_3	17.8	27.1	18
X_4	24.6	28.8	20
X_5	31.8	30.4	21
X_6	39.4	32.1	22
X_7	47.4	33.8	23
X_8	55.8	35.5	24
X_9	64.7	37.1	25
X_{10}	74.0	38.8	26
X_{11}	83.7	40.5	28
X_{12}	93.8	42.2	29
X_{13}	104.3	43.8	30
X_{14}	115.3	45.5	31
X_{15}	126.7	47.2	32
X_{16}	138.5	48.9	33
X_{17}	150.7	50.5	34
X_{18}	163.3	52.2	36
X_{19}	176.3	53.9	37
X_{20}	189.8	55.6	38
X_{21}	203.7	57.2	39
X_{22}	218.0	58.9	40
X_{23}	232.7	60.6	41
X_{24}	247.9	62.3	42
X_{25}	263.4	63.9	43
X_{26}	279.4	65.6	45
X_{27}	295.8	67.3	46
X_{28}	312.6	68.9	47
X_{29}	329.9	70.6	48
X_{30}	347.5	72.3	49
X_{31}	365.6	74.0	50
X_{32}	384.1	75.6	51
X_{33}	403.0	77.3	53
X_{34}	422.3	79.0	54
X_{35}	442.1	80.7	55
X_{36}	462.3	82.3	56
X_{37}	482.9	84.0	57
X_{38}	503.9	85.7	58
X_{39}	525.3	87.4	59
X_{40}	547.1	89.0	61
X_{41}	569.4	90.7	62
X_{42}	592.1	92.4	63
X_{43}	615.2	94.1	64
X_{44}	638.7	95.7	65

Table A-15: Desired Speed of 20 mi/h with 6.7 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	29.4	20
X_1	7.4	31.1	21
X_2	15.1	32.8	22
X_3	23.3	34.4	23
X_4	31.9	36.1	25
X_5	40.9	37.8	26
X_6	50.4	39.5	27
X_7	60.2	41.1	28
X_8	70.5	42.8	29
X_9	81.2	44.5	30
X_{10}	92.3	46.2	31
X_{11}	103.9	47.8	33
X_{12}	115.8	49.5	34
X_{13}	128.2	51.2	35
X_{14}	141.0	52.9	36
X_{15}	154.2	54.5	37
X_{16}	167.9	56.2	38
X_{17}	181.9	57.9	39
X_{18}	196.4	59.6	41
X_{19}	211.3	61.2	42
X_{20}	226.6	62.9	43
X_{21}	242.3	64.6	44
X_{22}	258.4	66.2	45
X_{23}	275.0	67.9	46
X_{24}	292.0	69.6	47
X_{25}	309.4	71.3	48
X_{26}	327.2	72.9	50
X_{27}	345.4	74.6	51
X_{28}	364.1	76.3	52
X_{29}	383.2	78.0	53
X_{30}	402.7	79.6	54
X_{31}	422.6	81.3	55
X_{32}	442.9	83.0	56
X_{33}	463.7	84.7	58
X_{34}	484.8	86.3	59
X_{35}	506.4	88.0	60
X_{36}	528.4	89.7	61
X_{37}	550.8	91.4	62
X_{38}	573.7	93.0	63
X_{39}	596.9	94.7	64
X_{40}	620.6	96.4	66

Table A-16: Desired Speed of 25 mi/h with 6.7 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	36.8	25
X_1	9.2	38.4	26
X_2	18.8	40.1	27
X_3	28.8	41.8	28
X_4	39.3	43.5	30
X_5	50.1	45.1	31
X_6	61.4	46.8	32
X_7	73.1	48.5	33
X_8	85.2	50.2	34
X_9	97.8	51.8	35
X_{10}	110.7	53.5	36
X_{11}	124.1	55.2	38
X_{12}	137.9	56.9	39
X_{13}	152.1	58.5	40
X_{14}	166.7	60.2	41
X_{15}	181.8	61.9	42
X_{16}	197.3	63.6	43
X_{17}	213.1	65.2	44
X_{18}	229.4	66.9	46
X_{19}	246.2	68.6	47
X_{20}	263.3	70.2	48
X_{21}	280.9	71.9	49
X_{22}	298.9	73.6	50
X_{23}	317.3	75.3	51
X_{24}	336.1	76.9	52
X_{25}	355.3	78.6	53
X_{26}	375.0	80.3	55
X_{27}	395.0	82.0	56
X_{28}	415.5	83.6	57
X_{29}	436.5	85.3	58
X_{30}	457.8	87.0	59
X_{31}	479.5	88.7	60
X_{32}	501.7	90.3	61
X_{33}	524.3	92.0	63
X_{34}	547.3	93.7	64
X_{35}	570.7	95.4	65

