Driver Perception of Horizontal Curves on a Simulated Two-Lane Rural Highway

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ABSTRACT

This report describes an experiment conducted in a driving simulator to assess perception of horizontal curves. The experiment investigated the effects of six factors (driver age and gender; degree of curvature, curve length and direction; and highway environment) on perception of curve sharpness and speed selection. The objectives were to: 1) measure the effect of the factors on perception and speed choice; 2) assess the value of the simulator as a research tool for curve perception; and 3) use the results as a baseline evaluation of countermeasures in future research. Subjects were fourteen young and fourteen middle-aged drivers. Subjects drove a driving simulator on two two-lane rural highways. An infinite clear zone bounded one highway, and a tree line starting 20-ft (6.096 m) from either roadside bounded the second highway. Curves varied by degree of curvature (two, six, and ten degrees), length (500 ft (152.4 m), 1500 ft (457.2 m)) and direction (right, left). Drivers verbally rated sharpness during curve approach. Results showed that: 1) both age groups drove the same speed on both highways, and curve ratings did not change across highways; 2) drivers drove slowest on ten-degree curves and fastest on two-degree curves; 3) drivers rated ten-degree curves the sharpest, followed by six- and two-degree curves; 4) drivers rated left curves sharper than right curves and drove slower on left curves than on right curves. The results suggest that the simulator is a suitable platform for human factors research on perception and speed selection on horizontal curves.

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1.0 INTRODUCTION

Six factors that may influence perception of horizontal curve sharpness were examined in the experiment reported here. The factors encompassed characteristics of the driver (age and gender), the highway environment (open spaces compared to tall objects in the periphery), and curve parameters (degree of curvature, curve length and direction). The experiment was conducted in a high-fidelity driving simulator. The objectives were to: 1) measure the effect of the six factors on driver perception of curve severity and driver speed selection; 2) assess the value of the simulated driving task as a research tool for perception and speed on curves; and 3) use the results as a baseline for the evaluation of perceptual countermeasures in future research.

Horizontal curves on two-lane rural highways are associated with a higher safety risk than either urban curves or rural tangents (*1*). The Insurance Institute for Highway Safety reported that about 12,000 people died in roadside hazard crashes in 1999 and 42 percent of these deaths occurred on curves (*2*). Crashes on rural highways occur more frequently and with more severe consequences on curved sections than they do on tangent sections (*2*,*3*,*4*). Crashes that occur on curves are due to: 1) vehicles running off the road and hitting fixed objects (such as trees), or rolling over; and 2) vehicles transgressing into the opposite lane and colliding with other vehicles or objects (*1,5*). Roadside hazard crashes occur with greater frequency on rural roads compared to urban roads and are most likely to occur on curves and/or downhill road sections (*3,6*).

Driving is more demanding on horizontal curve segments than on tangents (*7*). To negotiate a horizontal curve, the driver monitors and anticipates changes in the horizontal alignment as he or she adjusts the speed and path of the vehicle with steering and braking controls (*8*). Research examining the level of workload imposed upon the driver found that driver workload increased on the approach to horizontal curves and peaked near the beginning of the curve (*9*). In addition, the dynamics of a vehicle once it enters a horizontal curve differ from those of a vehicle traversing a straight segment of highway. A vehicle traveling a straight path is subject only to the downward pull of gravity and the friction between the tires and the pavement. In addition to these forces, a vehicle on a horizontal curve is affected by lateral forces. Specifically, a vehicle moving in a circular path is pulled radially outward by an inertial force. This force is counteracted by a centripetal force (created by superelevation and side friction) that keeps the vehicle on the roadway (*10*). Lastly, vehicles tend to shift laterally in the lane upon entry and exit from horizontal curves (*6*).

