

VISUAL DEMAND OF DRIVING CURVES AS DETERMINED BY VISUAL OCCLUSION

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Abstract

The visual demand of driving was determined using the visual occlusion method. In this method, drivers pressed a switch to get a half-second glimpse of the road. Otherwise, the road was occluded. Visual demand was defined as the proportion of time the road was visible.

Twenty-four licensed motorists from 3 age groups (18-24, 35-54, 55+) drove a simulated single-lane road consisting of 12 separated curves of 4 curve radii (582 m, 291 m, 194 m, and 146 m) and 3 deflection angles (20°, 45°, 90°). Subjective ratings of demand were obtained for each curve.

Based on the occlusion data, mean demand values for curves were determined. Visual demand increased significantly with the reciprocal of curve radius and increased considerably with driver age. Mean demand values were 0.34 for a straight section and 0.61 for the sharpest curves examined.

Most remarkable was the considerable sensitivity of the demand profiles to curve variations, particularly given the small data set. Occlusion-based demand appears to be very sensitive to variations in road geometry and to the driver's age.

1. INTRODUCTION

There is a strong relationship between crashes, roadway-based geometric inconsistency, and driver workload (Messer, 1980; Krammes and Glascock 1992; Wooldridge, 1992). Since assessing driver workload is essential in establishing this relationship, numerous techniques have been developed to assess driver workload (Green, Lin and Bagian, 1993; Hicks and Wierwille, 1979; Hulse, Dingus, Fischer, and Wierwille, 1989).

In general, workload measurement techniques fit into five broad categories: (1) primary task measurement (measurement of steering performance such as lane variance), (2) secondary task measurement (measurement of performance in an additional task which is performed while driving), (3) physiological measures (such as heart rate variability), (4) subjective techniques (ratings of workload), and (5) visual occlusion. In the current study, visual occlusion was the primary means of workload measurement.

Visual occlusion was first proposed as a measure of workload by Senders, Kristofferson, Levison, Dietrich, and Ward (1967). They identified the tradeoff between speed and acceptable occlusion duration and developed a quantitative expression to represent the moment-to-moment uncertainty of driving. Since then there have been about a dozen studies using the visual occlusion technique. For a detailed review of these studies see Green (1998).

Only Senders (1967), Godthelp (1984), Shafer (1995), and Mourant (1997) explicitly examined driving on curves, although Senders and Mourant did not present explicit results concerning the effects of curve radius or length. Similarly, the work of Godthelp is of interest in that it concerned a single occlusion period at the beginning of the curve rather than intermittent occlusion as the curve was driven. None of the studies examined the effects of road curvature on driving in a simulator. Moreover, the number of subjects in these studies was too small to effectively study age-related differences in performance. Finally, none of the studies investigated where drivers looked when they were driving under visual occlusion.

Accordingly, several questions were examined in this study:

1. *In a driving simulator, how does the visual demand for curves vary as a function of curve radius and deflection angle?*
2. *In a driving simulator, how does the visual demand vary as a function of the driver's age?*
3. *When the driver's vision is intermittently occluded while driving in a simulator, where does the driver look when the scene is visible?*

This study is part of a more comprehensive study performed by the Texas Transportation Institute (TTI) in collaboration with the University of Michigan Transportation Research Institute (UMTRI) (Fitzpatrick et al, 1999). Both parts of the study used visual occlusion to measure how the visual demand of drivers was affected by the curvature of the road. The research conducted by TTI was performed on a test track and on the road. The research conducted by UMTRI employed matching curves and was performed in a driving simulator.

2. METHOD

2.1. Apparatus

The study was conducted in the UMTRI driving simulator (Figure 1), a fixed-based, low-cost device, based on a network of Macintosh computers (MacAdam, Green, and Reed, 1993). The simulator consists of a mockup of a car (1985 Chrysler Laser); a projection screen; a torque motor connected to the steering wheel to provide realistic damped torque feedback; a sound system to provide engine-, drive train-, tire-, and wind-noise; a computer system to project images of an instrument panel; and a simulated hood to provide a realistic driver's view. The projection screen, offering a field of view of 33° horizontal and 23° vertical, is located 6.0 m in front of the driver. Bass shakers provide limited vertical vibration to induce some sensation of motion thus reducing the likelihood of simulator sickness.