Table A-17: Desired Speed of 30 mi/h with 6.7 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed ft/s	Speed mi/h
X_0	0.0	44.1	30
X_1	11.0	45.8	31
X_2	22.5	47.5	32
X_3	34.3	49.1	33
X_4	46.6	50.8	35
X_5	59.3	52.5	36
X_6	72.4	54.2	37
X_7	86.0	55.8	38
X_8	99.9	57.5	39
X_9	114.3	59.2	40
X_{10}	129.1	60.9	41
X_{11}	144.3	62.5	43
X_{12}	159.9	64.2	44
X_{13}	176.0	65.9	45
X_{14}	192.5	67.6	46
X_{15}	209.3	69.2	47
X_{16}	226.7	70.9	48
X_{17}	244.4	72.6	49
X_{18}	262.5	74.3	51
X_{19}	281.1	75.9	52
X_{20}	300.1	77.6	53
X_{21}	319.5	79.3	54
X_{22}	339.3	80.9	55
X_{23}	359.5	82.6	56
X_{24}	380.2	84.3	57
X_{25}	401.3	86.0	58
X_{26}	422.7	87.6	60
X_{27}	444.7	89.3	61
X_{28}	467.0	91.0	62
X_{29}	489.7	92.7	63
X_{30}	512.9	94.3	64
X_{31}	536.5	96.0	65

Table A-18: Desired Speed of 35 mi/h with 6.7 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	51.5	35
X_1	12.9	53.1	36
X_2	26.1	54.8	37
X_3	39.8	56.5	38
X_4	54.0	58.2	40
X_5	68.5	59.8	41
X_6	83.5	61.5	42
X_7	98.8	63.2	43
X_8	114.6	64.9	44
X_9	130.8	66.5	45
X_{10}	147.5	68.2	46
X_{11}	164.5	69.9	48
X_{12}	182.0	71.6	49
X_{13}	199.9	73.2	50
X_{14}	218.2	74.9	51
X_{15}	236.9	76.6	52
X_{16}	256.1	78.3	53
X_{17}	275.6	79.9	54
X_{18}	295.6	81.6	56
X_{19}	316.0	83.3	57
X_{20}	336.8	84.9	58
X_{21}	358.1	86.6	59
X_{22}	379.7	88.3	60
X_{23}	401.8	90.0	61
X_{24}	424.3	91.6	62
X_{25}	447.2	93.3	63
X_{26}	470.5	95.0	65

Table A-19: Desired Speed of 40 mi/h with 6.7 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	58.8	40
X_1	14.7	60.5	41
X_2	29.8	62.2	42
X_3	45.4	63.8	43
X_4	61.3	65.5	45
X_5	77.7	67.2	46
X_6	94.5	68.9	47
X_7	111.7	70.5	48
X_8	129.3	72.2	49
X_9	147.4	73.9	50
X_{10}	165.8	75.6	51
X_{11}	184.7	77.2	53
X_{12}	204.0	78.9	54
X_{13}	223.8	80.6	55
X_{14}	243.9	82.3	56
X_{15}	264.5	83.9	57
X_{16}	285.5	85.6	58
X_{17}	306.9	87.3	59
X_{18}	328.7	88.9	61
X_{19}	350.9	90.6	62
X_{20}	373.6	92.3	63
X_{21}	396.6	94.0	64
X_{22}	420.1	95.6	65

