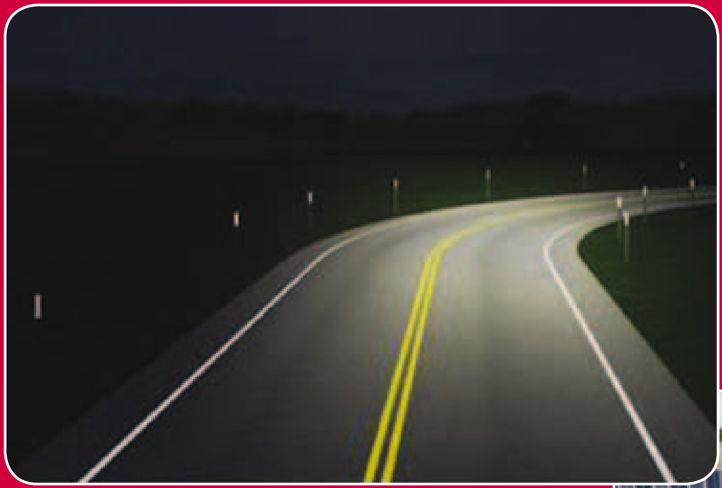
Simulator Evaluation of Low-Cost Safety Improvements on Rural Two-Lane Undivided Roads: Nighttime Delineation of Curves and Traffic Calming for Small Towns

PUBLICATION NO. FHWA-HRT-09-061 FEBRUARY 2010



U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

Motor vehicle crashes on the Nation's roadways extract a high toll on American productivity and quality of life. Highway and traffic engineers have been in pursuit of relatively low-cost safety improvements that might have the potential to reduce crashes, save lives, reduce injuries, and lower property damage. For many rural areas, low-cost safety treatments are the only affordable option.

This report describes a driving simulator experiment designed to evaluate two sets of alternative low-cost safety improvements for rural areas. The first set of improvements is directed at enhancing the visibility of curves on rural two-lane undivided roads at night. The second set of improvements is directed at slowing traffic on rural two-lane undivided roads in small towns. This report should be of interest to highway engineers, traffic engineers, highway safety specialists, local planners, researchers, and others involved in the design and operation of rural roadways.

Raymond A. Krammes
Acting Director, Office of Safety
Research and Development

TECHNICAL DOCUMENTATION PAGE

1. Report No. FHWA-HRT-09-061	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Simulator Evaluation of Low-Cost Safety Improvements on Rural Two-Lane Undivided Roads: Nighttime Delineation for Curves and Traffic Calming for Small Towns		5. Report Date February 2010 6. Performing Organization Code:
7. Author(s) John A. Molino, Bryan J. Katz, Megan B. Hermosillo, Erin E. Dagnall, and Jason F. Kennedy		8. Performing Organization Report No.
9. Performing Organization Name and Address Science Applications International Corporation (SAIC) 8301 Greensboro Drive, M/S T1-12-3 McLean, VA 22102		10. Work Unit No. 11. Contract or Grant No. DTFH61-08-C-00006
12. Sponsoring Agency Name and Address Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final Report January 2007–October 2009 14. Sponsoring Agency Code

15. Supplementary Notes

The FHWA Contracting Officer's Technical Representative (COTR) was Thomas Granda (HRDS-07). The FHWA Points of Contact for the Low Cost Safety Improvements Pooled Fund Study were Roya Amjadi and Carol Tan (HRDS-06).

16. Abstract

This experiment was sponsored by the Low Cost Safety Improvements Pooled Fund Study. It focused on two areas: (1) advanced detection and speed reduction for curves in rural two-lane roads at night and (2) traffic calming for small rural towns during the day. The experiment was conducted in the Federal Highway Administration's (FHWA) Highway Driving Simulator (HDS). Speed reduction in curves yielded the following order of tested treatments (from best to worst): (1) post-mounted delineators (PMDs) enhanced by streaming light-emitting diode (LED) lights slowed drivers down the most (9 mi/h (14.5 km/h)); (2) standard PMDs slowed drivers down by 7 to 8 mi/h (11.3 to 12.9 km/h); and (3) edge lines slowed drivers down by 2 mi/h (3.2 km/h). The same order was obtained for increases in the distance at which drivers were able to identify either the direction or the severity of the curve ahead as follows: streaming LED PMDs increased detection distance the most (560 to 1,065 ft (171 to 325 m)); standard PMDs increased detection distance by 45 to 200 ft (13.7 to 61 m); and edge lines increased detection distance by zero to 25 ft (zero to 7.6 m). PMDs performed better than pavement markings. The streaming PMDs solution offered the greatest potential increase in recognition distance. Speed reduction in towns yielded the following order of tested treatments: (1) chicanes slowed drivers down the most by 4 to 9 mi/h (6.4 to 14.5 km/h); (2) parked cars on both sides of the road slowed drivers 4 mi/h (6.4 km/h); and (3) bulb-outs resulted in only a small speed reduction of 1 mi/h (1.6 km/h) or none at all. In the case of towns, two low-cost safety solutions are worthy of further study: (1) adding painted chicanes to town entrances and (2) providing for and encouraging parking in the town. The results of this experiment do not take into account other hazardous factors that exist in the real world. Therefore, field validation is recommended for most of the above findings.

17. Key Words Roadway safety, Visibility, Curve navigation, Pavement markings, Delineators, Traffic calming, Bulb-outs, Chicanes, Driving simulators	18. Distribution Statement No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 68	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed pages authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report describes a driving simulator experiment designed to evaluate two sets of alternative low-cost safety improvements for rural areas. The experiment was sponsored by the Low Cost Safety Improvements Pooled Fund Study. The first set of improvements was directed toward enhancing the visibility of curves on rural two-lane undivided roads at night. The focus in this case was on achieving advanced detection and speed reduction in such curves. The second set of improvements was directed toward slowing traffic on rural two-lane undivided roads in small towns during the day. The focus in this case was on achieving traffic calming within the town. The experiment was conducted in the Federal Highway Administration (FHWA) Highway Driving Simulator (HDS). The two sets of potential low-cost safety improvements were combined into a single driving scenario.

Speed reduction in curves yielded the following order of tested treatments (from best to worst): (1) post-mounted delineators (PMDs) enhanced by streaming light-emitting diode (LED) lights slowed drivers down the most by an average of 9 mi/h (14.5 km/h); (2) standard PMDs slowed drivers down by 7 to 8 mi/h (11.3 to 12.9 km/h); and (3) edge lines slowed drivers down by 2 mi/h (3.2 km/h). The same order was obtained for increases in the distance at which drivers were able to identify either the direction or the severity of the curve ahead as follows: streaming LED PMDs increased detection the most (560 to 1,065 ft (171 to 325 m)); standard PMDs increased detection distance by 45 to 200 ft (13.7 to 61 m); and edge lines increased detection distance by zero to 25 ft (zero to 7.6 m). PMDs with edge lines performed better than pavement markings alone. The streaming PMDs solution offered the greatest potential increase in recognition distance.

Speed reduction in towns yielded the following order of tested treatments: (1) chicanes slowed drivers down the most by an average of 4 to 9 mi/h (6.4 to 14.5 km/h); (2) parked cars on both sides of the road slowed drivers down by approximately 4 mi/h (6.4 km/h); and (3) bulb-outs (sometimes known as neck-downs) resulted in only a small speed reduction of 1 mi/h (1.6 km/h) or none at all.

In summary, curves using PMDs with edge lines performed better in terms of slowing drivers down than curves using pavement markings alone. The streaming PMDs solution offered the most dramatic potential benefit in terms of advanced curve detection and is worthy of further research. For towns, chicanes slowed drivers down the most followed by parked cars on both sides of the road. Additional study and consideration should be given to adding painted chicanes to town entrances and providing and encouraging parking in the town. The results of this experiment do not take into account other hazardous factors which exist in the real world since it was performed in a simulated environment. Therefore, field validation is recommended for most of the above findings.

CHAPTER 1. INTRODUCTION

BACKGROUND

Safety Problem

This experiment investigated low-cost visibility enhancements for navigating rural horizontal curves at night. According to the Fatality Analysis Reporting System, of the 37,248 fatal crashes in 2007, 6,495 (17.4 percent) were on horizontal curve sections of two-lane rural roads.(1) Of those, 2,739 (42.2 percent) occurred at night. Previous data indicate that approximately 25 percent of all vehicle miles traveled (VMT) occur at night. Actually, rural local roads may have less than 25 percent of VMT occurring at night. Even if one adjusts for the more conservative total VMT, the exposure rate is more than twice as high at night compared to the day. Thus, fatal crashes on rural curves at night represent an important crash category, and improving the visibility of rural curves at night has been shown to reduce this type of crash.(2)

This experiment also investigated low-cost treatments for reducing speeds on main roads through small towns. The *Speed Management Strategic Initiative* states that in 2003, 86 percent of speeding-related fatalities occurred on roads that were not interstate highways, and the highest speeding-related fatality rates occurred on local and collector roads where the lowest speed limits were posted.(3) The strategic initiative report also suggests that further research should be conducted to identify and promote engineering measures to better manage speed and to achieve appropriate speeds on main roads through towns not suitable for traditional traffic-calming techniques. The present experiment investigated the speed-calming effects of chicanes located at the beginning and end of a town. Additionally, bulb-outs were evaluated at intersection locations in a town.

Ultimately, the goal for improving safety is to reduce the number of fatalities, injuries, and crashes. This experiment used speed reduction as a safety surrogate measure for crashes since speed is a major contributing factor in run-off-road crashes at horizontal curves as well as in the increased risk of a crash while negotiating small towns due to added hazards such as intersections and pedestrians. In the case of curves, curve detection distance serves as an additional safety surrogate measure for crashes. It is assumed that the further away a driver can detect a curve ahead in the road, the more time the driver has to react to the curve and the less likely the driver is to crash.

Pooled Fund Study Sponsorship

This experiment was sponsored by the Low Cost Safety Improvements Pooled Fund Study (PFS) Number TPF-5(099). This PFS was formed to evaluate the safety effectiveness of strategies identified in the *National Cooperative Highway Research Program (NCHRP) Report 500 Series Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*.(4) This PFS focuses on the evaluation of strategies through rigorous before-after crash evaluations of sites within the United States.(5) In cases where the quality and/or quantity of before-after crash data are/is not sufficient, other methodologies are considered, including the use of safety surrogate data collected from driving simulators.

In June 2007, the Technical Advisory Committee for the PFS met to discuss possible safety improvement strategies that might be evaluated effectively in the FHWA HDS. The selection criteria for study strategies included both the expected relative benefits and costs of each candidate treatment as well as the feasibility of implementing each candidate treatment in the HDS. Two areas were identified for the testing of alternative treatments: (1) visibility improvements to help drivers safely navigate curves in rural roads at night and (2) traffic-calming improvements to slow drivers down when passing through small rural towns during the day. A single laboratory experiment was devised to address both of these research areas, and a draft list of research questions was developed.

Candidate Safety Treatments

The initial set of visibility enhancements that were considered for rural curves included edge lines, retroreflective raised pavement markers (RRPMs), PMDs, and chevrons. However, only a limited number of alternative treatment types could be effectively studied in a single driving simulator experiment. RRPMs were eliminated because the high contrast ratio of newly applied RRPMs was difficult to reproduce in the driving simulator. Chevrons were eliminated because a large body of relatively consistent research literature already exists on that topic. Past research on chevrons has proven their effectiveness for many years. *Development of Accident Reduction Factors* summarizes many of these earlier studies and data analyses from State databases.(6) From the data, crash reductions ranging anywhere from 20 to 71 percent were found when chevrons were installed.

Edge lines and PMDs were selected as the best alternatives for a single simulator study. Both are relatively easy to simulate and are commonly used to improve driver safety on rural curves as a countermeasure for run-off-road crashes at night. Research shows that introducing and enhancing edge lines has a wide range of results from decreasing vehicle speeds by 3.1 mi/h (5 km/h) to increasing vehicle speeds by 6.6 mi/h (10.6 km/h).(7) Although the overall effect of combining the results of multiple studies was not statistically different from zero, individual experiments under different conditions showed results different from zero. In terms of driver preview distances for curves driven at night, Molino et al. calculated anywhere from a 12- to 70-percent improvement in curve detection distance due to edge lines.(8)

PMDs have also been found to reduce crash rates on relatively sharp curves at night. Highways with PMDs have lower crash rates than those without PMDs.(2) Agent and Creasey performed field and laboratory investigations which indicated that PMDs have a beneficial effect, although pavement markings have an even greater beneficial effect based on vehicle speed and lane encroachment.(9) Meanwhile, Montella evaluated the safety effectiveness of various horizontal curve delineation treatments in Italy.(10) A treatment using sequential flashing beacons was part of this evaluation. When sequential flashing beacons were added to chevrons and curve warning signs, the reported number of crashes decreased by 77 percent compared to the expected number using an Empirical Bayes analysis. A variation of these sequential flashing beacons was investigated in this experiment where simulated reflectorized PMDs enhanced by LED lamps produced a similar sequential streaming pattern of lights.

The current experiment also investigated potential low-cost speed reduction techniques for small towns. The initial set of traffic-calming treatments that may have been applied in small towns included bulb-outs, chicanes, medians, and the presence of parked cars. Medians were eliminated because only a limited number of alternative treatment types could be effectively studied in a single driving simulator experiment. Chicanes and bulb-outs were selected because they are commonly employed to slow drivers down in populated areas. *Chicanes* are curb extensions that form a series of reverse curves to force a driver to slow down. There are several resources available regarding the design of chicanes, but their effectiveness has not been determined through rigorous research. *Traffic Calming: State of the Practice* refers to an installation of chicanes and speed tables in Montgomery County, MD, where speeds decreased from 34 to 30 mi/h (54.7 to 48.3 km/h) with volume decreases from 1,500 to 1,390 vehicles per day.(11) In another location where raised crosswalks, raised intersections, and chicanes were applied in Cambridge, MA, speed reductions from 30 to 21 mi/h (48.3 to 33.8 km/h) were observed. It is important to recognize that those analyses consisted of only one location with multiple treatments, so the effects of individual treatments cannot be disaggregated. *Traffic Calming: State of the Practice* also documents reductions in crash frequencies. However, in cases where traffic volumes also decreased, such data may not be valid. Marek and Walgren found that chicanes were effective at reducing 85th-percentile speeds at four different locations in Seattle, WA, with reductions between 5 and 13 mi/h (8 to 20.9 km/h) inside the chicane area and between 1 and 6 mi/h (1.6 and 9.7 km/h) outside the chicane area (after the chicane had been passed).(12)

Bulb-outs are curb extensions that are generally located at intersections. They are designed to reduce the curb-to-curb roadway width in order to slow drivers down. King analyzed the effect of bulb-outs in New York City, NY, and found that at four of six surveyed locations, the overall severity rates for crashes were reduced after bulb-outs were installed.(13) Furthermore, at two of three locations, the injury severity rate was also reduced. Huang and Cynecki performed an analysis at two locations each in Cambridge, MA, and Seattle, WA, to determine whether drivers would yield to pedestrians with the addition of bulb-out treatments.(14) The results for Cambridge were inconclusive. In Seattle, there was no change in vehicle yielding behavior; however, the researchers did not discuss whether or not drivers reduced speeds in the vicinity of intersections with bulb-outs.

It is possible to combine half bulb-outs and implement them with painted or raised medians. In this manner, the traffic lane can be narrowed by a similar amount, but conflicting traffic can be separated, helping to prevent head-on or sideswipe opposite direction crashes. For chicanes, a similar kind of additional median barrier may be needed to reduce the likelihood of vehicles running into each other. In this instance, truck, off-tracking, and emergency vehicle use become possible issues. However, these combined strategies were beyond the scope of the current experiment.

In summary, the effects of edge lines for reducing speed in curves are inconclusive, but there is some evidence that edge lines can increase curve detection distance. PMDs tend to decrease speed and reduce crashes on curves, and streaming lights have been shown to lower crash rates. This experiment's hypothesis states that both edge lines and PMDs will lower vehicle speeds before and in curves and increase curve detection distances. For speed calming, chicanes have been shown to reduce vehicle speeds, and bulb-outs have been shown to reduce crash rates. However, both of these treatments may pose other safety hazards. The bulb-out compresses the lane width at the intersection, and the chicane deflects and narrows the roadway before the intersection. These configurations may slow down the traffic but may introduce other safety problems. For example, when considering the situation of driving through an intersection and encountering through vehicles from the opposite direction and/or turning vehicles coming from the intersecting street, bulb-outs restrict the traffic lanes and may thereby make the intersection less safe. Similarly, when considering driving through a chicane and encountering through vehicles from the opposite direction, the chicane forces tight turning maneuvers in a constricted area and may thereby make the immediate roadway less safe. Despite these safety concerns, the hypothesis states that both chicanes and bulb-outs will reduce vehicle speeds in small towns. However, when one considers the above safety reservations regarding the implementation of chicanes and bulb-outs, this hypothesis needs to be tested by means of field validation. The simulation environment of this experiment could not effectively represent many inherent dangers of implementing such treatments.