1.1 Study Motivation

Measures to reduce the severity of run-off-road crashes include providing clear zones, installing crash-worthy roadside devices and flattening hazardous curves. In addition, traffic engineering countermeasures are employed to help drivers stay in their lane and to minimize the consequences of running or skidding off the road (*11*). Such measures include pavement markings, delineators, advisory speed and curve warning signs, and rumble strips. Posted advisory speed limits may have a diminished safety effect because of inconsistency across jurisdictions that may lead some drivers to select speeds based on personal interpretation of roadway features (*12*). Moreover, the criteria for identifying potentially hazardous curves are weak, leaving some hazardous curves unmarked (*13*,*14*).

Investigation of curve perception in order to develop effective countermeasures to curve hazard is warranted because curves on rural highways have a high crash rate, and the current curve warning system may not be communicating effectively to drivers. The current experiment was conducted to support the development of guidance to improve signing, delineation, and roadway geometry. A component of current Federal Highway Administration (FHWA) curve research includes the use of a high-fidelity driving simulator. The simulator allows controlled and safe testing, but the validity of the driving measures must be evaluated. Hence, one motivation for the study was to evaluate the value of the simulator in measuring perception of curves, to be followed by a field validation. If appropriate, the study results can serve as a baseline for the evaluation of novel countermeasures in future studies.

1.2 Experimental Factors

To gain baseline measures of curve perception, experimental factors were used that would be carried forth in a program of research on curve perception. The factors were selected to include characteristics of the driver, the roadway environment, and geometric design.

1.3 Age and Gender

The difference between young drivers (16 to 24 years old) and more mature drivers is significant in terms of safety (*15*,*16*). Regarding performance on curves, drivers between 16 and 17 years were 3.1 times more likely to be

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involved in a collision on a curve than middle-aged drivers (*2*). Young drivers are more likely to be involved in a crash than drivers of any other age, a finding that holds for female and male drivers (*17*). Men have a higher crash rate than women on a per-license basis, but when the greater number of miles driven by men is taken into account, the rate is similar (*15*).

Differences between young and middle-aged drivers are also found in driving-related behaviors such as visual search and attention. Research has shown that more mature drivers focused their visual attention on the forward view more so than did novice drivers (*15*,*16*). In addition, more mature drivers produced the appropriate amplitude of steering wheel rotation by anticipating the characteristics of the curve. In contrast, the novice drivers sampled a narrower field of view that was closer to the front of the vehicle. Compared to more mature drivers, young drivers used less efficient visual cues for directional control and lane keeping (*15*,*16*). Young drivers tend to be slower and less reliable at identifying hazardous conditions on the road, focusing on traffic in the immediate view and not seeing traffic hazards that are upstream or emerging (*15*,*16*). Young drivers, particularly males, tend to overestimate their ability to control a vehicle when speeding and tailgating (*15*,*17*).

1.4 Roadway Environment

A roadside with vertical objects (in this case, tall trees) was included in the experimental design to evaluate whether visual stimuli in the periphery would affect driver evaluation of curve sharpness and speed. Previous research suggests that features of the visual environment can influence perception of speed and possibly curve hazard. For example, drivers drove significantly slower on a tree-lined road than on a road bounded by open space, possibly because the peripheral visual stimuli enhanced perception of speed or decreased sight distance (*18*).

1.5 Curve Parameters

Degree of curvature has also been associated with crash risk. For example, a crash risk on two-lane rural highways was found to be higher on sharper curves (*19*). In a survey of 300 fatal crash sites in Georgia and 300 comparison sites, results showed that curves with more than 6 degrees of curvature combined with downhill gradients of 2 percent or more were overly represented in fatal crashes. In addition, half of fatal crashes occurred at or near curves greater than six degrees of curvature regardless of gradient (*20*). Yet, other research has not found a relationship between curvature and crash rate. For example, an analysis of 1600 curves, degree of curvature, curve length and total angle did not show a relationship with crash rate (*21*), or a relationship between gradient and crash occurrence (*20*). Although the findings on curvature and crash risk are mixed, they suggest that drivers on occasion select unsafe speeds on horizontal curves, resulting in collisions. To explore perception of a range of curves, the experimental design included very sharp (10-degree) to moderately sharp (six degree) to not sharp (two degree) curves. The curves were balanced by direction. In addition, curves could be one of two lengths: 500-ft (152.4 m) or 1500-ft (457.2 m). Using two lengths served the purposes of: 1) reducing the predictability of curved segments in the scenario; and 2) investigating whether length affected perception or speed selection.