Table A-20: Desired Speed of 45 mi/h with 6.7 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	66.2	45
X_1	16.5	67.8	46
X_2	33.5	69.5	47
X_3	50.9	71.2	48
X_4	68.7	72.9	50
X_5	86.9	74.5	51
X_6	105.5	76.2	52
X_7	124.6	77.9	53
X_8	144.0	79.6	54
X_9	163.9	81.2	55
X_{10}	184.2	82.9	56
X_{11}	204.9	84.6	58
X_{12}	226.1	86.3	59
X_{13}	247.7	87.9	60
X_{14}	269.6	89.6	61
X_{15}	292.0	91.3	62
X_{16}	314.9	93.0	63
X_{17}	338.1	94.6	64
X_{18}	361.7	96.3	66

Table A-21: Desired Speed of 50 mi/h with 6.7 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	73.5	50
X_1	18.4	75.2	51
X_2	37.2	76.9	52
X_3	56.4	78.5	53
X_4	76.0	80.2	55
X_5	96.1	81.9	56
X_6	116.5	83.6	57
X_7	137.4	85.2	58
X_8	158.7	86.9	59
X_9	180.5	88.6	60
X_{10}	202.6	90.3	61
X_{11}	225.2	91.9	63
X_{12}	248.1	93.6	64
X_{13}	271.5	95.3	65

Table A-22: Desired Speed of 55 mi/h with 6.7 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	80.9	55
X_1	20.2	82.5	56
X_2	40.8	84.2	57
X_3	61.9	85.9	58
X_4	83.4	87.6	60
X_5	105.3	89.2	61
X_6	127.6	90.9	62
X_7	150.3	92.6	63
X_8	173.4	94.3	64
X_9	197.0	95.9	65

Table A-23: Desired Speed of 5 mi/h with 10 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	7.4	5
X_1	1.8	9.9	7
X_2	4.3	12.4	8
X_3	7.4	14.9	10
X_4	11.1	17.4	12
X_5	15.4	19.9	14
X_6	20.4	22.4	15
X_7	26.0	24.9	17
X_8	32.2	27.4	19
X_9	39.0	29.9	20
X_{10}	46.5	32.4	22
X_{11}	54.6	34.9	24
X_{12}	63.3	37.4	25
X_{13}	72.6	39.9	27
X_{14}	82.6	42.4	29
X_{15}	93.2	44.9	31
X_{16}	104.4	47.4	32
X_{17}	116.2	49.9	34
X_{18}	128.7	52.4	36
X_{19}	141.8	54.9	37
X_{20}	155.5	57.4	39
X_{21}	169.8	59.9	41
X_{22}	184.8	62.4	42
X_{23}	200.4	64.9	44
X_{24}	216.6	67.4	46
X_{25}	233.4	69.9	48
X_{26}	250.9	72.4	49
X_{27}	269.0	74.9	51
X_{28}	287.7	77.4	53
X_{29}	307.0	79.9	54
X_{30}	327.0	82.4	56
X_{31}	347.6	84.9	58
X_{32}	368.8	87.4	59
X_{33}	390.6	89.9	61
X_{34}	413.1	92.4	63
X_{35}	436.2	94.9	65

Table A-24: Desired Speed of 10 mi/h with 10 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	14.7	10
X_1	3.7	17.2	12
X_2	8.0	19.7	13
X_3	12.9	22.2	15
X_4	18.5	24.7	17
X_5	24.6	27.2	19
X_6	31.4	29.7	20
X_7	38.9	32.2	22
X_8	46.9	34.7	24
X_9	55.6	37.2	25
X_{10}	64.9	39.7	27
X_{11}	74.8	42.2	29
X_{12}	85.4	44.7	30
X_{13}	96.5	47.2	32
X_{14}	108.3	49.7	34
X_{15}	120.8	52.2	36
X_{16}	133.8	54.7	37
X_{17}	147.5	57.2	39
X_{18}	161.8	59.7	41
X_{19}	176.7	62.2	42
X_{20}	192.3	64.7	44
X_{21}	208.4	67.2	46
X_{22}	225.2	69.7	47
X_{23}	242.7	72.2	49
X_{24}	260.7	74.7	51
X_{25}	279.4	77.2	53
X_{26}	298.7	79.7	54
X_{27}	318.6	82.2	56
X_{28}	339.2	84.7	58
X_{29}	360.3	87.2	59
X_{30}	382.1	89.7	61
X_{31}	404.6	92.2	63
X_{32}	427.6	94.7	64
X_{33}	451.3	97.2	66