RESEARCH QUESTIONS

Curves

The research questions concerning speed and acceleration for curves are as follows:

- How do the different visibility treatments work to slow drivers down?
- What is the order of the four different visibility treatment conditions in terms of their effectiveness in slowing drivers down?
- Is there an overall effect of right versus left curves on driver speed profiles?
- Is there an overall effect of sharp versus less sharp curves on driver speed profiles?
- Is there an overall adaptation effect?
- Do drivers slow down or speed up across the three experimental driving sessions?
- How do the different visibility treatments affect driver acceleration?

The research questions concerning detecting the direction and severity of curves are as follows:

- How well do drivers perform on curve feature detection for the different visibility treatments?
- How do the different treatments affect the distance from which curve direction and severity are detected by drivers?
- What is the order of the four different visibility treatment conditions in terms of their effectiveness in improving curve feature detection distance?
- Does feature detection distance change across the three experimental driving sessions?
- Is there an overall effect of multiple exposures?

- Is learning a factor in interpreting novel visibility treatments?
- What is the effect of providing drivers with information regarding the curve direction and severity cues for the streaming PMDs condition?
- Is there an effect of right versus left curves on feature detection distance?
- Is there an effect of sharp versus less sharp curves on feature detection distance?
- What is the relationship between slowing drivers down and improving direction and severity detection distance on curves across the four treatment conditions?

Towns

The research questions concerning speed and acceleration for towns are as follows:

- How do the different traffic-calming treatments perform to slow drivers down?
- What is the order of the five different traffic-calming treatment conditions in terms of their effectiveness in slowing drivers down?
- Is there an adaptation effect?
- Do drivers slow down or speed up across the three experimental driving sessions?
- How do the different traffic-calming treatments affect driver acceleration?
- Do some of the treatments slow drivers down before reaching the town while others slow the drivers down only inside the town?

CHAPTER 2. METHOD

This experiment investigated visibility enhancements for rural curves and speed-calming treatments for small towns. The curves and towns were combined into a single driving simulator scenario to increase the efficiency of the experiment and reduce boredom for the participants. Consequently, the methodology first describes the elements which were common to both the curves and the towns. It then describes the elements that were specific to either the curves or the towns alone.

COMMONALITIES FOR BOTH CURVES AND TOWNS

Experimental Sessions

The participants received each treatment condition. The curves or towns were separated by a long tangent segment of roadway, and the approach to each curve or town was regarded as an independent trial. It was assumed that there would be little or no carry-over from one trial to the next. Each drive consisted of 26 trials with 20 curves and 6 towns in a quasi-random order separated by a tangent. These tangent segments were 20, 25, 30, 35, or 40 s in duration (driving at 55 mi/h (88.5 km/h)), presented in a uniform random distribution so that each curve or town appeared at a different distance down the road on any given trial. At the beginning of the tangent preceding a town, the simulated driving condition instantly changed from night to day. At the end of the town, the simulated driving condition instantly changed back to night.

Each participant was tested on two different days. The first day consisted of a familiarization drive, a training drive, a practice drive, and a single test drive. The familiarization and training drives were employed so that the participants were acquainted with the driving simulator and became comfortable with handling the car. The practice drive served as a primer for the first test drive, including only the baseline conditions. On the second day, participants completed three more drives. The first drive on the second day was another practice drive, which served as a refresher from day 1. The participants then completed two test drives like the test drive from the first day. The order of particular curve and town treatments was different for each test drive.

Participants

The participants were licensed drivers between the ages of 18 and 88 (the mean age was 57.6). They were recruited from the FHWA Human Centered Systems participant database, from word-of-mouth, and from newspaper and online advertising in the greater Washington, DC, metropolitan area. Of the 36 participants who completed the experiment, half were under 65 years of age (the range was 18–64 years old with a mean age of 41.7), and half were above 65 years of age (the range was 66–88 years old with a mean age of 73.6). Each age group (younger and older) was evenly distributed between males and females. The distribution of research participant characteristics is shown in table 1. Although the sample of participants was balanced for age and gender, these factors were not analyzed in the experiment. Participants were given a vision screening test to ensure that they met a minimum visual acuity requirement of at least 20/40 in at least one eye (corrected if necessary). Of the 40 research participants who began the experiment, 4 dropped out as a result of simulator sickness.

Table 1. Distribution of research participant characteristics.

Participant	Gender	Age	Age Group
1	Female	24	Younger (18–64)
2	Female	45	Younger (18–64)
3	Female	61	Younger (18–64)
4	Female	35	Younger (18–64)
5	Female	54	Younger (18–64)
6	Female	52	Younger (18–64)
7	Female	20	Younger (18–64)
8	Female	47	Younger (18–64)
9	Female	59	Younger (18–64)
10	Female	68	Older (65–88)
11	Female	73	Older (65–88)
12	Female	71	Older (65–88)
13	Female	81	Older (65–88)
14	Female	70	Older (65–88)
15	Female	74	Older (65–88)
16	Female	79	Older (65–88)
17	Female	67	Older (65–88)
18	Female	78	Older (65–88)
19	Male	46	Younger (18–64)
20	Male	23	Younger (18–64)
21	Male	64	Younger (18–64)
22	Male	18	Younger (18–64)
23	Male	50	Younger (18–64)
24	Male	54	Younger (18–64)
25	Male	26	Younger (18–64)
26	Male	26	Younger (18–64)
27	Male	46	Younger (18–64)
28	Male	66	Older (65–88)
29	Male	69	Older (65–88)
30	Male	75	Older (65–88)
31	Male	71	Older (65–88)
32	Male	71	Older (65–88)
33	Male	78	Older (65–88)
34	Male	68	Older (65–88)
35	Male	88	Older (65–88)
36	Male	77	Older (65–88)

Driving Simulator

The FHWA HDS is a relatively high-fidelity research simulator. Simulator components include a 1998 Saturn SL1 automobile cab and chassis, five projectors, and a cylindrical projector screen. Each projector has a resolution of 2,048 pixels horizontally and 1,536 pixels vertically. The image on the screen wraps 240 degrees around the forward view. Measured horizontally, the projection screen is 9 ft (2.7 m) from the driver's eye point. Under the vehicle chassis, there is a 3 degree-of-freedom motion system which is capable of moving the vehicle approximately ±12 degrees in pitch and roll and ±4 inches (10.2 cm) in heave. A sound system provides engine, wind, tire, and other environmental sounds. Rear view mirrors are simulated using 4.8-inch (12-cm)-high by 7.8-inch (19.7-cm)-wide color liquid crystal displays that have a resolution of 800 pixels horizontally and 480 pixels vertically. A picture of the FHWA HDS is shown in figure 1.

Figure 1. Photo. FHWA HDS.

The vehicle dynamics model is calibrated to approximate the characteristics of a small passenger sedan, and data capture is synchronized to the frame rate of the graphics cards (mean rate = 100 frames per second). Data recorded from the vehicle dynamics model includes speed, longitudinal acceleration, lateral acceleration, throttle position, brake force, vehicle position, and heading. A description of the basic simulator system architecture may be found in *Advanced Rendering Cluster for Highway Experimental Research*.(15) Only speed and longitudinal acceleration were analyzed in this experiment. The HDS has an infrared camera system to monitor the research participants' faces for signs of possible simulator sickness. There is also an intercom system so that the experimenter can maintain verbal communication with the research participants at all times.

Common Procedures

Day 1

Upon arrival, participants read and signed an informed consent form. They were then given a vision screening and a verbally administered health screener. The participants were led to the driving simulator where they were asked to complete a Simulator Sickness Questionnaire (SSQ) and were given a test of postural stability by means of sway magnetometry.(16,17) The same SSQ and postural stability tests were administered after each test drive in the simulator.

Participants were given instructions to read before each driving session. Then, the experimenter reiterated important information and answered questions. Day 1 began with a familiarization drive. This session lasted approximately 3 minutes or until the participants felt comfortable handling the simulator. The participants then took a 5-minute break and completed another SSQ. The next session was curve training where participants drove a series of eight horizontal curves which gradually increased in severity. This session lasted approximately 5 minutes or until the participants felt comfortable negotiating the curves. A 5-minute break and SSQ followed.

Participants progressed to the practice session, which consisted exclusively of the baseline conditions for both the curves and towns. They negotiated eight curves and three towns in this scenario. Participants were instructed to maintain a speed of 55 mi/h (88.5 km/h) on the tangents; however, they could slow to any speed for the curves and towns. They were asked to drive through the curves and towns as they normally would in the real world, to obey the law, and to observe posted speed limits. This practice drive lasted approximately 12 minutes. Upon completion, participants were given a 5-minute break. The first experimental test drive was conducted similarly to the practice drive, and the ordering of conditions in the test drive was randomly assigned before participants arrived. This first test drive lasted approximately 20 minutes.

Day 2

Participants returned for their second day within a week of their first day. They were asked to complete another baseline SSQ and postural stability test. Participants were given instructions to read before each drive just as on the first day. The experimenter reiterated important information and answered any questions. The first drive, which lasted approximately 12 minutes, was the same as the practice drive from day 1 and served as a refresher for the participants. Upon completion, participants were given a 5-minute break and read the instructions for the next experimental test drive.

Day 2 continued with two experimental test drives, which were the same as the test drive from the first day except that conditions were in a different random order for each drive. The first test drive lasted approximately 20 minutes. Following this test drive, participants were given a short break. They were then given the instructions for the final test drive, including a brief explanation of the meaning of the streaming light patterns. Participants then drove one final test drive in the same manner as the previous test drive. Upon completion of the final test drive, participants were given a final questionnaire, debriefed, and paid for their participation.

CURVES

Simulated Safety Improvements for Curves

All curves and their preceding tangents consisted of two-lane rural roadways driven at night with no fixed roadway lighting. There was no traffic on the roadway in either direction. Although traffic could have been simulated, the glare from oncoming headlights was more difficult to simulate; therefore, it was decided to employ basic driving conditions without any traffic and to depend upon possible future studies to add the complexities of traffic and glare.

Table 2 shows the curve roadway characteristics. The rural tangent and curve roadway segments had lane widths of 11 ft (3.4 m) with 3-ft (0.9-m) paved shoulders on either side. The radius of curvature was either 100 ft (30.5 m) for the sharp curves or 300 ft (91.4 m) for the less sharp curves. The deflection angle was 60 degrees for both types of curves. Both types of curves were quite sharp, and drivers needed to slow down to negotiate either type. Such curves would have posted advisory speeds of 20 or 30 mi/h (32.2 or 48.3 km/h), respectively, but no speed postings were present. The term *gentle* was used to distinguish the less sharp curves for the research participants. There were an equal number of right-hand and left-hand curves. There was no superelevation on any of the curves. While the simulator could reproduce the effects of superelevation to some degree, the reproduction of these effects was only partial and uncertain; therefore, it was decided not to employ any. The rural scenery on either side of the curves and their approaching tangents consisted of open farmland, stretches of trees, and occasional farm houses or barns. Only a small portion of this scenery was visible to the participants due to the nighttime driving environment. There were no curve warning signs preceding the curves. Advance warning signs were purposely not employed so as to measure the effects of the pavement markings and the PMDs themselves to enhance driver detection of curves ahead. At the beginning of half of the tangent sections following a town, there was a speed limit sign indicating 55 mi/h (88.5 km/h).

Table 2. Curve roadway characteristics.

Curve	Direction	Lane Width (ft)	Shoulder Width (ft)	Radius (ft)	Deflection Angle (degrees)	Typical Posted Advisory Speed in Real World (mi/h)
1	Left	11	3	100	60	20
2	Left	11	3	100	60	20
3	Left	11	3	100	60	20
4	Left	11	3	100	60	20
5	Left	11	3	100	60	20
6	Right	11	3	100	60	20
7	Right	11	3	100	60	20
8	Right	11	3	100	60	20
9	Right	11	3	100	60	20
10	Right	11	3	100	60	20
11	Left	11	3	300	60	30
12	Left	11	3	300	60	30
13	Left	11	3	300	60	30
14	Left	11	3	300	60	30
15	Left	11	3	300	60	30
16	Right	11	3	300	60	30
17	Right	11	3	300	60	30
18	Right	11	3	300	60	30
19	Right	11	3	300	60	30
20	Right	11	3	300	60	30

1 ft = 0.305 m
1 mi = 1.61 km

For the curves, the baseline condition consisted of standard 4-inch (101.6-mm)-wide double yellow centerlines on the roadway, both on the preceding tangent and on the curve itself (see figure 2). In the case of the curves, the first low-cost safety improvement beyond the centerlines was the addition of conventional 4-inch (101.6-mm) white edge lines to both sides of the roadway both on the preceding tangent as well as on the curve (see figure 3).


Figure 2. Screenshot. Curve baseline condition.


Figure 3. Screenshot. Edge lines condition.

All figures (except figure 1) depicting driving scenes represent simulator screen captures that were taken from a higher angle than the driver's eye level in order to better display the features of the treatments. For the nighttime curve scenes, this elevated vantage point also resulted in an unrealistically elevated headlight angle relative to the roadway. Thus, for the curve scenes, the illumination, shading, and reflection patterns differed somewhat from those in the actual simulator scenes viewed by the research participants.

The next levels of improvement involved the application of various configurations of reflectorized PMDs in addition to the 4-inch (101.6-mm) edge lines and centerlines. The first PMD configuration was the standard installation of delineators on the far side of each curve, which is one of the options indicated in the *Manual of Uniform Traffic Control Devices (MUTCD)*.[18] This single side PMD condition is shown in figure 4. The second PMD configuration provided PMDs on both sides of the roadway (not a currently adopted *MUTCD* option). This PMD condition is shown in figure 5. For both of these configurations, the reflectorized delineators were spaced according to the formula given in *MUTCD*, and both centerlines and edge lines were present. Thus, up to this point, all curve treatments were additive. From the baseline condition, the first treatment added was edge lines, followed by PMDs on the far side of the curve, and then PMDs on the both sides of the curve.

Figure 4. Screenshot. Single side PMDs condition.

Figure 5. Screenshot. Both sides PMDs condition.

The third configuration employed similarly spaced PMDs with simulated LED lamps at the top of each post (above the standard reflector panel; see figure 6). These enhanced delineators were located on the far side of each curve. The LED lamps were programmed to create a repetitive streaming light pattern moving in the direction of the road curvature. The LED lights streamed faster for sharp curves and slower for gentle curves. The repetition rate of the streaming light patterns was 3 Hz for sharp curves and 1 Hz for gentle curves. Thus, the LED-enhanced delineators provided information on both the direction and the severity of approaching curves.

In the streaming PMD condition displayed in figure 6, edge lines were also present. The streaming nature of the stimulus could not be conveyed in the static simulator screen capture. In the simulator, the lights were briefly illuminated (for approximately 250 ms) in a sequential manner to create a moving pattern which would traverse the scene from the lower right to the middle left at different rates depending upon the severity of the curve. Such a streaming light technology for rural two-lane curves is not yet mature, but it has some precedent in other countries where it has been applied to curves on limited access roads using only a directional cue.(10) In the current experiment, the streaming lights were operating continuously. They were not activated by the approaching vehicle by means of detecting its headlights, noise, or motion, although such activation might be appropriate for implementation on rural two-lane roads at night.

Figure 6. Screenshot. Streaming PMDs condition.

These five conditions (four treatments plus the baseline) were paired with four combinations of roadway geometry: right curves, left curves, sharp curves (100-ft (30.5-m) radius), and gentle curves (300-ft (91.4-m) radius). This made for a total of 20 unique curve segments in the experiment. All experimental drives contained each of these 20 curves in a different order. The luminance of the curve treatments, the roadway, and the background scene were measured in the simulator by means of a photometer with a 6-minute spot. Measurements were taken at different simulated scene distances relative to the driver's eye point, but the distance most illuminated by the vehicle headlights in the simulation was taken as the most relevant. This position was 82 ft (25 m) ahead of the driver's eye point. This position would be roughly equivalent to the center of the illuminated circle ahead of the vehicle in figure 6. Table 3 shows the luminance measurements made at that location. At simulated distances greater than 82 ft (25 m), the stimulus luminance was often below the sensitivity range of the photometer.