3.0 METHOD

3.1 Subjects

Fourteen young (ages 19 to 23) and fourteen middle-aged (ages 24 to 41) licensed drivers participated in the study. The age groups were balanced by gender. The drivers were volunteers from a local university or recruits contacted via the subject listing maintained at the FHWA.

3.2 Materials and Apparatus

The Simulator. The study was conducted in the FHWA highway driving-simulator. The simulator was fully interactive, used high-resolution computer-generated graphics, and consisted of a 4-door Saturn model car cab and a large projection screen in front of the car cab. The simulator did not have a motion base. An image that was 144-in. (365.76 cm) wide and 66-in. (167.64 cm) high projected the roadway scenes onto the forward screen. The driver's eye-point was about 27-in. (68.58 cm) high from the bottom of the image. The driver could not see the bottom edge of the image. The vehicle's steering wheel, accelerator pedal, and brake pedal were fully interactive with the scenario, enabling the driver to control vehicle speed and path through the simulated highway.

Tangent Sections. Each highway had 49 tangent segments either 750-ft (228.6 m) or 1500-ft (457.2 m) long. Each tangent alternated with a curve; tangent length (750-ft (228.6 m) or 1500-ft (457.2 m)) was randomly assigned to reduce predictability in the highway.

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<u>Curves</u>. Each highway had 48 curve segments. The curves were defined by: (1) the degree of curvature (two, six, or ten degrees); (2) curve length (500 ft (152.4 m) or 1500 ft (457.2 m)); and (3) direction (right or left). Each type of curve occurred in the highway four times per scenario. Because the subjects drove two routes, they rated each type of curve eight times.

<u>The Highways</u>. Drivers drove on two simulated two-lane rural highways, with 10-ft wide lanes, no shoulders, white edge lines, and a yellow double centerline. Ten-ft lanes are a common lane width on a rural highway. The posted speed limit was 55 mph (88.5 kph). The highways had identical horizontal and vertical alignment (0.0) but different roadside environments. One highway had an infinite clear zone. The second highway had a tree line beginning 20 ft from either side of the road.

3.3 Design
The study used a mixed-factorial experimental design. Driver age was the between-subjects factor with a young driver group (19-23 years old) and a middle-aged driver group (24-41 years old). (Drivers under the age of 18 years were not recruited because of the complications involved when using minors as research subjects.) The within-subjects factors were 1) roadside environment (infinite clear zone with no trees and 20-ft clear zone with an adjacent tree line), 2) degree of curvature (two, six, and ten degrees), 3) curve length (500-ft (152.4 m) and 1500-ft (457.2 m)), and 4) curve direction (right and left), as shown in Table 1. Each age group had an equal number of males and females. Dependent measures were driver ratings of the sharpness of curves and vehicle speed. The experimental design was two (age group) by two (gender) by two (roadside environment) by three (degree of curvature) by two (curve length) by two (curve direction).

TABLE 1The Repeated-Measures Factors

Factors	Levels																							
Roadside Env.	Infinite Clear Zone and No Trees												20-ft Clear Zone and Tree Line											
Curvature	2°				6°				10°				2°				6°				10°			
Curve Length (ft)	500		1500		500		1500		500		1500		500		1500		500		1500		500		1500	
Direction of Curve	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R

