UMTRI-94-21 June 1994

Driver Eye Fixations on Rural Roads: Insight into Safe Driving Behavior

Colleen Serafin

UMTRI The University of Michigan Transportation Research Institute

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Driver Eye Fixations on Rural Roads: Insight into Safe Driving Behavior		5. Report Date June 1994
		6. Performing Organization Code account 029576
7. Author(s) Colleen Serafin		8. Performing Organization Report No. UMTRI-94-21
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, Michigan 48109-2150 U.S.A.		10. Work Unit no. (TRAIS)
		11. Contract or Grant No. DTFH61-92-X-00018
12. Sponsoring Agency Name and Address Federal Highway Administration 6300 Georgetown Pike, Rm. T-204 McLean, VA 22101		13. Type of Report and Period Covered interim, 6/29/93-6/28/94
		14. Sponsoring Agency Code

15. Supplementary Notes

Agreement Officer's Technical Representative (AOTR): Jerry Reagan, HSR-20

This report describes an investigation of driver eye fixations on straight and curved rural roads. Thirty-two participants (sixteen under 35 years, sixteen over 60 years) drove on a 4.6 mile two-lane road while wearing an eye-mark camera to record eye fixations. While data were collected for the entire route, only data from four road segments were analyzed (one straight segment and three left curves of 3, 13, and 21 degrees).

The results indicate that there were some differences in driver eye fixations depending on the curvature of the road. A higher percentage of fixations was found for the right scenery on the straight segment (17 percent) than on the curves (3 percent). Also, higher fixation percentages were found for the center line, right lane, and right scenery on the 3 degree curve (23 percent) than on the 21 degree curve (3 percent). Drivers made more fixations on the 21 degree curve (41) than on the 13 degree curve (34). On all of the road segments, drivers tended to fixate as far down the road as they could. The overall mean fixation duration was 158 milliseconds. Fixation durations were longer to oncoming cars (506 milliseconds) than to any other feature (146 milliseconds). The location of eye fixations was not influenced by age. Younger drivers, however, had slightly longer (174 milliseconds) but fewer fixations (30) than older drivers (145 milliseconds, 36 fixations).

The data from this study will be utilized in the development of theoretical and computer simulation models that will describe and predict driver eye-fixation patterns given various road and driver characteristics. In future work, the simulation model will be validated. The ultimate goal of the modeling effort is to provide baseline data for driving that will lead to safe and easy-to-use in-vehicle displays by helping to identify the attentional demands of driving.

17. Key Words	18. Distribution Statement
eye fixations, visual attention, information input, ergonomics, human factors engineering	unrestricted

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
None	None	69	

PREFACE

In 1992, the University of Michigan Transportation Research Institute (UMTRI) was awarded a grant agreement sponsored by the United States Department of Transportation (DOT)/Federal Highway Administration (FHWA) to pursue research in areas of traffic safety. The agreement period was for one year with the possibility of two one-year extensions. Thus, a total of three years were covered under the agreement.

During the first year, an on-road study was performed examining eye fixations of eight drivers on straight versus curved rural roads. This work is described in *Preliminary Examination of Driver Eye Fixations on Rural Roads: Insight into Safe Driving Behavior* (Serafin, 1993).

In the second year, the on-road study was expanded; an experiment examining eye fixations of 32 drivers was performed on the same road. Analysis of the data is currently in progress. In addition, theoretical and computer models are being developed which describe and predict driver eye patterns, respectively. Data from the on-road study will be utilized to complete the development of the models. In the future, these models can be used to predict fixation patterns; on-road data collection will be unnecessary.

This interim report summarizes the data collected for 32 participants. It does not include the work in progress: further data analysis and model development.

Work planned for the third, and final, year is to complete the data analysis from the on-road study, to complete the development of the models, and to perform a model validation experiment. A final technical report will summarize the on-road study, as well as provide a model of driver eye fixations on rural roads.