Table 3. Luminance of nighttime visual stimuli.

Scene Element	Luminance, cd/m^2
Centerline	5.4
Right edge line	3.7
Left edge line	1.7
Right reflectorized PMD	8.0
Left reflectorized PMD	7.7
Streaming LED-enhanced PMD (on cycle)	9.3
Right-lane asphalt	2.6
Left-lane asphalt	1.1

1 cd/m^2 = 0.2919 fl

Procedures Specific to Curves

Day 1

Participants were instructed to verbally indicate the direction and severity of each approaching curve as soon as they were confident that they could identify the particular roadway feature. They said “right” or “left” when they could predict the direction of the curve ahead followed by “sharp” or “gentle” when they could predict its severity. The only other word that they were allowed to say was “wrong” if they needed to correct the previous response. The task required participants to use whatever information was available to them to predict the direction and severity of the curves as far ahead of the curve as possible.

The output of a separate microphone was recorded by the simulator software system to recognize the onset of verbal responses made by the research participant. The voice onset times for the responses “right,” “left,” “sharp,” and “gentle” were captured, and the distance from this voice onset to the point of curvature (PC) of the curve ahead was computed. This automated system provided feature recognition distances for the curve stimuli. The experimenter recorded the correctness of each verbal response by means of a keypad entry.

Day 2

Day 2 consisted of a refresher practice drive and two test drives. Following the first test drive, participants were given a short break. They were then given a one-page questionnaire to ascertain how well the participants learned the meaning of the streaming lights on their own. Next, the participants were given the instructions for the final test drive. Included at the end of these instructions was a brief explanation of the streaming light patterns and how these patterns indicated both the direction and the severity of the upcoming curve.

TOWNS

Simulated Safety Improvements for Towns

For the town portion of the experiment, a single small town was simulated, and it was approached an equal number of times from each direction. The town was always presented in simulated daylight and consisted of a main two-lane roadway with marked parking spaces on each side. The town was about 1.5 blocks long with an intersection at each end of a straight central block, which was 250 ft (76.2 m) long. Single-story and two-story commercial and residential buildings lined both sides of the central block and extended 50 ft (15.2 m) on either side of the intersections at the entrance and exit of the town. Thus, each town segment was about 450 ft (137 m) long and was preceded and followed by a long rural tangent. There was no traffic on the roadway in either direction. There were sidewalks along each side of the main road within the town limits, painted crosswalks, access ramps at all intersections, and typical traffic signs for a small town. There were no pedestrians in the town. Also, the towns had no speed limit signs either before or in the town, but half of the time, there were 55 mi/h (88.5 km/h) speed limit signs on the town exits to remind the participants to accelerate to 55 mi/h (88.5 km/h) in the long tangent ahead. Table 4 shows the town roadway characteristics. Although speed limit signs were only on half of the town exits, the instructions to the research participants were to maintain a 55-mi/h (88.5-km/h) speed in all long tangent roadway sections.

Table 4. Town roadway characteristics.

Town	Low-Cost Treatment	Lane Width (ft)	Parking Lane (ft)	Sidewalk (ft)	Town Exit Speed Limit (mi/h)
1	None (baseline)	11	8	5	55
2	Parked cars	11	8	5	55
3	Curb and gutter bulb-outs	11	8	5	55
4	Painted bulb-outs	11	8	5	55
5	Curb and gutter chicanes	11	8	5	55
6	Painted chicanes	11	8	5	55

1 ft = 0.305 m
1 mi = 1.61 km

For the towns, the baseline condition consisted of standard 4-inch (101.6-mm)-wide double yellow centerlines on the roadway, both on the preceding tangent and in the town itself. This baseline condition is shown in figure 7. As was the case for the figures depicting the curve stimuli, an elevated vantage point was employed in figure 7 and in all of the subsequent figures depicting town stimuli. This elevated vantage point is higher than the one employed to portray the curves to reveal the more complicated roadway geometry associated with the town stimuli. The baseline condition had no cars parked in any of the marked parking spaces. By way of contrast, an additional condition was investigated with cars parked in most of the marked parking spaces on both sides of the main road. The parked cars condition is shown in figure 8. The first low-cost safety improvement for the towns, beyond the centerlines, was the addition of bulb-outs at all intersections in the town. These bulb-outs were simulated as curb and gutter modifications.

This curb and gutter bulb-out condition is shown in figure 9. In addition, a less expensive bulb-out configuration was implemented by means of pavement markings alone. This painted bulb-out condition is shown in figure 10. These bulb-outs were applied to both main road intersections in the simulated town (four bulb-outs per intersection or eight bulb-outs altogether). These bulb-outs were designed to reduce driver speed through the town without having a significant negative impact on traffic operations. Each travel lane was 11 ft (3.4 m) wide in the bulb-outs.

The next low-cost safety improvement consisted of chicanes at the entrance and exit of the town. These chicanes were first implemented in the standard manner by means of curb and gutter modifications. The chicanes were designed with adequately long taper lengths to achieve appropriate speeds while also allowing for large truck traffic. This curb and gutter chicanes condition is shown in figure 11. The chicanes were also implemented by means of pavement markings only. This painted chicanes condition is shown in figure 12. Each experimental drive contained one each of these six conditions in a different order with three approaches from each direction.

Figure 7. Screenshot. Town baseline condition.

Figure 8. Screenshot. Parked cars condition.

Figure 9. Screenshot. Curb and gutter bulb-outs condition.

Figure 10. Screenshot. Painted bulb-outs condition.

Figure 11. Screenshot. Curb and gutter chicanes condition.

Figure 12. Screenshot. Painted chicanes condition.

Design of Small Towns and Traffic-Calming Treatments

A state-of-practice search was performed to design an appropriate typical roadway cross section for the small town as well as to devise the bulb-out and chicane treatments. The town roadway cross section consisted of two 11-ft (3.3-m)-wide travel lanes and two 8-ft (2.4-m) parking lanes with a 5-ft (1.5-m) sidewalk on each side of the road. The total distance from curb to curb was

38 ft (11.6 m). For determining an appropriate design for the bulb-out, examples were obtained from the Delaware Department of Transportation (DelDOT) as well as from San Diego, CA; Washington, DC; and Fairbanks, AK. The bulb-out designs from these sources were fairly similar with slight variations. Ultimately, a bulb-out design was developed as shown in figure 9 and figure 10. The bulb-outs protruded only 8 ft (2.4 m) into the roadway on each side, leaving the full 11-ft (3.3-m) travel lane width in each direction. They extended 16 ft (4.8 m) along the edge of the travel lane and flared back to the parking curb at a 45-degree angle. Thus, the overall extent of the bulb-outs was 24 ft (7.3 m) with curb radii ranging from 2.5 to 6 ft (0.76 to 1.8 m).

Chicane examples were obtained from the DelDOT as well as from Cambridge, MA; State College, PA; San Diego, CA; Washington, DC; and Fairbanks, AK. Unlike the bulb-outs, chicane designs were different from each other in individual cases. Chicanes are often designed for a specific residential or neighborhood situation and not as a general treatment for a main road through a small town; however, State College, PA, implemented chicanes on one of its primary roads through the town. This site provided the basis for the design that was incorporated into the driving simulator (see figure 11 and figure 12). Figure 13 shows a plan view of the curb and gutter chicane. To provide a comfortable yet effective lateral shift when entering the town, the lanes shifted laterally 3 ft (0.9 m) and then 6 ft (1.8 m) in the opposite direction over a total distance of 88 ft (26.8 m). At that point, the lanes remained displaced by 3 ft (0.9 m) before shifting back to match up with their original cross section at the first intersection (see figure 11 through figure 13). The minimum radius of curvature was approximately 325 ft (99.1 m), and the shifts were sufficiently gradual to maintain speeds of approximately 20 mi/h (32.2 km/h). These gradual shifts were also designed to minimize truck off-tracking and to facilitate emergency vehicle use. The painted chicane followed the same geometry. The chicanes were placed at either end of the town before the beginning of the town itself. The beginning of the town without the chicane was located at the beginning of the first parking space shown in figure 12 (traveling from right to left).

Figure 13. Screenshot. Plan view of chicane geometry.

RESEARCH DESIGN

The experiment was conducted in the FHWA HDS. The driving simulator offered a cost-effective method to study the effects of potential safety countermeasures on driver behavior. In addition, field validation is recommended for safe application of countermeasures that have not been previously proven. The current experiment investigated countermeasures for two different safety problems: (1) running off the road on rural curves at night and (2) speeding through small towns. For the nighttime rural curves, two safety surrogate measures were used to infer possible reductions in run-off-the-road crashes: (1) reduced driving speed in the curve and (2) increased curve direction and severity detection distance. The experiment employed rural curves and individual small town segments preceded by a two-lane rural roadway tangent of about 30 s on average. Each participant drove in 3 experimental sessions, each consisting of 20 curves and 6 towns in a different order. Before the final session, the participants were given additional information on the coding cues for the curve condition that employed streaming PMD lights.

Run-Off Road Countermeasures

The following countermeasures were tested: edge lines, two configurations of standard PMDs, and PMDs enhanced with streaming LED lights. There were four safety treatments and one baseline condition for a total of five types of roadway delineation. The 5 curve conditions were combined with 2 curve directions (right and left) and 2 curve severities (sharp and gentle) for a total of 20 unique curves. Between the second and third test drive in the simulator, the participants were informed how to interpret the enhanced PMD condition with streaming LED lights.

Small Town Speeding Countermeasures

There were five safety treatments and one baseline condition for a total of six configurations of towns. The selected low-cost safety improvements for small towns included bulb-outs, chicanes, and the presence of parked cars along both sides of the road. This latter condition was included to test the hypothesis that parked cars might serve as a speed-calming measure. The bulb-outs and chicanes were simulated in two ways: (1) concrete curbs and gutters and (2) pavement-marking paint.

Measures of Effectiveness

The measures of effectiveness were vehicle speed and acceleration at various sampling points along the roadway. In addition to speed and acceleration, vehicle position in the travel lane as well as the magnitude and frequency of corrective steering are all important safety surrogate measures when navigating a horizontal curve. It was possible to measure both vehicle position in the travel lane and corrective steering actions in the FHWA HDS. However, these measurements were beyond the scope of this experiment. Time-stamped voice responses were also recorded to indicate driver feature detection for both the direction and severity of curves ahead in the roadway. In addition, questionnaire responses were obtained after certain driving sessions.

CHAPTER 3. RESULTS

CURVES

Speed Profiles for Curves

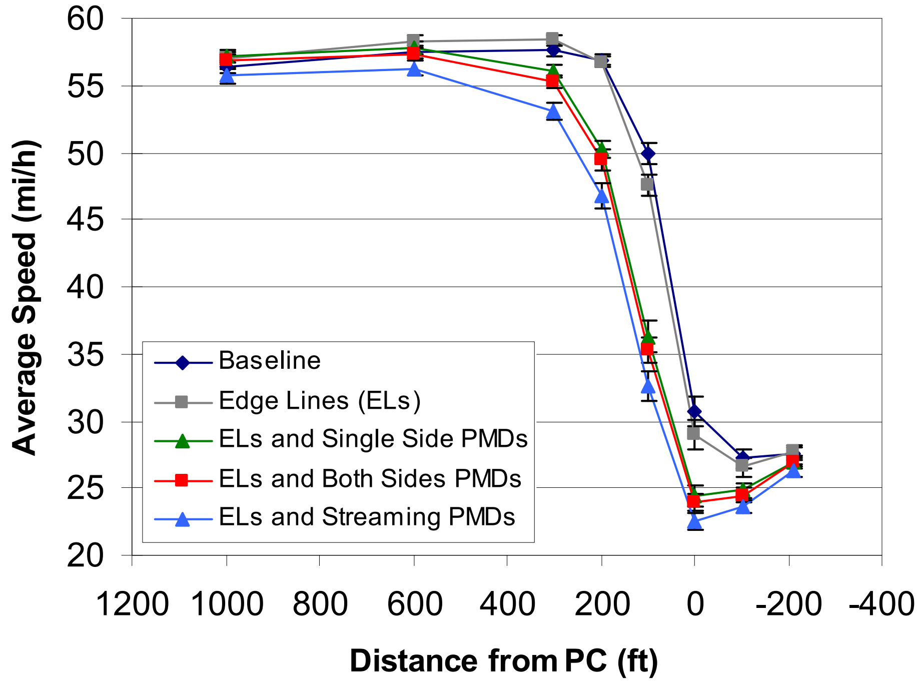
In this experiment, the effects of various low-cost safety improvements on driving speed were explored by means of speed profiles. In the case of curves, these speed profiles showed the average driving speed as a function of distance from the PC for the five curve treatment conditions. For example, the data in figure 14 represent speed profiles for sharp curves. In this instance, the data portray average speeds across all participants, both curve directions, and all three drives. Data are shown for all eight measurement locations. Positive distances indicate measurement locations ahead of the curve (before the PC), and negative distances indicate distances in the curve (after the PC). Error bars represent one standard error of the mean. The data constituting these speed profiles were analyzed according to a multivariate analysis of variance (MANOVA) approach to repeated measures.

Effects of Possible Interactions

A major interest in this experiment was the effect of various visibility treatments to reduce driving speed. However, the experimental design included several other important variables which could interact with these observed treatment effects on driving speed. These other variables were the severity of the curve (sharp or gentle), the direction of the curve (right or left), and the degree of driving exposure in the simulator (experimental drive 1, 2, or 3). In the following sections, the effects of these three variables will be explored as they relate to the speed profiles for the various treatment conditions as well as their interactions.

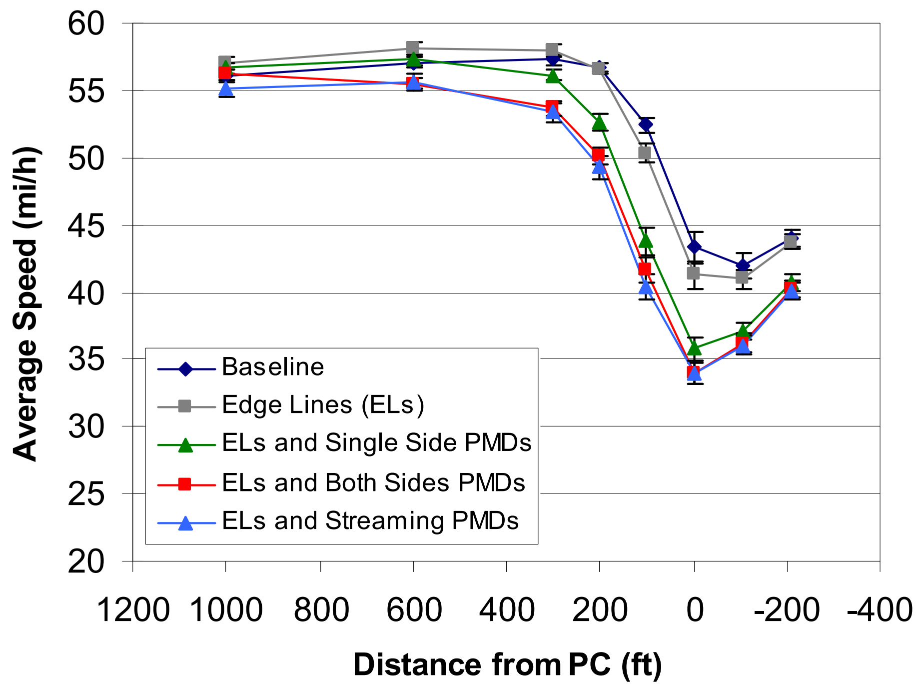
Curve Severity

As previously indicated, figure 14 shows the speed profiles for sharp curves. The point of tangency (PT) for the sharp curves was at about -105 ft (-32 m). The initial entry speed was high for all curves because the participants were asked to maintain a speed of 55 mi/h (88.5 km/h) in the long tangent sections preceding the curves. In the case of the sharp curves, drivers slowed down from approximately 57 mi/h (91.7 km/h) when they were 600 ft (182.9 m) away from the curve to approximately 23 mi/h (37 km/h) at the PC for the delineators and to approximately 30 mi/h (48.3 km/h) at the PC for the pavement markings. Figure 15 shows the speed profiles for gentle curves. The PT for the gentle curves was at about -314 ft (- 95.7 m). In this case, from about 57 mi/h (91.7 km/h) at 600 ft before the curve, drivers slowed down at the PC to about 35 mi/h (56.3 km/h) for the delineators and to about 43 mi/h (69.2 km/h) for the pavement markings. In the curve itself, the average driving speed was about 10 mi/h (16 km/h) slower for the sharp curves than for the gentle curves. This difference in speed between sharp and gentle curves was statistically significant ($F (1, 35) = 818$, $p < 0.001$) and corresponded to the calculated but not posted advisory speed difference of 10 mi/h (16 km/h). As evidenced in the different slopes and shapes for the curves in figure 14 and figure 15, there was also a statistically significant treatment by severity by location interaction ($F (28, 8) = 18.6$, $p < 0.001$). However, as can be seen in the figures, for distances less than 600 ft (183 m), the visibility treatments aligned themselves in a consistent pattern.