3.4 Procedure
Upon arrival at the FHWA's Turner-Fairbank Highway Research Center (TFHRC), each driver read and signed an informed consent form and a one-page instruction sheet. The experimenter escorted the driver to the simulator and described the Saturn controls. The driver drove a practice scenario of about 8-10 minutes. During the practice drive, the experimenter sat in the front passenger seat to guide the driver through the training and to evaluate whether the driver showed symptoms of simulator sickness. After the practice drive, the experimenter left the car cab for the control room and observed the driver and simulation via a video screen. The experimenter maintained communication with the driver through a small, inconspicuous microphone mounted in the front and speakers in the rear of the cab. When the scenario appeared, the driver put the gearshift in drive and pressed the accelerator pedal to proceed. The experimenter prompted the driver to rate each curve about 325 to 400 ft (99.06 to 121.92 m) (or about 4 to 5 seconds at 55 mph (88.5 kph) before the curve. The experimenter timed the query by observing an index representing the roadway segments in the control room. The drivers rated each curve by saying one of the following responses: very flat, flat, moderate, sharp, very sharp. The experimenter recorded the verbal rating. Stop signs on both sides of the road signaled the end of each test run, at which point the driver stopped the vehicle and waited for the next scenario to appear. After the conclusion of the second test run, the participants were debriefed and paid $30.00.

4.0 RESULTS

4.1 Ratings and Speed: Means and Standard Deviations
Because each curve was repeated four times in each scenario (i.e., highway) each subject's response is represented by an average of the four trials with the same curve. Mean speed was the average speed of the vehicle as it traversed the curve, sampled at a rate of 30 megahertz per second, beginning from the point of curvature to the point of tangency.

Drivers rated 10-degree curves sharpest, followed by six-degree curves and then two-degree curves. Similarly, drivers drove slowest on 10-degree curves, followed by the six- and two-degree curves. Mean curve ratings and standard deviations (*SD*) are shown in Table 2. Table 3 shows the mean speeds and standard deviations.

TABLE 2 Ratings: Mean and Standard Deviation (*SD*) by Degree of Curvature, Curve Length, Curve Direction, and Roadside Environment

	Mean	*SD*
All Curves	3.2	.38
Two Degree Curves	2.5	.49
Six Degree Curves	3.4	.43
Ten Degree Curves	3.7	.38
500-ft Curves (152.4 m)	3.2	.38
1500-ft Curves (457.2 m)	3.2	.40
Right Curves	3.0	.52
Left Curves	3.4	.31
Curves on highway with no trees	3.2	.37
Curves on highway with tree line	3.2	.44

TABLE 3 Speed: Mean, *SD*, and Minimum and Maximum Values by Degree of Curvature, Curve Length, Curve Direction, and Roadside Environment

	Mean (mph)	Mean (kph)	SD	Min	Max
All Curves	62	100	6.56	46	72
Two Degree Curves	67	108	6.35	53	79
Six Degree Curves	62	100	7.05	44	72
Ten Degree Curves	58	93	6.74	40	69
500-ft Curves (152.4 m)	62	100	6.86	45	72
1500-ft Curves (457.2 m)	62	100	6.33	47	72
Right Curves	63		6.71	46	73
Left Curves	62	100	6.48	46	72
Curves on highway with no trees	63	101	7.25	40	73
Curves on highway with tree line	62	100	6.89	49	79

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4.2 Statistical Tests: MANOVA and ANOVAs

Evaluating the statistical significance of the results entailed conducting: 1) an omnibus test using a Multiple Analysis of Variance (MANOVA); and 2) two Analyses of Variance (ANOVA), one on perception (as measured from the ratings) and one on speed. For each ANOVA, the main effects are described first, followed by a report of the interaction effects.

The MANOVA tested the effects of age group, gender, the curve parameters (degree of curvature, curve length, direction), and roadside environment on perception and speed. The MANOVA showed that:

- Degree of curvature had a main effect;
- Degree of curvature and curve length had an interaction effect;
- Degree of curvature and roadside environment had an interaction effect; and
- Curve direction and roadside environment had an interaction effect.

An ANOVA for ratings and an ANOVA for speed were used to indicate the source of the statistical differences. Note that age group and gender were not included as independent variables in the ANOVAs since neither had effects on the dependent variables.