Figure 1. The simulator setup (note: the road scene image is enhanced for clarity)

An LCD plate from commercial occlusion goggles (Translucent Technologies PLATO S-2 spectacles, Milgram, 1987) was mounted on the lens of the overhead projector displaying the road scene. The plate changed from translucent to transparent when a foot switch mounted on

the firewall near the driver's left foot was pressed. Depression of the switch allowed the road scene to be viewed for 0.5 seconds. (The switch had to be released and depressed for each glance.) The occlusion device was synchronized with the simulator by manually starting the simulator the first time the driver pressed on the foot switch.

Driver eye fixations were recorded by a prototype version of the Headhunter recording system being developed by ISCAN, Inc. of Burlington, MA. This corneal reflection-based system consists of a head piece and two cameras (one capturing an IR source reflected from the driver's eye and a second showing the view straight ahead and moving with the driver's head), an IR reflective mirror, computers to process and store the data, and two video monitors. The fixation point appeared on the video monitor as a small circle on the scene.

2.2. Test Participants

Twenty-four licensed drivers served as subjects. Most were recruited through a local newspaper advertisement. There were 4 men and 4 women in each of three age groups (18-24, 35-54, 55+). Seven subjects had participated in previous studies involving the simulator, but none had participated in an occlusion study. The mean annual mileage the subjects had driven was 20,000 km. About half of them wore contact lenses and two of the older subjects wore glasses. The mean corrected visual acuity for subjects was approximately 20/23, with a range of 20/13 to 20/50 (the maximum allowed in this study).

2.3. Experimental Design

In the repeated measures design used, there were two between-subject factors: (1) age (young, middle, old) and (2) sex (male, female); and four within-subject factors: (1) curve radius (four levels), (2) deflection angle (three levels), (3) curve direction (right, left), and (4) three repetitions. Figure 2 shows the test course and the geometry of the 12 test curves. Curve order was fixed throughout the runs to be consistent with the work done in TTI. Curve direction was randomized throughout the road so that half of the curves were in each direction in each run. The test course – a single 3.7 m lane – was 8.7 km long and took about 7 minutes to drive at 72.5 km/h. Although the horizon could be seen at all times, sight distance of the road was limited to 180 m.

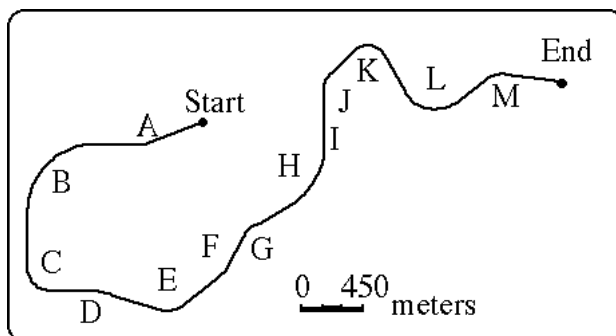


Figure 2a. The test course layout

		Curve Radius [m]			
		582	291	194	146
Deflection Angle	20°	D	F	G	A
	45°	H	E	J	M
	90°	B	L	C	K

Figure 2b. The geometry of the curves

3. RESULTS

The raw data from this experiment consisted of 50,177 key presses to obtain vision, collected from 24 subjects in 6 runs through the test course. The individual observations represent immediate visual demand during the time interval between requests for vision. The

expression for calculating visual demand as cited by Shafer is shown in equation 1. Shorter intervals between keypresses indicate higher visual demand. In a strict technical sense, workload is the consequence of visual demand.

$$\text{VisD}_i = \frac{0.5}{t_i - t_{i-1}}$$

VisD_i = visual demand over time interval from t_{i-1} to t_i
 t_{i-1} = clock reading at previous information request [s]
 t_i = clock reading at current information request [s]
 0.5 = time increment during which subject had vision [s] (1)

3.1. Visual Demand Profiles

Figure 3 shows profiles for curves of 45° deflection angle averaged across all the subjects. On the Y-axis, 0.0 represents the occlusion device always closed (low visual demand) and 1.0 would represent always open (high visual demand). The four curves in the figure, representing the different curve radii, are almost identical up to 100 m before the beginning of the curve. The plots for other curves show a similar pattern of visual demand. The visual demand values are low at the beginning of the approach tangent, increase toward the end of the approach tangent, peak near the beginning of the curve, decrease throughout the curve, level off by the end of the curve, and remain at the same level through the departure tangent. Variability between different runs was moderate but this pattern was maintained throughout the runs for all the subjects.