1 ft = 0.305 m
1 mi = 1.61 km

Figure 14. Graph. Average speed as a function of the distance from the PC for sharp curves.



1 ft = 0.305 m
1 mi = 1.61 km

Figure 15. Graph. Average speed as a function of the distance from the PC for gentle curves.

Curve Direction

In the curve itself, the average driving speed was about 1 mi/h (1.6 km/h) slower for the right curve than for the left curve (not shown). Such a difference might be expected since the right curves had a slightly shorter turning radius than the left curves. The difference in speed between right and left curves was statistically significant but small ($F (1, 35) = 13.8$, $p < 0.001$). The functions for the right versus left curves looked similar to the functions for the sharp versus gentle curves shown in figure 14 and figure 15 except that the differences in speed were smaller in the curve itself. There was also a significant treatment by direction interaction ($F (4, 32) = 3.63$, $p < 0.015$). Nevertheless, for distances less than 600 ft (183 m), the visibility treatments aligned themselves in a consistent pattern.

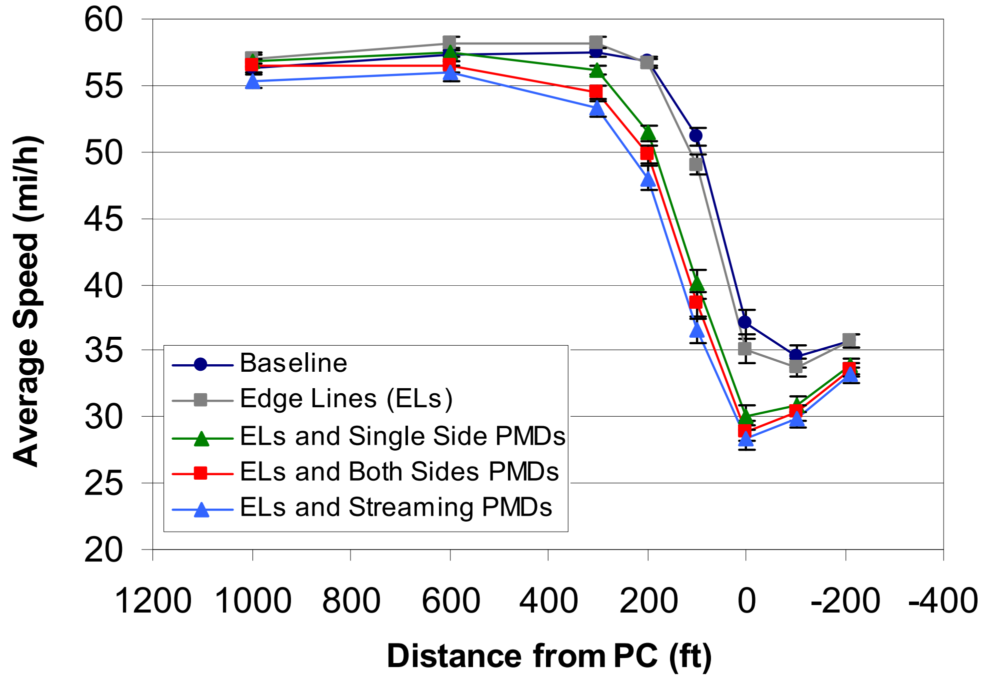
Drive

Despite multiple differences (days, instructions, etc.) across the three experimental driving sessions, the drive effect was not statistically significant. Thus, drivers did not speed up or slow down across driving sessions, and no adaptation or learning was observed. The treatment by drive interaction was also not statistically significant.

Effects of Treatments

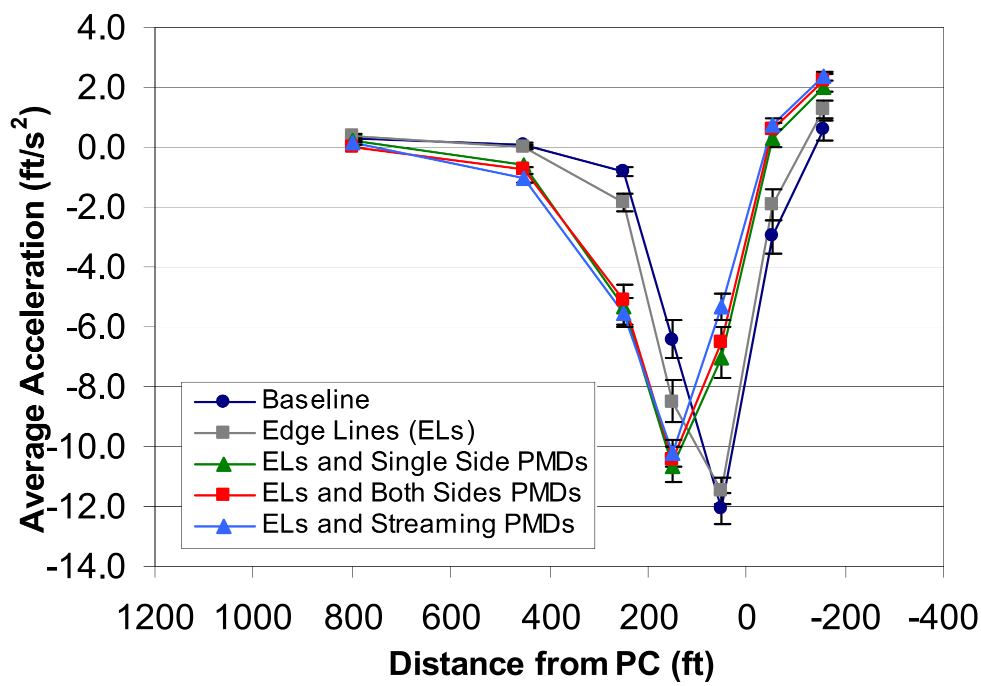
Figure 16 shows the average driving speed as a function of distance from the PC for the five curve treatment conditions. Figure 17 refers to corresponding curve acceleration data which will be described later. The data represent speed profiles in terms of average speeds across all participants, curve geometries, and drives. The error bars represent one standard error of the mean, and data are shown for all eight measurement locations.

The speed profiles in figure 16 indicate a constant portion in the far tangent, then a rapid deceleration, followed by a shallow dip. As indicated by this distinct shape, the location effect was statistically significant ($F (7, 29) = 536$, $p < 0.001$). The drivers tended to slow down from about 57 mi/h (91.7 km/h) at 600 ft (183 m) before the curve to about 28 to 37 mi/h (45 to 59.5 km/h) at the PC depending on the type of treatment. The treatments tended to organize into two groups: (1) pavement markings (baseline (centerlines only) and edge lines (centerlines with edge lines)) and (2) delineators (single side PMDs, both sides PMDs, and streaming PMDs). This treatment effect was statistically significant ($F (4, 32) = 51.7$, $p < 0.001$). The delineators were more effective than the pavement markings in slowing the drivers down earlier and to a greater degree. Before the curve itself, the shapes of the speed profile functions were similar for both types of safety countermeasures. However, in the curve, the minimum speed was achieved earlier for the delineators at the PC, and later, for the pavement markings at the middle of the curve. Thus, there was a difference in shape for the two different groups of speed profiles. In addition, before the visibility treatments had much effect at 1,000 ft (305 m) away from the PC and after the curve had been passed at the PT, there was little observed speed difference among the treatments as anticipated. As expected from these minor differences in the shapes of the profiles, there was a statistically significant treatment by location interaction ($F (28, 8) = 25.4$, $p < 0.001$). Nevertheless, for distances less than 600 ft (183 m), the consistent treatment effect was evident over the entire range of locations with no reversals in order.



1 ft = 0.305 m
1 mi = 1.61 km

Figure 16. Graph. Average speed as a function of the distance from the PC.



1 ft = 0.305 m
1 mi = 1.61 km

Figure 17. Graph. Average acceleration as a function of the distance from the PC.

At 100 ft (30.5 m) before the curve, curves with pavement markings had an average speed of about 51 mi/h (82 km/h), and curves with delineators had an average speed of about

39 mi/h (62.8 km/h), which was a 12-mi/h (19.3-km/h) difference. At the PC, the delineators slowed the drivers down about 7 mi/h (11.3 km/h) more than the pavement markings. Closer than 200 ft from the curve within the pavement markings category, the presence of an edge line may have reduced driver speed by about 1 to 2 mi/h (1.6 to 3.2 km/h) relative to the baseline. This seemed to be a consistent but small effect. Closer than 600 ft from the curve within the delineator category, the PMD conditions represented a consistent order in terms of their effectiveness in slowing the driver down. From least effective to most effective, this order was single side PMDs, both sides PMDs, and streaming PMDs. The relative effects of the different PMD configurations were orderly but small.

This rank order was confirmed by a series of statistical tests. Pair-wise analysis of variance (ANOVA) comparisons were made between the baseline condition and each visibility enhancement to the baseline as well as between neighboring pairs in the above order of treatment effectiveness. All of these seven pair-wise comparisons revealed a statistically significant treatment effect except for baseline versus edge lines. This outcome may have been due to the fact that edge lines were applied to the entire tangent roadway segment before the curve as well as through the curve. The data indicate that the application of edge lines in these straight tangent roadway segments may have actually increased vehicle speed relative to the baseline at distances of greater than 200 ft (61 m) ahead of the curve. Over the distance of 1,000 to 300 ft (305 to 91.4 m), this increase in speed was statistically significant ($F(4, 32) = 11.3$, $p < 0.001$). When only the distances of 200 ft (61 m) or less were considered, the baseline versus edge lines comparison was statistically significant ($F(4, 32) = 73.3$, $p < 0.001$). Thus, the four safety countermeasures may be ranked as indicated above.

At 1,000 ft (305 m) from the curve, the streaming PMDs had a slightly lower speed than all of the other conditions (about 1 to 2 mi/h (1.6 to 3.2 km/h) difference). This difference was statistically significant ($F(4, 29) = 13.5$, $p < 0.001$). This outcome might be expected because at night, the streaming PMDs can be seen from greater than 1,000 ft (305 m) away.

Speed Reductions for Curves

In figure 16, the PC (zero ft (zero m)) and the middle of the curve (-105 ft (-32 m) for combined data) are important locations for measuring driver behavior. These locations bound the first half of the curve where it is important that the driver has slowed the vehicle down to a safe speed for entering and navigating the curve. For different curve safety countermeasures, table 5 shows the average vehicle speed at the PC and at the middle of the curve along with the corresponding speed reduction advantages relative to the baseline speed. For average speeds, standard errors of the mean are shown in parentheses.

Columns 2 and 4 in table 5 represent two important vertical slices of the data portrayed in figure 16. The visibility treatments in table 5 are arranged in order of increasing effectiveness in achieving a lower speed at either the PC or the middle of the curve. An examination of the standard errors reveals that most are below 1 mi/h (1.6 km/h). Thus, when comparing pairs of speeds in table 5, speed reductions of 2 mi/h (3.2 km/h) or greater are likely to be statistically significant. The PC was selected as the most appropriate single location to measure and compare possible speed reduction advantages for two reasons. First, if drivers entered a curve at an excessive speed, it was often too late to take the necessary compensatory actions to safely navigate the curve. Second, for curves with relatively small deflection angles (60 degrees in this experiment), drivers tended to accelerate by the middle of the curve in anticipation of exiting the curve.

Table 5. Average speed and speed reduction advantage in curves (mi/h).

Treatment Condition	Average Speed at Point of Curvature (SE)	Reduction Advantage Relative to Baseline	Average Speed at Middle of Curve (SE)	Reduction Advantage Relative to Baseline
Baseline	37.0 (1.11)	0	34.6 (0.76)	0
Edge lines	35.1 (1.02)	1.9	33.8 (0.68)	0.8
Single side PMDs	30.1 (0.75)	6.9	31.0 (0.60)	3.6
Both sides PMDs	29.0 (0.68)	8.0	30.3 (0.57)	4.3
Streaming PMDs	28.3 (0.71)	8.7	29.8 (0.59)	4.8

1 mi = 1.61 km
Note: Standard error (SE) is shown in parentheses.

From figure 16 and table 5, it is clear that the four enhanced visibility treatment conditions showed a consistent order in terms of their effectiveness in slowing drivers down relative to the baseline. In this regard, the relative speed reduction advantages at the PC may be rounded to whole numbers and taken as a figure of merit. If this is done, the following order was observed, from least effective to most effective: edge lines (2 mi/h (3.2 km/h)), single side PMDs (7 mi/h (11.3 km/h)), both sides PMDs (8 mi/h (12.9 km/h)), and streaming PMDs (9 mi/h (14.5 km/h)). Overall as a group, the delineators were more effective than the pavement markings in slowing drivers down both before and in the curves. Pair-wise statistical comparisons were computed for the 20 combinations of all 5 average speeds at the PC (see column 2). All 20 comparisons revealed a statistically significant difference, confirming the above order of treatments. Similar pair-wise comparisons were computed for the middle of the curve location (column 4) with the same outcome. All 20 comparisons revealed a statistically significant difference.

Acceleration Profiles for Curves

Figure 17 shows the average longitudinal acceleration of the vehicle as a function of distance from the PC for the five different curve visibility treatment conditions. The data represent acceleration profiles which complement the corresponding speed profiles portrayed in figure 16. The error bars in figure 17 represent one standard error of the mean. Since acceleration determinations were computed from differences in speed, measurements for only seven intermediate locations are shown. The acceleration profiles had a pronounced V-shape and were organized into the same two groups of treatments as were found for the speed profiles—delineators and pavement markings. As expected from this distinct shape, the location effect was statistically significant ($F(6, 27) = 360$, $p < 0.001$). Such a correspondence was expected since the acceleration profiles were derived from the speed profiles and represented a different perspective on the same driver performance. As seen in figure 17, when compared with the pavement markings, the delineators revealed a gentler and more spread-out V-shaped function with a less pronounced negative acceleration dip that occurred well before the PC. By contrast, the pavement markings revealed a more severe and narrow V-shaped function with a more pronounced negative acceleration dip occurring later in the curve approach at the PC. In general, the delineators were associated with a smoother and earlier deceleration pattern than the pavement markings. This treatment effect was statistically significant ($F (4, 29) = 10.6$, $p < 0.001$). The effects of both curve severity ($F (1, 32) = 258$, $p < 0.001$) and drive ($F (2, 31) = 8.39$, $p < 0.001$) were also statistically significant.

Feature Detection for Curves

The participants stated "right" or "left" followed by "sharp" or "gentle" as soon as they detected the direction and severity of the curve ahead. They also had the opportunity to change or correct their judgments as they came closer to the curve. Only the last response counted for both correctness and distance to the curve. Two measures were derived from these responses: (1) the percentage of correct responses for each feature (direction and severity) and (2) the percentage of times the feature was detected without the necessity to make a change in the response. Another measure was the feature detection distance for the last response given. Table 6 shows the percentage of correct responses for curve direction detection and curve severity detection (columns 2 and 3). The table also shows the percentage of times that the feature was detected without a change from the initial response (columns 4 and 5).

Table 6. Percentage of correct responses and no change responses for feature detection.

Visibility Treatment	Percent Correct, Direction Detection	Percent Correct, Severity Detection	Percent No Change, Direction Detection	Percent No Change, Severity Detection	Number Of Responses, (*n*)
Baseline	100	83.8	98.8	90.7	432
Edge lines	99.4	82.9	98.8	91.7	432
Single side PMDs	99.9	84.7	94.2	88.4	432
Both sides PMDs	99.9	82.2	96.1	89.6	432
Streaming PMDs	99.9	78.7	99.5	91.6	432
Overall	99.7	82.5	97.5	90.4	2,160

As is evident in the table, the sample of participants in this experiment performed extremely well in correctly detecting the direction of the curve ahead (99.7 percent correct overall). The participants were also quite confident in their judgments of curve direction, making 97.5 percent of their overall responses without any corrections.