4.3 Ratings: ANOVA Results

The ANOVA using a 3 (degree of curvature) by 2 (curve length) by 2 (curve direction) by 2 (roadside environment) repeated-measures design on ratings showed: 1) main effect of degree of curvature; 2) main effect of curve direction; 3) a two-way interaction effect of roadside environment and degree of curvature; and 4) a two-way interaction effect of curve length and curve direction.

4.3.1 Ratings: Main Effect of Degree of Curvature

Drivers rated ten-degree curves the sharpest (mean=3.7), followed by six-degree curves (mean=3.4) and two-degree curves (mean=2.5). Degree of curvature had a very large effect in that it accounted for 84 percent of the variability in the ratings (as demonstrated by its eta squared of 0.835)[1] and a significant effect (F (1,27) = 74.78, p<. 05).

4.3.2 Ratings: Main Effect of Curve Direction

Drivers rated left curves as being significantly sharper than right curves. Left curves had a mean rating of 3.35, compared to right curves, which were rated slightly less sharp with a mean rating of 3.05. The absolute difference between the ratings was small but statistically significant (F (1,27) = 18.21, p<. 05).

4.3.3 Ratings: Interaction Effect of Degree of Curvature and Roadside Environment

Drivers rated six-degree curves in the infinite zone the same as six-degree curves with the tree line (mean=3.4), but they rated the two-degree curves with the tree line lower (mean=2.5) than two-degree curves in the infinite zone (mean=2.6). Drivers rated 10-degree curves in the infinite zone lower (mean=3.6) than ten-degree curves with the tree line (mean=3.7), as shown in Figure 1. The differences are small, but statistically significant (F (2,26) = 4.08, p<. 05). The data suggest that the roadside environment influenced the perception of the most extreme curves (i.e., the sharpest and the flattest).

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1 The eta squared represents the proportion of total variability (1.00) in the curve ratings accounted for by the degree of curvature factor.

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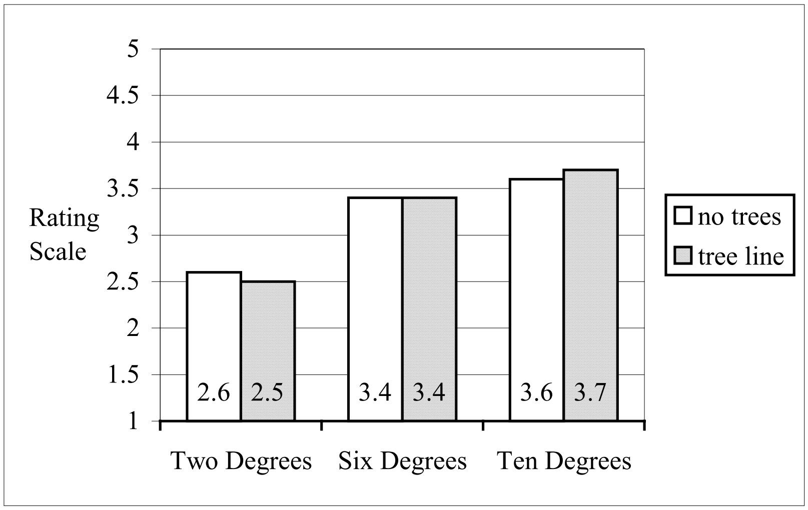

FIGURE 1 Ratings: The interaction effect by degree of curvature and roadside environment.

4.3.4 Ratings: Interaction Effect of Curve Direction and Curve Length

Drivers rated left curves the same regardless of their length, but they rated 1500-ft (457.2 m), right curves sharper (mean=3.1) than 500-ft (152.4 m), right curves (mean=2.9), which was a statistically significant difference (F (2,27) = 21.60, p<. 05). Figure 2 illustrates the interaction effect between direction and curve length.