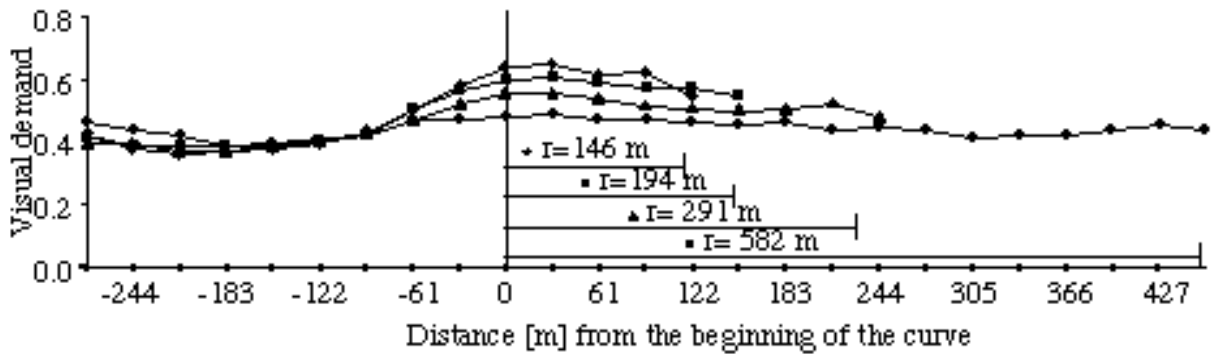


Figure 3. Average visual demand for curves with 45° deflection

3.2. Statistical Analysis of Visual Demand

Visual demand was estimated as the mean of all the observations within the first half of the curve, as in previous TTI studies. These estimated values were then analyzed using a repeated measures Analysis of Variance (ANOVA) model. All levels of interaction were included in this model. Only significant effects of the ANOVA are discussed in this section.

The ANOVA indicated that the effects of curve radius ($p < 0.0001$) and of deflection angle ($p < 0.01$) were statistically significant (Figure 4). Standard deviations ranged from 0.11 to 0.13. As expected, visual demand was higher in sharper curves. The effect of road curvature on visual demand was nearly linear. Using a stepwise regression with an inclusion criteria of $p < 0.05$, only curve radius entered the regression. Due to the large variability between subjects, the regression model only explains a small part of the variability ($R^2 = 0.22$). Nevertheless, the regression describes the linear relation between curvature within each of the subjects (Eq. 2). When age is added to the model, R^2 increases to 0.37 (Eq. 3). The regression models are:

$$\text{Visual demand} = 0.388 + 33.2/r \quad (2)$$

$$\text{Visual demand} = 0.257 + 33.2/r + 0.003 \cdot \text{age} \quad (3)$$

(r = radius of the curve in meters; age = the subject's age in years.)

Older subjects had higher visual demand (Figure 4). However, due to large variations between subjects, this effect was only marginally significant ($p < 0.1$). The interaction between age and curve radius was significant ($p < 0.0001$). For young subjects, visual demand increased from 0.30 on a straight road to 0.37 on a curved road. For older subjects, however, visual demand increased from 0.38 to 0.55. Apparently, the mere presence of a curve was a strong loading factor for older subjects.

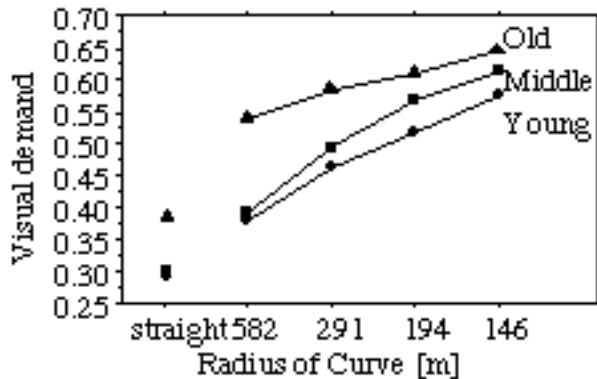


Figure 4. The effect of curvature on visual demand in three age groups.