The sample of participants did not perform as well in correctly detecting the severity of the curve ahead (82.5 percent correct overall). Nevertheless, since guessing would yield 50 percent correct responding, even their performance on the severity detection task was well above chance. If the normal approximation to the binomial is employed to the worst case in table 6 ($p = 0.787$; $P = 0.500$; $n = 432$), the probability of obtaining a sample correct response rate of 78.7 percent when the population correct response rate is 50.0 percent is extremely small ($z = 11.91$, $p < 0.001$). Thus, although the participants were making a substantial number of errors in detecting the severity of the curve ahead, they were still performing considerably better than chance (over 80 percent correct). As might be expected, their confidence in these severity judgments was not as strong as their confidence in the corresponding direction judgments, making only 90.4 percent of their overall severity responses without any corrections as opposed to 97.5 percent of their overall direction responses. Still, over 90 percent of all severity judgments were made without the necessity to make a change. This reduced performance on curve severity judgments relative to curve direction judgments indicates that additional visual cues may need to be provided to the driver to assist in detecting the severity of approaching curves.

Of the 379 errors made in estimating curve severity, 49.9 percent were made estimating right curves, and 50.1 percent were made estimating left curves. Thus, it was equally easy to estimate the direction of right or left curves. Of the same 379 errors, 42.7 percent were made estimating sharp curves, and 57.3 percent were made estimating gentle curves. If the normal approximation to the binomial is employed again, this discrepancy is extremely unlikely ($z = 2.84$, $p < 0.003$). The participants found it easier to estimate the severity of sharp curves than gentle curves. This outcome might be expected since both sharp and gentle curves had the same deflection angle of 60 degrees. This situation resulted in the sharper curves having a more compressed forward field of view, providing more simultaneous foveal visual cues for estimating the radius of curvature. It is interesting to note that the streaming PMDs condition performed the worst in terms of correct curve severity estimation. This result is surprising considering that the streaming PMDs condition was the only visual stimulus which incorporated a supplemental coding scheme to indicate curve severity. Apparently, this coding scheme was difficult to comprehend, and the rapid moving light patterns may have obscured other cues normally used to estimate curve severity (e.g., radius of curvature).

Curve Direction Detection Distance

Figure 18 shows the average curve direction detection distance for the five visibility treatments as a function of the number of the drive. The right side of the figure shows the results collapsed across all three drives. The error bars represent one standard error of the mean.

Curve geometry had no effect on curve direction detection—both curve severity and direction effects were not statistically significant. However, both the treatment by drive ($F (8, 28) = 3.13$, $p < 0.012$) and the treatment by severity ($F (4, 32) = 4.20$, $p < 0.008$) interactions were statistically significant. The treatment by drive interaction is apparent in the positively accelerating shapes of the bar charts given in figure 18 when compared across drives. The treatment by severity interaction was reflected primarily in a skew for the streaming PMDs condition (not shown). Despite these interactions, a consistent pattern of average detection distance for curve direction across treatments is evident in figure 18. This consistent pattern persists across all three drives and is also reflected across both curve severities (sharp versus gentle). Such a uniform pattern indicates the existence of a significant main effect of the visibility treatments themselves in addition to significant interactions with drive and curve severity. As evident in figure 18, the five different visibility treatments were organized into three groups: pavement markings, conventional PMDs, and streaming PMDs. Over all drives, this main treatment effect was statistically significant ($F (4, 32) = 66.9$, $p < 0.001$).

For curves with only pavement markings (baseline and edge lines), the direction of the curve could be detected from an average distance of 225 to 260 ft (68.6 to 79.2 m). By contrast, for curves with conventional reflectorized PMDs (single side PMDs and both sides PMDs), the direction of the curve could be detected at almost twice that distance between 385 and 465 ft

(117 and 142 m). It is of interest to note that the both sides PMDs condition had a lower average direction detection distance (383 ft (117 m)) than the single side PMDs condition (466 ft (142 m)). This outcome may be the result of possible visual confusion caused by the larger number of PMD posts simultaneously in view for the both sides PMDs condition and their more complex geometric arrangement, making direction estimation more difficult. Nevertheless, as far as the speed reductions were concerned (see table 5), the both sides PMDs condition posed a more formidable visual array and slowed drivers down more than the single side PMDs condition by about 1 mi/h (1.6 km/h). The greatest improvement in direction detection distance was afforded by the LED-enhanced PMDs (streaming PMDs). For these sequential flashing PMDs, the average curve direction detection distance ranged from about 1,100 to 1,500 ft (335 m to 457 m), which was five times the baseline distance of about 225 to 260 ft (68.6 to 79.2 m). Since this streaming PMD condition was continuously operating and not activated by an approaching vehicle, the sequential pattern of flashing lights could be seen from a great distance.

The four enhanced visibility treatment conditions represented a consistent order in terms of their effectiveness in increasing the distance at which the participants could detect the direction of curves ahead in the roadway. As can be seen in figure 18, a similar order was maintained across all three drives, and this order was the same for all drives combined. Similar to what was done for vehicle speed, the relative detection distance advantages offered by the different treatments may be rounded to 5-ft (1.52-m) increments and taken as a figure of merit. When this is done, the following order was observed for direction detection distance from least effective to most effective: edge lines (25 ft (7.62 m)), both sides PMDs (130 ft (39.6 m)), single side PMDs (200 ft (61.0 m)), and streaming PMDs (1,065 ft (325 m)). For all three drives, the most dramatic improvement in average direction detection distance was associated with the streaming PMDs condition, a 1,065-ft (325 m) advantage over baseline in the combined case.

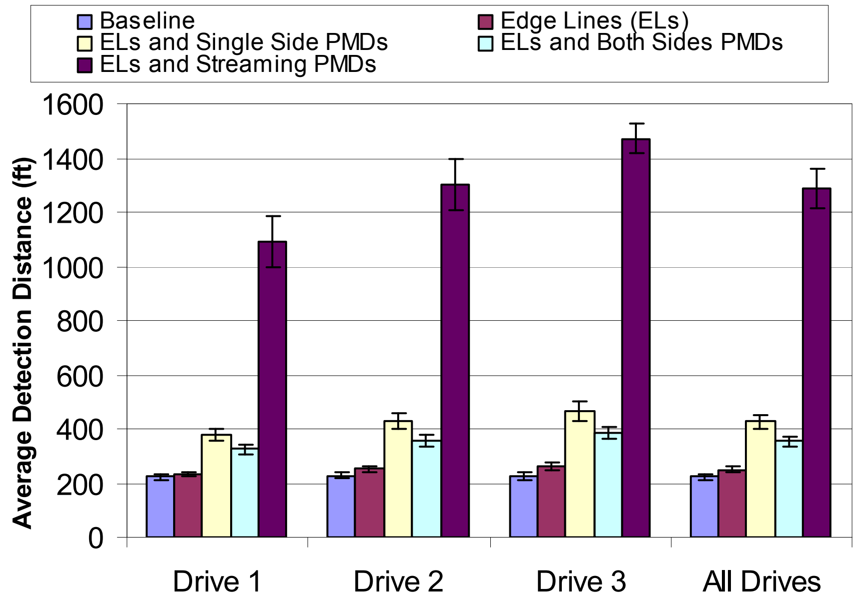
Pair-wise ANOVA comparisons were made between the baseline condition and each additional visibility enhancement as well as between neighboring pairs in the above order of treatment effectiveness. These pair-wise comparisons were only conducted on the combined data from drives 1 and 2 since the instructions to the participants changed on day 3. All of these seven pair-wise comparisons revealed a statistically significant treatment effect. Thus, as concerns enhancing direction detection distance for curves, the four safety countermeasures can be ranked as indicated above.

The enhanced direction detection distance for the streaming PMDs condition was increased to a 1,247-ft (380-m) advantage relative to the baseline when only drive 3 data were considered. The corresponding advantage relative to the baseline for drive 2 was 1,079 ft (329 m). Just prior to drive 3, the participants were informed of the meaning of the streaming PMD coded cues, including the cue for direction. This change in instructions could have been responsible for the observed increase in average detection distance for drive 3. Comparison of the advantages from drives 2 and 3 indicated that, in terms of direction detection distance, explaining the direction cue to the participants could result in a possible 16-percent advantage over having the participants figure out the meaning for themselves. However, this increased advantage is relatively small and could be due to learning which might have taken place even if no additional information had been provided in the instructions.

Figure 18 also reveals a consistent adaptation or learning effect across the three drives, with the average curve direction detection distance increasing in each category with progressive drives. This drive effect was statistically significant ($F(2, 34) = 20.2$, $p < 0.001$). For the streaming PMDs condition, the drive 1 direction detection distance advantage was 864 ft (263 m) relative to the baseline, and the drive 2 advantage was 1,079 ft (329 m) for a gain of approximately 25 percent. If adaptation were linear, the detection distance advantage might be expected to be about 1,348 ft (411 m) for drive 3, which was greater than the 1,247 ft (380 m) that was observed. In fact, this 25-percent adaptation effect could completely account for the 16-percent increased advantage attributed earlier to being informed of the curve direction cue encoded in the streaming PMDs condition. Thus, the research participants were likely learning the meaning of the curve direction cue on their own. This cue was highly intuitive (streaming toward the right meant a right curve was approaching, and streaming toward the left meant a left curve was approaching) and probably did not require additional instructions for most of the research participants. The results of the questionnaire revealed a similar high degree of learning. After drive 2, before receiving any instructions, 83 percent of the participants knew the meaning of the direction cue. After drive 3 and receiving the instructions, 97 percent knew the meaning.

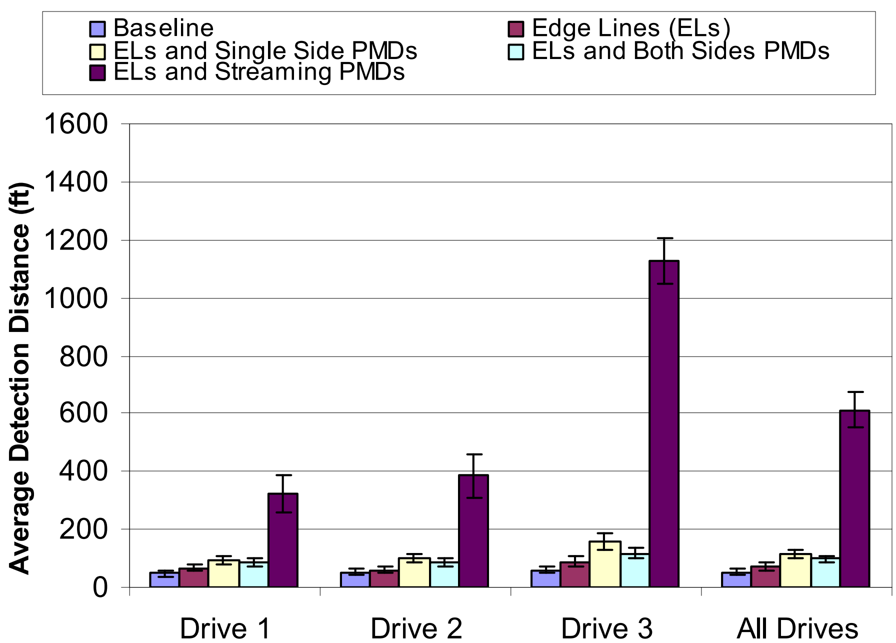
Curve Severity Detection Distance

Overall, similar relative results were found for the average distance at which the participants could detect the severity of a curve ahead in the roadway, but the absolute magnitudes were smaller. Figure 19 shows the average curve severity detection distance for the five visibility treatments as a function of the number of the drive. Similar to direction detection distance, the right-hand side of figure 19 shows the severity detection distance results collapsed across all three drives.



1 ft = 0.305 m

Figure 18. Graph. Average curve direction detection distance as a function of drive.



1 ft = 0.305 m

Figure 19. Graph. Average curve severity detection distance as a function of drive.

For severity detection distance, the effects of curve geometry were mixed. The sharp curves (222 ft (67.7 m)) had a greater average detection distance than the gentle curves (158 ft (48.2 m)). This curve severity effect was statistically significant (F (1, 35) = 40.6, $p < 0.001$), but the curve direction effect was not. In addition, there were two statistically significant interactions, the same two as were found for curve direction detection distance: (1) treatment by drive (F (8, 28) = 12.1, $p < 0.001$) and (2) treatment by severity (F (4, 32) = 5.48, $p < 0.002$).

These interactions were reflected in the data relationships in the same way as for direction detection distance. There was also a statistically significant treatment by severity by direction interaction ($F(4, 32) = 2.84$, $p < 0.004$).

A consistent pattern of average detection distance for curve severity across treatments is evident in figure 19. This consistent pattern persists across all three drives, both curve severities and both curve directions. As evident in figure 19, for severity detection distance, the five different visibility treatments organized themselves into two major groups: (1) streaming PMDs and (2) all others. For all conditions other than streaming PMDs, the average curve severity detection distance was about 55 to 115 ft (16.8 to 35.1 m). The average curve severity detection distance was much greater for the streaming PMDs condition (612 ft (187 m)). Across all drives, this treatment effect was statistically significant ($F(4, 32) = 28.0$, $p < 0.001$).

Figure 19 also reveals a consistent adaptation or learning effect across the three drives, with the average curve severity detection distance increasing in each category with progressive drives similar to what was found for curve direction detection distance in figure 19. This drive effect for severity detection distance was statistically significant ($F(2, 34) = 42.5$, $p < 0.001$). As with direction detection, the most dramatic improvement in average severity detection distance was associated with the streaming PMDs. For the streaming PMDs condition, on drives 1 and 2, the participants could detect curve severity at a distance of about 325 to 385 ft (99.1 to 117 m) with no special instructions as to the meaning of the curve severity cue. On drive 3, after the participants were informed of the meaning of the severity cue, the average curve severity detection distance increased to about 1,127 ft (344 m), representing an advantage of 1,074 ft (327 m) relative to the baseline condition. Since the corresponding day 2 advantage relative to the baseline was 333 ft (102 m), providing information to the participants concerning the severity cue coded in the streaming PMD lights resulted in a 300-percent increase in relative detection distance advantage over letting the participants figure out the meaning for themselves.

The participants had difficulty learning the meaning of the curve severity cue on their own. In terms of severity detection distance, their performance improved dramatically after being informed of the meaning of the curve severity cue. Such an increase is not likely to be the result of adaptation, as can be seen in figure 19. For the streaming PMDs condition, the detection distance advantage in the first drive was 271 ft (82.6 m) relative to the baseline, and the advantage for the second drive was 333 ft (102 m) for a gain of only about 23 percent. If adaptation was linear, the detection distance advantage might be expected to be about 410 ft (125 m) for drive 3 instead of the 1,074 ft (327 m) that was observed. The results of the questionnaire revealed a similar picture. After drive 2 before receiving any instructions, only 64 percent of the participants knew the meaning of the severity cue. After receiving the instructions for drive 3, 97 percent of the participants knew the meaning.

Except for the streaming PMDs condition, the average curve severity detection distances in figure 19 were much shorter than the corresponding average curve direction detection distances in figure 18 by a factor of two to four times. This outcome indicates that at a given distance ahead of a curve, other factors being equal, detecting the direction (right versus left) of the curve is likely to be easier than detecting the severity (radius) of the curve. To make performance equivalent for the two curve features, additional visual information would need to be provided to the driver in the form of distinct cues for curve severity.

Relative to the baseline, the four enhanced visibility treatment conditions represented a consistent order in terms of their effectiveness in increasing the distance at which the participants could detect the severity of curves ahead in the roadway. This relationship was discernable despite the fact that, except for the streaming PMDs condition, all of the average detection distance values were rather low and close together. As can be seen in figure 19 and table 7 (columns 4 and 5), a similar order was maintained across all three drives, and this order was the same for all drives combined. If increased curve severity detection distance is taken as the figure of merit, this order was as follows (from least effective to most effective): edge lines (20 ft (6.1 m)), both sides PMDs (45 ft (13.7 m)), single side PMDs (65 ft (19.8 m)), and streaming PMDs (560 ft (170 m)).

Pair-wise ANOVA comparisons were conducted as was done for direction detection distance. All of these seven pair-wise comparisons revealed a statistically significant treatment effect except for two. The first exception was between the baseline and the edge lines. In this experiment, there was no advantage of adding edge lines for increasing severity detection distance. The second exception was between single side PMDs and both sides PMDs. In this case, both of these conditions were statistically different from the baseline. However, for detecting the severity of curves ahead, it did not matter whether reflectorized PMDs were on one side of the curve or on both sides. Thus, for detecting the severity of curves, the safety countermeasures devolved into only two ranks: both reflectorized PMDs (45 to 65 ft(13.7 to 19.8 m)) and streaming PMDs (560 ft (171 m)).