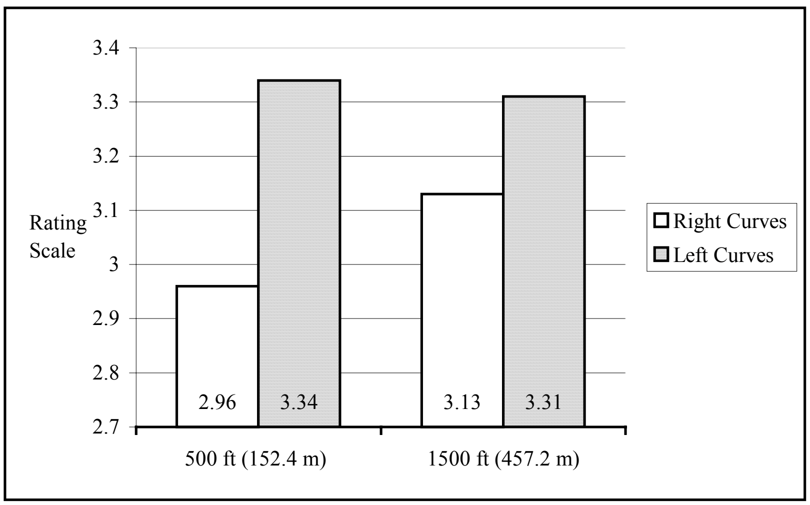

FIGURE 2 Ratings: The interaction effect of curve direction and curve length.

4.4 Speed: ANOVA Results

An ANOVA using a three (degree of curvature) by two (curve length) by two (curve direction) by two (roadside environment) design was conducted. The ANOVA showed: 1) main effect of degree of curvature; 2) main effect of curve direction; and 3) the following two-way interaction effects between: the roadside environment and degree of curvature; the roadside environment and curve direction; and degree of curvature and curve direction.

4.4.1 Speed: Main Effects of Degree of Curvature

Drivers drove fastest on two-degree curves (mean=67 mph (108 kph)), moderately fast on six-degree curves (mean speed=62 mph (100 kph)), and slowest on the ten degree curves (mean speed=58 mph (93 kph)) (F (2,54)=197.39, p<. 05).

4.4.2 Speed: Main Effects of Curve Direction

Drivers drove slower on left curves (mean=62 mph (100 kph)) than on right curves (mean=63 mph (101 kph)). The

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finding parallels the findings on perception because drivers rated left curves sharper than right curves. The difference is small but significant (F (1,27)=14.55, p<. 05).

4.4.3 Speed: Interaction Effect of Degree of Curvature and Roadside Environment
Drivers drove slower (mean speed=57 mph (92 kph)) on ten-degree curves with trees than on ten-degree curves with an infinite clear zone (mean speed=59 mph (95 kph)), (F (2, 54)=11.75, p<. 05), shown in Figure 3.

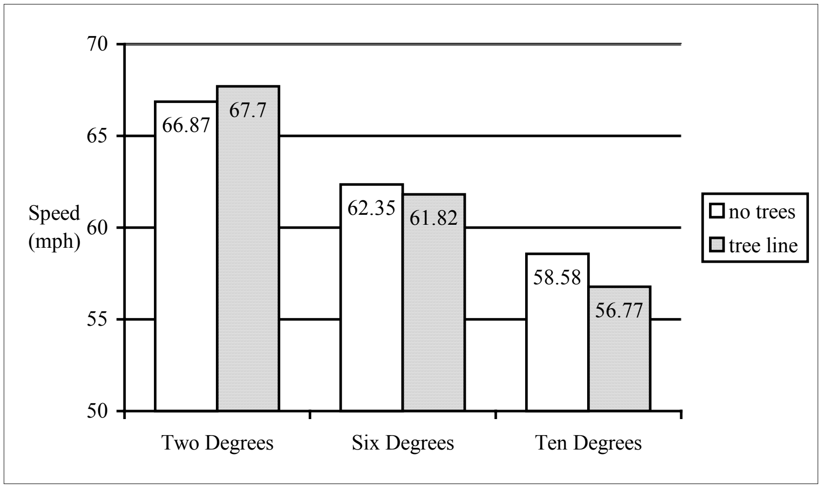

FIGURE 3 Speed: Degree of curvature and roadside environment.