Visual demand did not change considerably as a function of deflection angle. Curves with a deflection angle of 90° are longer, therefore drivers can stabilize the vehicle and need fewer glances than at the beginning of the curve. On the other hand, these curves may be perceived as more demanding and therefore curve entry effects are negated. Thus, an increase in curve length does not increase the mean visual demand of half the curve. It does, however, increase the duration in which a driver would be exposed to an elevated level.

3.3. Maximum Visual Demand

For each curve, the location of the maximum visual demand was determined. Seventy percent of these locations were within 100 m of the beginning of the curve.

3.4. Point of Rise in Visual Demand

To determine at what point the subjects started looking more frequently at the road, sets of four consecutive intervals between keypresses were examined. A rise in visual demand was identified when the second interval was shorter than the first, and the fourth interval was yet shorter. This method captured all linear rises, as well as rises with a local drop (at the third keypress).

The average location of the rising point was 92 meters before the point of curvature, with a standard deviation of 47 meters. A repeated measures model, similar to the model for visual demand values, was applied to the point of rise data. Due to the large variability in the data, only a few factors were found to be significant. Some trends in the location of the point of rise were: (1) it occurred earlier in sharper curves ($r=146$ m: -100 ± 40 m vs. $r=582$ m: -88 ± 54 m); (2) it occurred earlier in older subjects (old: -101 ± 48 m vs. young: -83 ± 45 m)

3.5. Glance Behavior

The eye fixation analysis examined data from 12 subjects (2 from each age-sex group) to provide a sense of the lateral glance behavior when driving curves. When using the occlusion device, the subjects tended not to change the position of their gaze very often. Most of the time, they preferred looking at the end of the road near the horizon. At times, they looked to either side of the road seeking anticipated changes in the curvature of the road. When a curve was recognized, the subjects usually started to look at the beginning of the curve. Upon entering the curve, when driving without occlusion, the subjects tended to follow one of the edges in backwards sequences, a fast saccade to the next marker, and then slow pursuit of the marker

and its near location until it was close to the vehicle. When the subjects' vision was occluded, they did not perform full backward sequences. They tended to maintain their head and eye position relatively stable as they passed the curve, basically looking at a point in the mid-range on one of the edges of the road. The high contrast between the road and its edge, and the constant movement of markers on the edge may have drawn subjects' attention to the sides of the road.

A quantitative analysis revealed that the subjects fixated inside the curve when the curve radius was high ($R=582\text{ m}$: 0.35 ± 0.4). However, in sharper curves more subjects fixated outside the curve ($R=146\text{ m}$: 0.62 ± 0.4 for left curves and 0.48 ± 0.4 for right curves). The difference between a sharp curve of 146 m radius to a curve of 582 m radius was significant (Scheffe's post hoc 2-way comparison $p=0.02$). The difference was more prominent in left curves than in right curves (Figure 5).

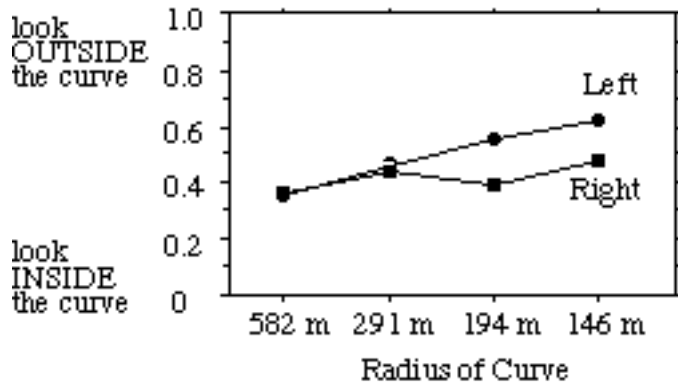


Figure 5. Where do drivers look as a function of curve radius?