For all drives, table 7 shows the average feature detection distance and distance advantage for the different curve visibility treatment conditions. Columns 2 and 4 give the data for the right-hand portions of figure 18 and figure 19. For each treatment condition, columns 3 and 5 give the relative advantages of the different treatments in increasing feature detection distance relative to the baseline. The visibility treatments in table 7 are arranged in order of increasing effectiveness in achieving a greater feature detection distance for both curve direction and curve severity. The last row in the table is an exception. This row shows the average feature detection distance for drive 3 only when the participants had just been informed of the meaning of the direction and severity cues coded in the patterns of steaming PMDs. An examination of the standard errors in table 7 reveals that most were below 25 ft (7.6 m) except for the streaming PMDs condition. For most treatments, when comparing pairs of distances in the table, distance reductions of 50 ft (15.2 m) or greater were likely to be statistically significant. In the case of streaming PMDs, this distance reduction criterion increased to150 ft (45.7 m) or greater due to increased variability in the detection distance data for this condition.

Table 7. Average feature detection distance and distance advantage for curves.

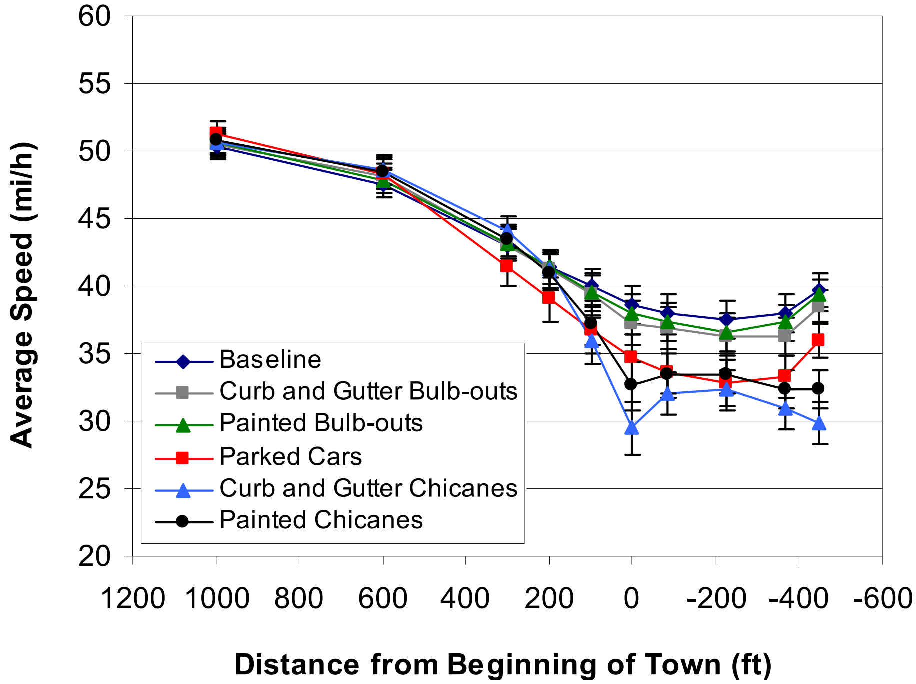
Treatment Condition	Average Direction Detection Distance, ft (SE)	Direction Distance Advantage Relative to Baseline, ft	Average Severity Detection Distance, ft (SE)	Severity Distance Advantage Relative to Baseline, ft
Baseline	225 (10.4)	0	53.4 (9.5)	0
Edge lines	249 (10.3)	24	71.6 (12.7)	18
Both sides PMDs	355 (17.4)	130	97.4 (11.0)	44
Single side PMDs	426 (26.7)	201	116 (14.7)	63
Streaming PMDs	1,288 (74.9)	1,063	612 (59.7)	559
Streaming PMDs (drive 3 only)	1,472 (55.5)	1,247	1,127 (80.7)	1,074

1 ft = 0.305 m
Note: Standard error (SE) is shown in parentheses.

TOWNS

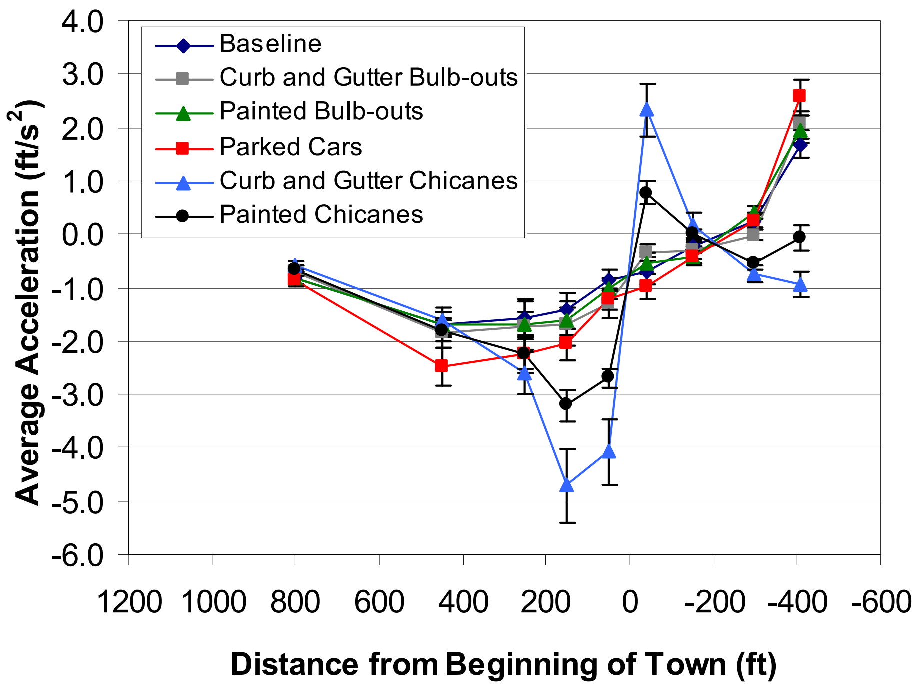
Speed Profiles for Towns

Figure 20 shows the average vehicle speed as a function of distance from the beginning of the town for the six different town treatment conditions. Figure 21 refers to corresponding acceleration data which will be described later. The data represent speed profiles in terms of averages across all participants and all days. The error bars represent one standard error of the mean. Data are shown for all 10 measurement locations. Positive distances indicate measurement locations ahead of the town, and negative distances indicate locations in the town. However, since speed calming inside the town was the major focus, all statistical tests were conducted on the five locations in the town from the beginning of the town (zero ft (zero m)) to the end of the town (-450 ft (-137 m)). As with the curve data, the town data were also analyzed according to a MANOVA approach to repeated measures.



1 ft = 0.305 m
1 mi = 1.61 km

Figure 20. Graph. Average speed as a function of the distance from the beginning of the town.



1 ft = 0.305 m

Figure 21. Graph. Average acceleration as a function of the distance from the beginning of the town.

The speed profiles in figure 20 indicate a gentle deceleration followed by a plateau. As indicated by this distinct overall shape, the location effect was statistically significant ($F (4, 31) = 11.1$, $p < 0.001$). The drivers slowed down from 50 mi/h (80.5 km/h) at 1,000 ft (305 m) before the town to 32–38 mi/h (51.5–61.2 km/h) at the middle of the town depending on the type of treatment. The treatments were organized into three groups: (1) baseline and bulb-outs (baseline, curb and gutter bulb-outs, and painted bulb-outs), (2) parked cars, and (3) chicanes (curb and gutter chicanes and painted chicanes). This treatment effect was statistically significant ($F (5, 30) = 12.5$, $p < 0.001$). However, the shapes of the speed profiles were different for the various traffic-calming treatments, in particular for the chicanes and parked cars conditions. As might be expected from the different shapes of the functions portrayed in figure 20, there was a statistically significant location by treatment interaction ($F (20, 15) = 3.05$, $p < 0.016$). The effect of drive was not statistically significant; thus, for speed in the town, there was no apparent adaptation or learning effect over the three drives.

The bulb-outs were the least effective traffic-calming countermeasures, slowing drivers down by only 1 to 1.5 mi/h (1.6 to 2.4 km/h) through the town relative to the baseline. The parked cars condition was intermediate in its effectiveness, slowing drivers down by 4 to 5 mi/h (6.4 to 8 km/h) relative to the baseline at the middle of the town. The chicanes were the most effective in slowing the drivers down through the town as a whole, slowing them by 6 to 9 mi/h (9.7 to 14.5 km/h) through the town relative to the baseline. The curb and gutter chicanes were more effective than the painted chicanes by about 1 to 3 mi/h (1.6 to 4.8 km/h), and all of these differences were statistically significant (see below). The shapes of the speed profile functions were similar for all of the five types of safety countermeasures except the chicanes. For all other countermeasures, the minimum speed was achieved near the middle of the town or slightly further into the town. For the chicanes, the minimum speed was achieved at the beginning and end of the town where the chicanes were located. In the town itself, the speed increased for the chicane conditions, reaching a local maximum at the middle of the town and decreasing again for the second chicane.

Across all five locations within the town, pair-wise ANOVA comparisons were made between the baseline condition and each individual speed-calming enhancement as well as between neighboring pairs in order of treatment effectiveness. All of the nine pair-wise comparisons revealed a statistically significant treatment effect except for the comparison between curb and gutter bulb-outs and painted bulb-outs. Both bulb-out conditions performed better than the baseline, but there was no statistically significant difference between the two implementations. This experiment found that the cheaper painted bulb-outs were just as effective as the more expensive curb and gutter bulb-outs, but neither one produced a substantial speed reduction effect (only about 1 mi/h (1.6 km/h)).

Speed Reductions for Towns

The beginning and middle of the town were important locations for measuring driver behavior. These locations bound the first part of the town where it was important that the driver slowed the vehicle down to a safe speed for entering and driving through the town. Table 8 shows the average speed at the beginning and at the middle of the town along with the corresponding speed reduction advantages relative to the baseline speed. If the relative speed reduction advantage at the beginning of the town was taken as the figure of merit (rounded to 0.5 mi/h (0.8 km/h)), the following order was observed from least effective to most effective: both bulb-outs (about 1 mi/h (1.6 km/h)), parked cars (4 mi/h (6.4 km/h)), painted chicanes (6 mi/h (9.7 km/h)), and curb and gutter chicanes (9 mi/h (14.5 km/h)). If the figure of merit was shifted to the middle of the town, the rankings have a slightly different order: both bulb-outs (about 1 mi/h (1.6 km/h)), painted chicanes (4 mi/h (6.4 km/h)), parked cars (4.5 mi/h (7.2 km/h)), and curb and gutter chicanes (5 mi/h (8 km/h)). As a result of the treatment by location interaction observed above, in this case, parked cars and painted chicanes changed places in the rank order. At the middle of town location, the speeding up in the center of the town that was observed with the chicanes offset some of the apparent advantage of the chicane treatment. This increase in speed was as much as 1 to 3 mi/h (1.6 to 4.8 km/h) faster than in the chicane itself.

Table 8. Average speed and speed reduction advantage in towns (mi/h).

Treatment Condition	Average Speed at Beginning of Town (SE)	Reduction Advantage Relative to Baseline	Average Speed at Middle of Town (SE)	Reduction Advantage Relative to Baseline
Baseline	38.6 (1.40)	0	37.5 (1.42)	0
Painted bulb-outs	38.0 (1.49)	0.6	36.6 (1.38)	0.9
Curb and gutter bulb-outs	37.2 (1.63)	1.4	36.3 (1.44)	1.2
Parked cars	34.6 (1.81)	4.0	32.8 (1.72)	4.7
Painted chicanes	32.6 (1.79)	6.0	33.5 (1.45)	4.0
Curb and gutter chicanes	29.5 (1.98)	9.1	32.3 (1.47)	5.2

1 mi = 1.61 km
Note: Standard error (SE) is shown in parentheses.

Since the effects of the various treatments were different for the beginning and middle of the town, both locations need to be considered in comparing the effectiveness of the various speed-calming treatments investigated in the current experiment. Therefore, pair-wise statistical comparisons were computed for the 30 combinations of all 6 average speeds both at the beginning of the town (column 2) and at the middle of the town (column 4). For the beginning of the town, all 30 pair-wise comparisons revealed statistically significant differences except the following three cases: (1) baseline versus painted bulb-outs, (2) baseline versus curb and gutter bulb-outs, and (3) painted bulb-outs versus curb and gutter bulb-outs. At the beginning of the town, the two types of bulb-outs were not different from each other, and neither type was different from the baseline. At this location, the only treatments which resulted in a speed reduction were the parked cars and chicanes conditions. For the middle of the town, all 30 pair-wise comparisons revealed a statistically significant difference except the following three cases: (1) painted bulb-outs versus curb and gutter bulb-outs, (2) parked cars versus painted chicanes, and (3) parked cars versus curb and gutter chicanes. At the middle of the town, the two types of bulb-outs were not different from each other, but both types were different from the baseline. In addition, there was no difference in speed reduction between the parked cars and either type of chicane implementation. At this location, the only treatments which resulted in a substantial speed reduction were the parked cars and chicanes conditions. Both types of bulb-outs had a very small effect on speed reduction (about 1 mi/h (1.6 km/h)).

Both chicane conditions were characterized by an increase in average vehicle speed in the middle portion of the town. This was to be expected since the chicanes themselves were located at both ends of the town. Under the chicane conditions, no speed-calming measures were employed in the middle portion of the town, allowing the drivers to speed up in the middle portion of the town only to slow down again for the second chicane at the exit from the town. Overall, parked cars and chicanes were considerably more effective than bulb-outs in slowing driver speed. In addition, the parked cars condition was associated with a more steady decrease in speed beginning further away from the town when compared with any of the other treatments. For example, at 100 ft (30.5 m) from the town, the parked cars condition had an average vehicle speed of 3 mi/h (4.8 km/h) less than the baseline condition. Such an outcome might be expected since the parked cars tended to be visible from further away than any of the other speed-calming treatments. The speed profiles for the towns also revealed that the participants were already slowing down from the instructed speed of 55 mi/h (88.5 km/h) in the tangents to about 51 mi/h (82 km/h) at 1,000 ft (305 m) before the town. This was also to be expected since the towns were driven in daylight conditions and could be seen by the driver from a greater distance (more than 1,000 ft (305 m)).

Acceleration Profiles for Towns

Figure 21 shows the average longitudinal acceleration of the vehicle as a function of distance from the beginning of the town for the six different speed-calming treatment conditions. As was the case for curves, the data represent acceleration profiles which complement the corresponding speed profiles portrayed in figure 20. As a result of the computation method, the data are shown for nine intermediate distance values (locations). As was the case for the speed profiles for the towns, all statistical tests were conducted only on the five locations inside the town. The acceleration profiles for the towns had a gentle overall U-shape. As expected from this overall shape, the location effect was statistically significant ($F(3, 30) = 21.6$, $p < 0.001$).

The major exception is that the chicanes had a pronounced jagged, saw-tooth shape in the middle. This saw-tooth pattern represents rapid deceleration to navigate the first chicane at the beginning of the town, acceleration through the first part of the town, and somewhat less rapid deceleration to navigate the second chicane toward the end of the town. In general, the acceleration profiles for the towns were organized into two groups of treatments: the chicanes and all other treatments with one exception for the parked cars condition. The parked cars condition revealed somewhat lower deceleration values before the town. Thus, within the town, decidedly different shapes were observed for the acceleration profiles for the six different traffic-calming treatments. As would be expected from these differently shaped profiles, the treatment by location interaction was statistically significant ($F(15, 18) = 4.77$, $p < 0.001$). However, as concerns the town acceleration profiles as a whole, the treatment effect was not statistically significant ($F(5, 28) = 2.47$, $p < 0.056$). In this case, the interaction between treatment and location was the significant factor. Different traffic-calming treatments produced different acceleration profiles.

CHAPTER 4. DISCUSSION AND SUMMARY

LIMITATIONS OF THE RESEARCH

The current experiment was conducted in the FHWA HDS. This simulator was partially validated in the past for research on nighttime driving on rural two-lane curves by means of similar field data; however, these validations have been for different curve geometries and for different driver responses.[19] In any case, there are inherent limitations to using simulator data to predict real-world driving responses. The simulator is often capable of producing similar relative results as those in the field for the purpose of ranking or comparing different treatments. This is one of the major strengths of using a driving simulator for highway safety research. However, when attempting to predict absolute quantities such as vehicle speeds or feature recognition distances, simulator-derived measurements may require scale factors or transformations before they can be used to estimate performance in the field.[20] In general, important relationships or patterns among data elements are usually preserved both in the simulator and in the field, but the simulator data often portray weaker and more variable results.