4.4.4 Speed: Interaction Effect of Degree of Curvature and Curve Direction
Divers drove slower (mean speed= 58 mph (89 kph)) on ten-degree curves, but they drove the absolute slowest on ten-degree curves that were heading left (mean speed=57 mph (92 kph) (F (2,54)=34.45, p<. 05).

4.4.5 Speed: Interaction Effect of Curve Direction and Roadside Environment
Drivers drove faster on right curves with the infinite clear zone (mean speed=63 mph (101 kph)) than on right curves with the tree line (mean speed=62 mph (100 kph)) (F (1,27)=4.46, p<. 05).

5.0 DISCUSSION

The findings of this study are related to curve perception as well as simulator use in perception research. The finding that drivers accurately perceived degree of curvature is an encouraging indication of the value of the simulator. The trend in the data is what one would expect in the driving environment, and the fact that drivers reliably differentiated between the two-, six-, and ten-degree curves suggests that the simulator is capable of presenting visual stimuli in a way that drivers respond to as if they were really on a road. The speed data support the findings on perception because the drivers chose speeds that correlated with their perception of curvature. In addition, field research replicates the finding that drivers drive slower on left curves on rural highways (*22*).

The dual finding that drivers 1) perceived left curves to be sharper than right curves and 2) drove slower on left curves than on right curves requires interpretation. Right turns are slightly sharper than left turns due to the fact that drivers are in the right lane of the highway. This difference is because the outside lane of the curve has a slightly larger radius than the inside lane. The subjects, however, perceived left turns to be sharper than right turns. One explanation for this discrepancy is that curve length may have influenced perception of sharpness. This interpretation suggests that drivers use more than degree of curvature as a visual cue for detecting sharpness. Drivers may also be using curve length as a cue. The left curve is slightly longer than the right curve. On the approach to the curve, the curve may appear slightly sharper when in fact it is only slightly longer. This explanation is supported by the fact that drivers rated the 1500-ft curves sharper than the 500-ft curves across equivalent degrees of curvature.

The similar pattern in perception and speed suggests that drivers assessed curves during the approach (when they provided the rating) and then adjusted vehicle speed to match their assessment of curve sharpness. Since the simulation did not include a motion base, drivers could not have experienced lateral acceleration on the curves. This finding could be interpreted in three ways: 1) the perceptual experience of the simulation was sufficiently strong to lead drivers to expect or anticipate the feeling of lateral acceleration, and so they slowed down for sharper curves; or 2) the drivers were aware of the absence of motion, so they assessed curve hazard primarily via visual cues, in contrast to the physical cues arising from lateral acceleration; or 3) drivers may have anticipated loss of control on curves based on their driving experience or experience in the simulator during practice.

Drivers drove the same mean speed regardless of roadside environment, with an approximate speed of 62 mph. This result parallels the perception data; drivers did not change their ratings of curve sharpness as a function of the roadside environment. The tree line scenario may not have affected speed because it was sufficiently far (20-ft) from the roadway edge. The 20-ft clear zone is greater than the American Association of State Highway and Transportation Officials (AASHTO) (*11*) 10-ft recommendation for rural roads but less than 30 ft recommendation for high-speed facilities.

The young and middle-aged drivers showed no difference in speed. This finding was not expected because previous research shows that young drivers tend to drive faster than middle-aged drivers. In this study, a tendency to speed may have been reduced by the presence of the experimenter and technician in the control room.

Future FHWA research on curve perception can build upon the data collected in this study. Performance measures obtained in the current experiment can be compared to performance measures obtained in scenarios that contain curve treatments to determine if the treatments improved perception or safe speed selection. For such comparisons to be meaningful, however, the capacity of the simulator to elicit typical driving responses to curve treatments must be established. One recommendation for the next research step is to conduct a field study using an instrumented vehicle to validate the results from the current study.

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