3.6. Subjective Ratings

Subjective ratings of the difficulty of the curves were collected using the Cooper-Harper scale (1969) as modified by Wooldridge of TTI. Subjects rated the test road while driving without the occlusion device (the preliminary run), and then twice while driving with the occlusion device in place (run 1 and run 5). Figure 6 shows that ratings increased linearly as the curve radius decreased and the deflection angle increased.

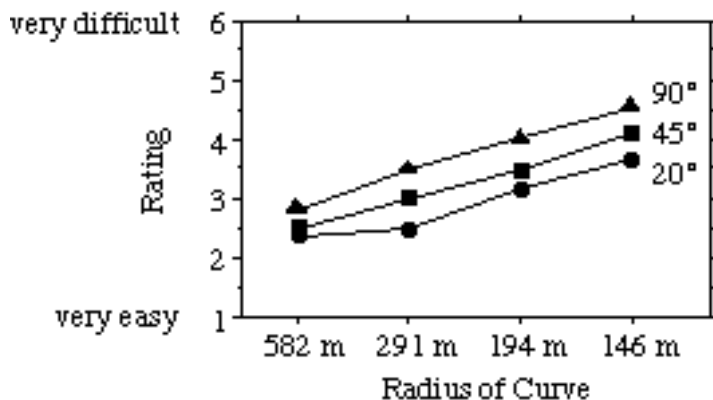


Figure 6. Subjective rating as a function of curve radius and deflection angle

A stepwise regression analysis of the ratings ($p<0.05$ for inclusion) was computed. The ratings were assumed to be continuous. Due to the large variability between subjects, the regression model does not explain a large portion of the variability ($R^2=0.20$). The model is:

$$\text{Rating} = 1.1 + 303.9/r + 0.013 \cdot \text{Deflection} + 0.017 \cdot \text{Age} \quad (4)$$

4. CONCLUSIONS

Question 1. In a driving simulator, how does the visual demand for curves vary as a function of curve radius and deflection angle?

Mean visual demand for curves was linearly related to the reciprocal of curve radius. Although the mean visual demand for a straight section was 0.34, it was 0.44 in curves of 582 m radius, and 0.61 in curves of 146 m radius.

Mean visual demand did not vary considerably as a function of deflection angle of the curve. It was 0.53, 0.54, and 0.52 for deflection angles of 20°, 45°, and 90° respectively. When inspecting only the area around the point of curvature, no difference was observed. Examination of the subjective ratings, however, shows that the subjects rated longer curves to be harder.

Question 2. In a driving simulator, how does the visual demand vary as a function of driver age?

Age was only slightly significant ($p < 0.1$). Neither sex nor the interaction between sex and age were significant. Although the number of subjects in each age-sex group was only four, a consistent age trend was observed in all the analyses. Older subjects required more keypresses, indicating greater visual demand. This trend was present in all curve radii as well as in straight road sections. In addition, the slight learning effect seen within runs did not affect the older subjects; visual demand did not decrease throughout the runs. Subjective ratings of the curves were higher for older subjects than for younger subjects. There was not enough statistical power in this study to significantly highlight the effects of age and sex on visual demand, but the trends seem consistent with other known effects of aging. It is important to note that the older age group consisted of subjects whose ages were between 58 and 68. A much stronger effect would be expected if subjects in this age group were all older than 65.

Question 3. When the driver's vision is intermittently occluded while driving in a simulator, where does the driver look when the scene is visible?

In general, subjects preferred to look at the imaginary focus of expansion in straight sections. In curved sections there was a tendency to fixate on one of the edges of the road while using backward sequences (saccade forward, and several pursuits backward). From time to time, subjects looked at random locations for short periods. These locations included scanning for approaching curves to the right or the left of the horizon line, and short glances to various points closer to the car.

When driver vision was limited by occlusion, many of the extraneous glances were not observed. In straight sections, the subjects tended to fixate on the imaginary focus of expansion, perhaps relying more extensively on the periphery. In curved sections, they fixated on one of the edges of the road and performed discrete forward sequences until the curve ended.

On average, the subjects preferred looking inside the curve when the curve radius was high. In sharper curves more subjects preferred looking outside the curve. This preference was more prominent in left curves than in right curves.

5. ACKNOWLEDGEMENT

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