In the case of nighttime visibility research, there are two major reasons for such discrepancies. First, driving in a simulator is different from driving in a real car. Driver judgments of speed, distance, and deceleration are sometimes difficult in a simulator. Consequently, under certain conditions, drivers may drive faster and decelerate more rapidly in a simulator than in a real car. Also, there is no other traffic on the road. Second, the simulator has difficulty creating certain visual contrast ratios that can be encountered on the roadway, especially at night. The luminance for the visual stimuli used in this experiment (see table 3) are probably adequate for simulating pavement markings and possibly for simulating PMDs; however, the visual projection system of the simulator is not adequate to characterize the high contrast ratios found with streaming LED lights. Although these contrast ratios are high, the size of the LED light source is small, and the duty cycle is low, so glare should not be a problem for the driver. The inability to reproduce these high contrast ratios in the simulator was partially compensated for by increasing the size of the streaming LED light sources when they were far away. Nevertheless, there are distinct limitations to reproducing nighttime driving scenes in a driving simulator.[20]

In the case of predicting the effects of daytime driving, the FHWA HDS has only been validated by means of similar field data for intersection traffic signals and for certain collision warning systems.[21] The simulator has not been validated for traffic calming in small rural towns. However, from the stimulus perspective, the towns were presented only in daylight and had no intense luminous sources of light in the scene (e.g., traffic signals, tail lights, etc). The objects in the scene all represented reflected light. This is an easier type of driving scene to simulate and does not usually require high contrast ratios.

In view of the above limitations, absolute quantitative results from this experiment need to be considered with caution for both of the curves and the towns. However, the driving simulator is an excellent tool for exploring the relative differences among roadway treatments. This exploration of relative differences formed the focus of this experiment, and the observed relative differences may be regarded with a certain degree of confidence. As was pointed out previously, this confidence needs to be tempered with careful prudence to avoid other risks which are difficult to reproduce in a driving simulator, like the safety hazards posed by drivers and passengers exiting from the left-side doors of parked cars. For these and other reasons, field validations are usually warranted before simulator findings are recommended for implementation.

CURVES

Summary of Findings for Curves

Four responses were measured for curves: speed, acceleration, curve direction detection distance, and curve severity detection distance. Table 9 summarizes the findings for three of these measures. The acceleration data were not summarized because they were derived from the speed data and portrayed similar relationships. Based on speed measurements at the point of curvature, columns 2 and 5 show the estimated average speed reductions for the various curve visibility improvements (in mi/h relative to the baseline rounded to the nearest 1 mi/h (1.61 km/h)) as well as the corresponding speed reduction rankings (from best to worst) for each.

Table 9. Estimated safety advantages and rank ordering of treatments for curves.

Treatment	Speed Reduction, mi/h	Direction Distance Increase, ft	Severity Distance Increase, ft	Speed Rank	Direction Rank	Severity Rank
Enhanced PMDs with streaming LED lights	9	1,065	560	1	1	1
Standard PMDs on both sides of the road	8	130	45–65	2	3	2
Standard PMDs on a single side of the road	7	200	45–65	3	2	2
4-inch (101.6-m) edge lines	2	25	0	4	4	3

1 ft = 0.305 m
1 mi = 1.61 km

Drivers performed almost perfectly in detecting the direction of curves ahead in the road (99.7 percent correct). In table 9, columns 3 and 6 show the estimated average curve direction detection distance increases for each treatment (relative to the baseline rounded to the nearest 5 ft (1.52 m)) as well as the corresponding detection distance rankings for each. The 25-ft (7.6-m) average detection distance increase (11 percent) for adding edge lines in this experiment was almost identical to the 24-ft (7.3-m) average increase (12 percent) found in an earlier simulator experiment conducted by Molino et al.[8] This correspondence was found despite the fact that the two simulator experiments employed curves of different radii and deflection angles. However, the absolute average detection distances were about 39 ft (11.9 m) greater in the current experiment. Such an outcome might be expected. Although the same simulator was employed, the graphics had been upgraded since the earlier experiment.

The absolute average direction detection distance for the single side PMDs condition in this experiment was 426 ft (130 m) (see table 7). Although under somewhat different conditions, a field study conducted by Turner et al. obtained an average curve detection distance of 656 ft (200 m).[22] A larger detection distance in the field might be expected for two reasons. First, the simulator was not able to produce the full visual contrast ratio experienced at night in the real world. Second, the field study used a 2-s search time from a stationary vehicle, which moved progressively closer to the curve in 100-ft (30.5-m) increments instead of a dynamic driving scenario which was used in this experiment.

Compared to curve direction detection, drivers did not perform as well on curve severity detection (only 82.5 percent correct). While this performance was better than chance, drivers had more difficulty detecting the severity of a curve than its direction. In table 9, columns 4 and 7 show the estimated average curve severity detection distance increases for each treatment as well as the corresponding detection distance rankings for each.

A comparison of findings across the three response categories in table 9 reveals two important relationships. First, if the standard reflectorized PMD conditions were collapsed, there was a consistent order across all three response categories. Enhanced PMDs with streaming lights performed the best, the standard reflectorized PMDs performed the next best, and the edge lines alone resulted in the weakest or no improvement. Second, the enhanced PMDs with streaming lights performed exceptionally well in terms of increasing curve feature detection but only moderately well in terms of slowing drivers down.

Answers to Research Questions for Curves

Based on this experiment, the research questions posed in the introduction are answered as follows:

- How do the different visibility treatments perform to slow drivers down? In order of effectiveness, the treatments were organized into two groups: (1) delineators with edge lines and (2) pavement markings (edge lines alone). The delineators achieved a minimum speed earlier at the PC and achieved a greater overall speed reduction. By contrast, the pavement markings achieved a minimum speed later (at the middle of the curve) and achieved a lower overall speed reduction.

- What is the order of the four different visibility treatment conditions in terms of their effectiveness in slowing drivers down? Table 9 shows the observed order. If driving speed at the PC is used as the primary measure, the effectiveness rankings have the following order from best to worst with the estimated speed reduction shown in parentheses: streaming PMDs (9 mi/h (14.5 km/h)), both sides PMDs (8 mi/h (12.9 km/h)), single side PMDs (7 mi/h (11.3 km/h)), and edge lines alone (2 mi/h (3.2 km/h)). All of the PMD conditions contained edge lines as well as PMDs.

- Is there an effect of right versus left curve on driver speed profiles? Across all treatments, on average, the driving speed through the left curves was 1 mi/h (1.6 km/h) faster than through the right curves.

- Is there an effect of sharp versus gentle curves on driver speed profiles? Across all treatments, on average, the driving speed through the gentle curves was 10 mi/h (16 km/h) faster than through the sharp curves.

- Is there an adaptation effect? There was no adaptation effect.

- Do drivers slow down or speed up across the three experimental driving sessions? On average, the drivers did not slow down or speed up across the three experimental sessions.

- How do the different visibility treatments affect driver acceleration? The acceleration profiles for the curves organized themselves into two groups of treatments: pavement markings and delineators. Both groups of acceleration profiles had a sharp V-shape overall. However, the delineators were associated with a smoother and earlier deceleration pattern than the pavement markings.

The research questions and answers concerning feature detection for curves are as follows:

- How well do drivers perform on curve feature detection for the different visibility treatments? The drivers performed considerably better than chance on feature detection across all visibility treatments. The overall percentage of correct curve direction detection was 99.7 percent. The overall percentage of correct curve severity detection was 82.5 percent.

- How do the different treatments affect the distance from which curve direction and severity are detected by drivers? The different visibility treatments had a strong differential effect on improving curve direction detection distance. The treatments had less of an effect on improving curve severity detection distance. Average curve direction detection distance was organized into three groups: (1) streaming PMDs with edge lines, (2) conventional PMDs with edge lines, and (3) pavement markings (edge lines alone). Average curve severity detection distance was organized into two groups: (1) streaming PMDs with edge lines and (2) all other treatments.

- What is the order of the four different visibility treatment conditions in terms of their effectiveness in improving curve feature detection distance? Table 9 shows the observed orders. From best to worst, the following curve direction detection distance rankings were found with the estimated detection distance increases relative to baseline given in parentheses: enhanced PMDs with streaming lights (1,065 ft (325 m)), standard PMDs only on the far side of the curve (200 ft (61 m)), standard PMDs on both sides of the curve (130 ft (39.6 m)), and standard 4-inch (101.6-m) edge lines alone (25 ft (7.6 m)). As concerns curve severity detection distance, the corresponding rankings were found as follows: enhanced PMDs with streaming lights (560 ft (170 m)) and standard reflectorized PMDs (25 to 45 ft (7.6 to 13.7 m)). The standard 4-inch (101.6-m) edge lines alone performed the worst, no better than the baseline. It must be recalled that all of the PMD conditions in this experiment contained edge lines as well.

- Does feature detection distance change across the three experimental driving sessions? Is there an effect of multiple exposures? Feature detection distance consistently increased across the three experimental driving sessions for both curve direction detection and curve severity detection.

- Is learning a factor in interpreting novel visibility treatments? There was a strong adaptation or learning effect during the course of the experiment with regard to curve feature detection for the streaming PMDs condition.

- What is the effect of providing drivers with information regarding the curve direction and severity cues for the streaming PMDs condition? The drivers tended to learn the intuitive curve direction cue on their own. Direction detection distance did not increase substantially over projected learning after the drivers were told the meaning of the curve direction cue. The drivers had difficulty learning the less intuitive curve severity cue on their own. Severity detection distance increased substantially over projected learning after the drivers were told the meaning of the curve severity cue.

- Is there an effect of right versus left curve on feature detection distance? For both curve direction and severity detection distances, the effects of the direction of the curve were not statistically significant.

- Is there an effect of sharp versus gentle curves on feature detection distance? For curve direction detection distance, the effect of the severity of the curve was not statistically significant. However, the sharp curves had a greater average curve severity detection distance than the gentle curves (222 ft (67.7 m) versus 158 ft (48.2 m)).

- What is the relationship between slowing the driver down and improving feature detection on curves across the four treatment conditions? Drivers did not begin to substantially reduce their speed until they were about 200 ft (61 m) ahead of the curve. Yet, the enhanced PMDs with streaming lights resulted in curve feature detection distances of over 1,000 ft (305 m) ahead of the curve. As a result, drivers were aware of important curve characteristics (perception) far ahead of the curve but did not slow down (behavior) until much closer to the curve. An inverse relationship appeared in the case of the standard reflectorized PMDs conditions (without streaming lights). The both sides PMDs condition had a lower average direction detection distance (383 ft (117 m)) than the single side PMDs condition (466 ft (142 m)). This outcome was the opposite of what was observed for vehicle speed reduction where the both sides PMDs condition slowed the drivers down more than the single side PMDs condition by about 1 mi/h (1.6 km/h). The additional visual stimuli in the both sides PMDs condition may have confused the driver's judgments of curve direction and severity, but the formidable array of cues on both sides of the road, although confusing, may have served as a stimulus to slow down.

Potential Safety Benefits for Curves

As indicated above, the results of this experiment are more likely to be valid for rankings and relative comparisons among different roadway treatments than for absolute determinations of speed reductions or increases in detection distance. In the case of navigating curves on rural two-lane roads at night, safety improvements were defined in terms of reducing driving speed before and in the curve and increasing curve feature detection distance. The results of the experiment indicated that edge lines offered a small potential safety benefit, and standard reflectorized PMDs with edge lines offered a somewhat greater benefit. In general, standard reflectorized PMDs with edge lines performed better than pavement markings alone. This result does not imply that edge lines are not needed. Edge lines are still needed to provide continuous delineation of the travel lane, especially at close range. As concerns whether reflectorized PMDs should be implemented on the far side of the curve only or on both sides of the curve, the results were mixed. Since standard PMDs are considered to be a low-cost safety improvement, implementing PMDs on both sides of the curve is not likely to represent a large incremental expense. Thus, implementation on both sides of the curve should be preferred. Of all the treatments explored, the streaming PMDs with edge lines offered the most potential safety benefit by far.

Novel Curve Treatment Solution

For both curve direction and severity, adding streaming PMDs to standard edge lines resulted in a dramatic increase in detection distance. Without being told the meanings of the visual cues coded in the novel streaming lights, drivers were aware of the direction of the curve ahead and, to a lesser extent, of the severity of the curve ahead well before the curve itself came into view.

Since the streaming lights moved in the direction of the curve ahead, the direction cue was intuitive. This curve direction cue was learned quickly and well. The severity cue was less intuitive. Drivers had more difficulty learning the meaning of this cue. However, once they were informed of the meaning of the severity cue by means of verbal instructions, drivers could detect curve severity almost as far away as curve direction, although their accuracy was not as good. Training and/or education may be required before implementing such a curve severity coding scheme.

Although drivers were aware of the existence of a curve and some of its features at a great distance before the curve, they did not start to substantially slow down until they were much closer to the curve. When they did slow down, drivers slowed the most for the streaming PMDs, but the relative speed reduction was not as dramatic as the increase in feature detection distance. This outcome does not necessarily imply that the drivers forgot the perceptual information or were unprepared to act on it. Despite advanced information, it would be expected that drivers would still try to reduce total trip time by maintaining their speed until they came closer to the curve. Moreover, with advanced information on curve direction and severity, drivers would presumably be better prepared to act appropriately in an unexpected emergency situation.

Although the streaming PMDs solution is not yet technically mature for two-lane rural roads, future research might reveal practical implementation options. If optimal implementation strategies were selected, and the resulting system gained widespread adoption, the preinstallation cost could possibly be kept low. While not likely to become an extremely low-cost treatment, for instance when compared to standard PMDs, such a streaming light PMD countermeasure could become comparatively inexpensive with time, especially relative to modifying curve geometry at locations with high crash frequencies. Unfortunately, an exploration of the potential future cost implications of implementing the streaming PMD countermeasure was beyond the scope of this experiment.

Recommendations

The results from the current experiment identified one potentially low-cost safety solution worthy of further study and consideration—reflectorized PMDs enhanced by streaming LED lights. Several recommendations are suggested on how to proceed with this streaming PMDs solution.

Optimal Light Patterns

Further experimentation needs to be conducted to investigate optimal sequential flashing patterns for streaming PMDs. As a part of the preliminary pilot study for the current experiment, some initial exploration was conducted on this issue. Three different overall patterns were tried: (1) lights streaming toward the driver, (2) lights simultaneously flashing, and (3) lights streaming away from the driver. The latter pattern proved the most effective, producing an intuitive cue for curve direction. However, the cue of streaming cycle rate to indicate curve severity was chosen with little experimentation. A different flashing pattern, still in the direction of the curve, may have been more effective as a cue for curve severity. Even if the streaming cycle rate proved effective, the particular rates used in the current experiment were found to be discriminable but not necessarily optimal. Furthermore, in this experiment, there were only two curve radii (severities) and one deflection angle. A suggested future simulation experiment might employ more variation in curve radii and a wider range of curve deflection angles to ensure sufficient generalization across the full spectrum of field implementations and corresponding coding schemes.

Advanced Information

Further experimentation needs to be conducted to investigate the behavioral effectiveness of providing advanced information about the characteristics of curves far ahead in the road. In the current experiment, at a great distance before the curve, drivers were aware of the existence of a curve and some of its features. However, they did not start to substantially slow down until they were much closer to the curve. In addition to producing a modest decrease in driving speed upon curve entry, this advanced information may have an important secondary benefit. With advanced information on curve direction and severity, drivers may be better prepared to act appropriately in an unexpected emergency situation. This hypothesis might be tested in a future driving simulator experiment. The driving simulator is well suited to testing drivers' reactions to emergency events with possible serious negative consequences.

Technology Development

The feasibility of implementing a streaming PMDs solution for curves on rural two-lane roads needs to be explored, and the cost of possible implementation is an important factor for consideration. The streaming light technology for rural two-lane curves is not yet mature, although it has some application precedent for limited access roadways in other countries.(8) In order to make this technology practical for remote rural locations and to reduce overall life-cycle costs, this technology would probably need to be implemented by solar power. If an array of streaming PMDs were connected together by underground wires, the entire array could be powered by a single solar panel and be sequenced by signal wires from a single control box. If each PMD were independent and self-sufficient, each one could be powered by its own small solar collector and sequenced by a system of radio frequency control. In this case, no underground wires would be needed, but the entire array would require exposure to adequate sunlight. In either case, in order to keep power consumption low, the streaming array could be activated by approaching traffic by sensing vehicle motion, headlights, noise, or other characteristics. The array could be made fault tolerant by automatically adjusting the streaming pattern of lights if a particular PMD in the array failed.