Table A-25: Desired Speed of 15 mi/h with 10 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	22.1	15
X_1	5.5	24.6	17
X_2	11.7	27.1	18
X_3	18.4	29.6	20
X_4	25.8	32.1	22
X_5	33.8	34.6	24
X_6	42.5	37.1	25
X_7	51.7	39.6	27
X_8	61.6	42.1	29
X_9	72.1	44.6	30
X_{10}	83.3	47.1	32
X_{11}	95.0	49.6	34
X_{12}	107.4	52.1	35
X_{13}	120.4	54.6	37
X_{14}	134.1	57.1	39
X_{15}	148.3	59.6	41
X_{16}	163.2	62.1	42
X_{17}	178.7	64.6	44
X_{18}	194.9	67.1	46
X_{19}	211.6	69.6	47
X_{20}	229.0	72.1	49
X_{21}	247.0	74.6	51
X_{22}	265.7	77.1	52
X_{23}	284.9	79.6	54
X_{24}	304.8	82.1	56
X_{25}	325.3	84.6	58
X_{26}	346.5	87.1	59
X_{27}	368.2	89.6	61
X_{28}	390.6	92.1	63
X_{29}	413.6	94.6	64
X_{30}	437.3	97.1	66

Table A-26: Desired Speed of 20 mi/h with 10 ft/s² Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	29.4	20
X_1	7.4	31.9	22
X_2	15.3	34.4	23
X_3	23.9	36.9	25
X_4	33.2	39.4	27
X_5	43.0	41.9	29
X_6	53.5	44.4	30
X_7	64.6	46.9	32
X_8	76.3	49.4	34
X_9	88.7	51.9	35
X_{10}	101.6	54.4	37
X_{11}	115.2	56.9	39
X_{12}	129.5	59.4	40
X_{13}	144.3	61.9	42
X_{14}	159.8	64.4	44
X_{15}	175.9	66.9	46
X_{16}	192.6	69.4	47
X_{17}	210.0	71.9	49
X_{18}	227.9	74.4	51
X_{19}	246.5	76.9	52
X_{20}	265.8	79.4	54
X_{21}	285.6	81.9	56
X_{22}	306.1	84.4	57
X_{23}	327.2	86.9	59
X_{24}	348.9	89.4	61
X_{25}	371.3	91.9	63
X_{26}	394.2	94.4	64
X_{27}	417.8	96.9	66

Table A-27: Desired Speed of 25 mi/h with 10 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	36.8	25
X_1	9.2	39.3	27
X_2	19.0	41.8	28
X_3	29.4	44.3	30
X_4	40.5	46.8	32
X_5	52.2	49.3	34
X_6	64.5	51.8	35
X_7	77.4	54.3	37
X_8	91.0	56.8	39
X_9	105.2	59.3	40
X_{10}	120.0	61.8	42
X_{11}	135.4	64.3	44
X_{12}	151.5	66.8	45
X_{13}	168.2	69.3	47
X_{14}	185.5	71.8	49
X_{15}	203.4	74.3	51
X_{16}	222.0	76.8	52
X_{17}	241.2	79.3	54
X_{18}	261.0	81.8	56
X_{19}	281.4	84.3	57
X_{20}	302.5	86.8	59
X_{21}	324.2	89.3	61
X_{22}	346.5	91.8	62
X_{23}	369.4	94.3	64
X_{24}	393.0	96.8	66

Table A-28: Desired Speed of 30 mi/h with 10 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	44.1	30
X_1	11.0	46.6	32
X_2	22.7	49.1	33
X_3	35.0	51.6	35
X_4	47.9	54.1	37
X_5	61.4	56.6	39
X_6	75.5	59.1	40
X_7	90.3	61.6	42
X_8	105.7	64.1	44
X_9	121.7	66.6	45
X_{10}	138.4	69.1	47
X_{11}	155.7	71.6	49
X_{12}	173.6	74.1	50
X_{13}	192.1	76.6	52
X_{14}	211.2	79.1	54
X_{15}	231.0	81.6	56
X_{16}	251.4	84.1	57
X_{17}	272.4	86.6	59
X_{18}	294.1	89.1	61
X_{19}	316.4	91.6	62
X_{20}	339.3	94.1	64
X_{21}	362.8	96.6	66