Field Studies

If the streaming PMDs solution seems feasible and cost effective, an experimental system needs to be constructed and tested both on a closed test track and later on a public roadway. The simulator data from this experiment need to be compared with field data collected under similar circumstances. The reductions in curve driving speed and increases in curve feature detection distances obtained in the laboratory need to be confirmed in the field. A closed test track experiment might be conducted using an experimental system of streaming PMDs and an instrumented vehicle. This suggested experiment might employ curves of different radii and deflection angles. Such an experiment should employ response measures similar to those used in this experiment: driving speed, longitudinal acceleration, curve direction detection distance, and curve severity detection distance. Data on lane position and lane excursions would also be useful.

If the results of such an experiment seem promising, a field test might be conducted on a public road outfitted with the experimental system of streaming PMDs. This experimental system should be applied on a few selected curves for a period of several weeks or months. A before/after/before field test might be devised. Such a field test might measure driving speed and deceleration on the selected curves before the experimental implementation of the streaming PMDs countermeasure has been put in place, during such an implementation, and after the implementation has been removed. The successful outcome of such a field test might reveal a baseline speed (and lane position) through the curve before the treatment, a significant decrease in speed (and possible improvement in lane keeping) during the treatment, and a recovery of the original baseline conditions after treatment removal.

TOWNS

Summary of Findings for Towns

The major findings regarding the relative advantages of the various speed-calming treatments are summarized in table 10. For both the beginning and middle of town locations, the table shows estimated average speed reductions (relative to the baseline condition) of the tested safety improvements as well as their rank ordering (from best to worst).

Table 10. Estimated speed reductions and rank ordering of treatments for towns.

Treatment	Beginning of Town Speed Reduction, mi/h	Middle of Town Speed Reduction, mi/h	Beginning of Town Rank	Middle of Town Rank
Curb and gutter chicanes	9	5	1	1
Painted chicanes	6	4	2	2
Parked cars on both sides of the road	4	4.5	3	2
Bulb-outs, either painted or curb and gutter	0	1	None	3

1 mi = 1.61 km

Answers to Research Questions for Towns

Based on the findings of this experiment, the research questions posed in the introduction are answered as follows:

- How do the different traffic-calming treatments perform to slow drivers down? In order of effectiveness, the treatments were organized into three groups: (1) chicanes, (2) parked cars, and (3) baseline and bulb-outs. Except for the chicanes, the minimum speed was achieved near the middle of the town or slightly further into the town. For the chicanes, the minimum speed was achieved at the beginning and end of the town where the chicanes were located. In the middle portion of the town, the speed increased, creating a local peak in the shape of the speed profile functions for the chicanes.

- What is the order of the five different traffic-calming treatment conditions in terms of their effectiveness in slowing drivers down? Table 10 shows the orders observed. When driving speed at the beginning of the town was used as the primary measure, the effectiveness rankings had the following order from best to worst with the estimated speed reduction shown in parentheses: curb and gutter chicanes (9 mi/h (14.5 km/h)), painted chicanes (6 mi/h (9.7 km/h)), and parked cars (4 mi/h (6.4 km/h)). When driving speed at the middle of the town was used as the primary measure, the effectiveness rankings had the following order: curb and gutter chicanes (5 mi/h (8 km/h)) and parked cars and painted chicanes (4 to 4.5 mi/h (6.4 to 7.2 km/h)). Both types of bulb-outs produced either a small reduction in speed (about 1 mi/h (1.6 km/h)) or did not perform significantly better than the baseline.

- Is there an adaptation effect? There was no adaptation effect.

- Do drivers slow down or speed up across the three experimental driving sessions? On average, the drivers did not slow down or speed up across the three experimental sessions.

- How do the different traffic-calming treatments affect driver acceleration? The acceleration profiles for the towns were organized into two groups of treatments: (1) chicanes and (2) all other treatments with one exception for the parked cars condition.

The parked cars condition revealed somewhat lower deceleration values before the town. The acceleration profiles for the chicanes had a pronounced jagged saw-tooth shape in the middle. This saw-tooth pattern represents rapid deceleration to navigate the first chicane at the beginning of the town, acceleration through the first part of the town, and somewhat less rapid deceleration to navigate the second chicane at the end of the town.

- Do some of the treatments slow drivers down before reaching the town while others slow drivers down only inside the town? All treatments slowed the drivers down before reaching the town. The chicanes tended to slow the drivers down the fastest and to the largest degree just before reaching the town. All of the other treatments tended to slow the drivers down the most while inside the town. In addition, the parked cars were associated with a more steady decrease in speed beginning further away from the town when compared with the other treatments.

Potential Safety Benefits for Towns

In the case of traffic calming for rural towns, safety improvements were defined in terms of reducing driving speed at the beginning and in the middle of the town. The results indicated that bulb-outs offered a small potential safety benefit or no benefit at all. Painted chicanes and parked cars on both sides of the road offered a greater benefit, and curb and gutter chicanes offered the most potential safety benefit. In general, chicanes and parked cars performed the best as traffic-calming countermeasures. Even the painted version of the chicanes performed well. This latter speed-calming measure is both effective and low in cost. If some parking spaces were eliminated at the entrances to the town, painted chicanes could be applied to slow drivers down. Flexible delineator posts could be added to the painted chicanes to reduce the tendency for drivers to cut the corners of the painted curves, possibly resulting in even greater speed reductions.

Alternatively, if the street were sufficiently wide, adding and encouraging parking on both sides could be implemented without any curb and gutter modifications. Thus, the parked cars solution could also prove to be both effective and low in cost. Although effective, curb and gutter chicanes would probably be more expensive than either painted chicanes or parked cars. The painted bulb-outs, while cheap, offer little or no advantage in terms of speed reduction. The curb and gutter bulb-outs would be expensive for an equally minor potential benefit.

Recommendations

For calming traffic in small towns, the results of the current experiment identified two relatively low-cost safety solutions as being worthy of further study and consideration: (1) providing for and encouraging parking in the town and (2) adding painted chicanes to the town entrances. However, the above results have not been validated in the field. As noted previously, simulations of driving through small towns do not take into account all hazardous factors involved in driving through real small towns. In order to achieve adequate field validation, several recommendations are suggested on how to proceed with these two potential solutions.

Parking

Adding parking to both sides of the main street in the town was an effective traffic-calming technique in this experiment. However, a field test in a small rural town should be conducted with cars parked on the main street both during the day and at night. If the town has present parking spaces which are underutilized, cars could be artificially introduced by renting a number of used cars from an automobile dealer and/or by parking rarely used private or public vehicles on the main road for a specified duration (several weeks, months, etc.). The density of parked cars could be changed radically from a normal sparse parking density to an experimentally introduced high parking density. As was suggested for streaming PMDs, a before/after/before field test might be devised where driving speed and deceleration would be measured both before and in the town. Such measurements would be made before the implementation of an increased density of parked cars had been put in place, during such an experimental implementation, and after the parked cars had been removed. A baseline speed, followed by a significant decrease in speed during the treatment and a return to the baseline would be the measure of success.

If the field test proved successful, long-term implementation might be attempted to create a higher density of parked cars in the town during times when traffic calming is most needed. A campaign might be launched to encourage more parking at appropriate times. Businesses and government entities could be encouraged to park cars on the main street instead of in parking lots and driveways. Public events and town meetings could specify parking on the main street. Public service and utility trucks could be requested to park on the main street when not in use. Such an increase in the number of parked cars is likely to be a very low-cost option if underutilized parking spaces are already available in the town or if parking can be easily implemented without any changes to the width of the main street or to any curb and gutter layout which might be present.

In the suggested field test scenarios using parked cars, especially in cases of only one travel lane in each direction, special attention needs to be given to assessing and balancing the possible safety hazards of vehicles, drivers, passengers, and pedestrians spontaneously entering the roadway. An additional consideration is the accommodation of bicycle traffic. Although the parked cars condition proved successful in slowing drivers down in the simulator, the suggestion to implement a parked cars solution in the real world needs further investigation.

Painted Chicanes

Based on the results of the current experiment, the most cost-effective solution for traffic calming in small towns is using painted chicanes. For extremely small towns (under 1,000 people), this may be the only affordable traffic-calming implementation. If the main street were wide enough at the beginning and end of the town or if some parking spaces could be eliminated at these locations, painted chicanes might be implemented with minimal cost. A small town might be selected which possesses these necessary characteristics. Painted chicanes could be implemented on an experimental basis. A before/after field test might be conducted where deceleration and speed were measured through the town. If a somewhat longer experimental "after" period were employed (e.g., 3 months) after 1 month of only painted chicanes, flexible vertical yellow delineators could be added to the painted chicanes for the second month and then removed for the third month. In this way, flexible yellow delineators could be tested for their ability to deter drivers from cutting the corners on the painted chicanes.

The recommended field test is only of the before/after design because it might be difficult to remove the pavement paint once applied. Also, if effective, continued implementation would prolong possible benefits. In the current experiment, the painted chicanes were effective in slowing down traffic at the beginning and end of the town. However, between the chicanes in the middle of the town, drivers tended to accelerate and drive at higher speeds. A combination of the parked cars and painted chicanes solutions could prove beneficial in this regard. If a higher density of parking could be encouraged even only in the middle portion of the town, the complementary advantages of both treatment types might be realized. This combination might be tested in a second field study in a different town.

In the above suggested field test scenarios using painted chicanes, especially in cases without a separating median, attention needs to be given to assessing and balancing the possible safety hazards of head-on or sideswipe opposite-direction crashes. In general, both bulb-outs and chicanes should only be implemented in well lit areas.

CONCLUSION

The current experiment focused on two areas: (1) advanced detection and speed reduction for curves in rural two-lane roads at night and (2) traffic calming for small rural towns during the day. For curves, PMDs with edge lines performed better in terms of slowing drivers down than pavement markings alone. The streaming PMDs solution with edge lines offered the most dramatic potential benefit in terms of advanced curve detection, and it is worthy of further study and consideration. In towns, chicanes slowed drivers down the most followed by parked cars on both sides of the road. As possible low-cost safety improvements (provided adequate field validation), adding painted chicanes to town entrances and providing and encouraging parking in the town are worthy of further study and consideration.

ACKNOWLEDGEMENTS

This experiment was conducted by the joint effort of many individuals and organizations. The authors wish to acknowledge valuable contributions from the following individuals: Raymond Krammes, Roya Amjadi, and Carol Tan for guidance and insight; Thomas Granda for oversight and support; Paul Tremont, William Perez, and Stephen Fleger for management and review; Pascal Beuse for data analysis, graphics, and editing; Lindsey Clark and Dana Duke for laboratory support; and FHWA HDS staff members Barry Wallick, Jason Williams, Peter Chou, Ryan Cartwright, and Michael Baumgartner for creating and sustaining the driving simulation. Thomas Welch from the Iowa Department of Transportation and Thomas Broderick from the Massachusetts Highway Department provided information on speed calming in small towns. Gilbert Soles from the Florida Department of Transportation provided information on streaming light patterns for roadway delineation. The authors also wish to acknowledge valuable contributions from the following organizations: the FHWA Turner-Fairbank Highway Research Center for providing laboratory facilities and staff and the Technical Advisory Committee for the Low Cost Safety Improvements Pooled Fund Study for providing input and direction from the perspective of engineering practice.

REFERENCES

1. National Highway Traffic Safety Administration. (2007). *Fatality Analysis Reporting System,* U.S. Department of Transportation, Washington, DC. Obtained from: http://www.fars.nhtsa.dot.gov. Site last accessed October 23, 2009.

2. Fitzpatrick, K., Balke, K., Harwood, D.W., and Anderson, I.B. (2000). "Accident Mitigation Guide for Congested Rural Two-Lane Highways," *NCHRP Report 500 Series*, Vol. 440, Transportation Research Board, Washington, DC.

3. National Highway Traffic Safety Administration. (2005). *Speed Management Strategic Initiative*, DOT-HS-809-924, U.S. Department of Transportation, Washington, DC.

4. National Cooperative Highway Research Program. (2003). "Guidance for Implementation of the AASHTO Strategic Highway Safety Plan," *NCHRP Report 500 Series,* Transportation Research Board, Washington, DC.

5. Transportation Pooled Fund. (2009). *Transportation Pooled Fund Program*, U.S. Department of Transportation, Washington, DC. Obtained from http://www.pooledfund.org/. Site last accessed March 10, 2009.

6. Agent, K.R., Stamatiadas, N., and Jones, S. (1996). *Development of Accident Reduction Factors*, KTC-96-13, Kentucky Transportation Center, University of Kentucky, Lexington, KY.

7. van Driel, C.J.G., Davidse, R.J., and van Maarseveen, M.F.A.M. (2004). "The Effects of an Edgeline on Speed and Lateral Position: A Meta-Analysis," *Accident Analysis and Prevention*, *36*(4), 671–682.

8. Molino, J., Katz, B., Duke, D., Opiela, K., Andersen, C., and Moyer, M. (2004). *Field Validation for the Relative Effectiveness of Combinations of Pavement Markings and RRPMs in Recognizing Curves at Night*, Transportation Research Board 2004 Annual Meeting CD-ROM, Transportation Research Board, Washington, DC.

9. Agent, K.R. and Creasey, T. (1986). *Delineation of Horizontal Curves*, Interim Report UKTRP-86-4, University of Kentucky, Lexington, KY.

10. Montella, A. (2009). *Safety Evaluation of Curve Delineation Improvements: An Empirical Bayes Observational Before-After Study*, Transportation Research Board 2009 Annual Meeting CD-ROM, Transportation Research Board, Washington, DC.

11. Ewing, R. (1999). *Traffic Calming: State of the Practice*, Institute of Transportation Engineers, Washington, DC.

12. Marek, J.C. and Walgren, S. (2000). *Mid-Block Speed Control: Chicanes and Speed Humps*, Seattle, WA. Obtained from: http://www.seattle.gov/transportation/docs/ITErevfin.pdf. Site last accessed October 23, 2009.

13. King, M.R. (1999). *Calming New York City Intersections*, Urban Street Symposium Conference Proceedings, Transportation Research Board, Washington, DC.

14. Huang, H.F. and Cynecki, M.J. (2000). "Effects of Traffic Calming Measures on Pedestrian and Motorist Behavior," *Transportation Research Record 1705*, Transportation Research Board, Washington, DC.

15. Williams, J.R., Chou, T.C., and Wallick, B.L. (2000). *Advanced Rendering Cluster for Highway Experimental Research (ARCHER)*, Proceedings of 2005 Driving Simulation Conference North America, Orlando, FL.

16. Kennedy, R.S., Lane, N.E., Berbaum, K.S., and Lilienthal, M.G. (1993). "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," *The International Journal of Aviation Psychology, 3*(3), 203–220.

17. Cobb, S.V. and Nichols, S.C. (1998). "Static Posture Tests for the Assessment of Postural Instability After Virtual Environment Use," *Brain Research Bulletin, 47*(5), 459–464.

18. Federal Highway Administration. (2003). *Manual of Uniform Traffic Control Devices (MUTCD)*, U.S. Department of Transportation, Washington, DC.

19. Molino, J., Katz, B., Donnell, E., and Opiela, K. (2008). *Using a Subjective Rating Scale in a Driving Simulator to Predict Real-World Stimulus-Response Relationships Concerning Nighttime Delineation for Curves*, 87th Transportation Research Board Annual Meeting, Washington, DC.

20. Molino, J., Opiela, K., Andersen, C., and Moyer, M. (2003). "Relative Luminance of Retroreflective Raised Pavement Markers and Pavement Markings Stripes on Simulated Rural Two-Lane Roads," *Transportation Research Record 1844*, Transportation Research Board, Washington, DC.

21. Inman, V., Davis, G., El-Shawarby, I., and Rakha, H. (2006). *Field and Driving Simulator Validations of System for Warning Potential Victims of Red-Light Violators,* 85th Transportation Research Board Annual Meeting, Washington, DC.

22. Turner, D., Nitzburg, M., and Knoblauch, R. (1998). "Ultraviolet Headlamp Technology for Nighttime Enhancement of Roadway Markings and Pedestrians," *Transportation Research Record 1636*, Transportation Research Board, Washington, DC.

HRDS-06/02-10(WEB)E