Table A-29: Desired Speed of 35 mi/h with 10 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	51.5	35
X_1	12.9	54.0	37
X_2	26.4	56.5	38
X_3	40.5	59.0	40
X_4	55.2	61.5	42
X_5	70.6	64.0	44
X_6	86.6	66.5	45
X_7	103.2	69.0	47
X_8	120.4	71.5	49
X_9	138.3	74.0	50
X_{10}	156.8	76.5	52
X_{11}	175.9	79.0	54
X_{12}	195.6	81.5	55
X_{13}	216.0	84.0	57
X_{14}	237.0	86.5	59
X_{15}	258.6	89.0	61
X_{16}	280.8	91.5	62
X_{17}	303.7	94.0	64
X_{18}	327.2	96.5	66

Table A-30: Desired Speed of 40 mi/h with 10 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	58.8	40
X_1	14.7	61.3	42
X_2	30.0	63.8	43
X_3	46.0	66.3	45
X_4	62.6	68.8	47
X_5	79.8	71.3	49
X_6	97.6	73.8	50
X_7	116.0	76.3	52
X_8	135.1	78.8	54
X_9	154.8	81.3	55
X_{10}	175.1	83.8	57
X_{11}	196.1	86.3	59
X_{12}	217.7	88.8	60
X_{13}	239.9	91.3	62
X_{14}	262.7	93.8	64
X_{15}	286.1	96.3	66

Table A-31: Desired Speed of 45 mi/h with 10 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	66.2	45
X_1	16.5	68.7	47
X_2	33.7	71.2	48
X_3	51.5	73.7	50
X_4	69.9	76.2	52
X_5	88.9	78.7	54
X_6	108.6	81.2	55
X_7	128.9	83.7	57
X_8	149.8	86.2	59
X_9	171.3	88.7	60
X_{10}	193.5	91.2	62
X_{11}	216.3	93.7	64
X_{12}	239.7	96.2	65

Table A-32: Desired Speed of 50 mi/h with 10 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	73.5	50
X_1	18.4	76.0	52
X_2	37.4	78.5	53
X_3	57.0	81.0	55
X_4	77.3	83.5	57
X_5	98.1	86.0	59
X_6	119.6	88.5	60
X_7	141.8	91.0	62
X_8	164.5	93.5	64
X_9	187.9	96.0	65

Table A-33: Desired Speed of 55 mi/h with 10 ft/s^2 Deceleration

Location of Bar	Distance (ft)	Speed	
		ft/s	mi/h
X_0	0.0	80.9	55
X_1	20.2	83.4	57
X_2	41.1	85.9	58
X_3	62.5	88.4	60
X_4	84.6	90.9	62
X_5	107.3	93.4	64
X_6	130.7	95.9	65

VITA

Bryan Katz was born in Somerville, New Jersey to Alan and Marcia Katz. After living in New Jersey and Connecticut for a short period, he moved to Haymarket, Virginia in 1985. In 1997, he graduated from Stonewall Jackson High School in Manassas, Virginia with an International Baccalaureate diploma and went on to pursue a Bachelor of Science in Civil Engineering at Virginia Tech. At Virginia Tech, he became active in the American Society of Civil Engineers and the Institute of Transportation Engineers. He graduated with his Bachelor's Degree in 2000, Master's Degree in 2001, and continued his academic studies at Virginia Tech to pursue a Doctor of Philosophy degree in Civil Engineering. For the past five years, he has been working for Science Applications International Corporation (SAIC) at Turner-Fairbank Highway Research Center where he has been a transportation engineer and project manager on transportation safety and human factors research projects. In September 2006, he married Katie (Redden) Katz and they have established a home in Christiansburg, Virginia.