ACKNOWLEDGMENTS

I would like to extend my sincere gratitude to the project director, Paul Green, for his guidance throughout this endeavor. Also, the support of many colleagues in the Human Factors Division at the University of Michigan Transportation Research Institute (UMTRI) is appreciated. I would especially like to thank Marie Williams who helped in the instrumentation of the test vehicle used in this study. Marie also wrote the computer programs that were used for reduction of the eye-fixation data and provided invaluable assistance with troubleshooting problems on the computer. This project would never have been possible without her support. Jill Fleming, Kellie George, Hideki Hada, Eileen Hoekstra, and Stewart Katz provided intellectual support, encouragement, and camaraderie. Special thanks are extended to Tandi Bagian and Jim Sayer who had the patience to listen to me when I needed someone to talk to throughout the year. I would also like to thank Jim for his support, encouragement, and intellectual contributions. Greg Johnson and Mike Campbell in the Engineering Research Division of UMTRI had a major role in the instrumentation of the test vehicle. Their support is sincerely appreciated. Finally, I would like to thank Eric Traube for his cheer throughout the year.

Funding for this research was provided by the United States Department of Transportation (DOT)/Federal Highway Administration (FHWA) grant agreement DTFH61-92-X-00018. The use of the eye-mark recorder used in this study was generously provided by Mitsubishi Motors Corporation of Japan.

TABLE OF CONTENTS

INTRODUCTION

Driving is primarily a visual task, yet the visual behavior of drivers is not well understood. Drivers not only need to look at the road, but also at various displays and mirrors in the vehicle. In fact, in-vehicle displays (touch screen CRTs for radio and climate control, traffic monitoring systems, etc.) under development may force the driver's visual attention away from the road for longer periods of time than do traditional displays. Before drivers' eye-fixation behavior with advanced displays can be understood, there is a need for baseline data that describe driver eye patterns in very simplistic situations, such as a rural road with little traffic and no traffic lights or stop signs. Of particular importance for the understanding of driver visual behavior are the perceptual cues used to safely maneuver a vehicle on a road.

Eye-fixation behavior in automobile drivers has been examined by several researchers. While this research has provided some insight into the visual behavior of drivers, the total amount of data that has been collected is small. Most of the data from the studies are not comparable to each other due to different driver or road characteristics, or different definitions of road features or fixations/glances. Thus, individual research efforts provide limited data, and a summary of the published data to adequately describe drivers' visual behavior is impossible due to inconsistencies among the studies.

It is the goal of this research project to provide information that will assist in the understanding of driver visual behavior. Descriptions of driver eye-fixation patterns on straight and curved rural roads will provide baseline data of visual behavior. Further, the data will be utilized in the development of theoretical and computer simulation models that will describe and predict driver eye-fixation patterns, respectively. Finally, the computer simulation model will be validated.

Specific data that will be incorporated into the computer model include:

- locations of eye fixations on the road and in the vehicle (including mirrors)
- mean fixation duration
- standard deviation of fixation duration
- probability of a transition to the next location on the road or in the vehicle

Through data collection and model simulation the following questions will be addressed:

1. For daytime driving on straight rural roads, what are driver eye patterns and transition probabilities between road features (e.g., right edge marker, left edge marker, center line), car mirrors, and in-vehicle features?
2. What is the relationship between degree of curvature and driver eye fixations?
3. How does age affect driver eye fixations?
4. How well does the computer model describe actual driving behavior?

The ultimate goal of the computer modeling will be to describe driver eye fixations given various road and driver characteristics. This will provide baseline data for driving that will lead to safe and easy-to-use in-vehicle displays by helping to identify the attentional demands of driving.

EYE-FIXATION LITERATURE

Driver eye-fixation patterns have been investigated by researchers in various situations. (See table 1.) While some studies report eye patterns on straight and curved rural two-lane roads, others report eye fixations on interstate highways. Some researchers have investigated situations where the driver follows a lead vehicle, whereas others investigated situations when traffic is absent. Other factors that have been varied include time of day, age, experience, road familiarity, and driver degradation. Researchers have also looked at eye patterns while driving with an auxiliary display.

The literature reviewed in detail for this report includes those studies that examined driving on straight and curved rural roads, and age. These references are summarized in a table in the appendix which provides the following information: method (simulator, on-road, etc.), type of road, time of day, subjects, independent variables, dependent variables, form of the results, results, and conclusions/comments. In addition, models of driver behavior are discussed.

Fixations on Straight and Curved Rural Roads During the Day

Drivers' eye fixations on straight and curved rural roads have been studied by several researchers. (See table 1.) These researchers have examined percentages of time and fixations on different features of the road (right edge, left edge, center line, etc.), durations of fixations, number of fixations sampled, vertical and horizontal distributions of eye positions, and eye patterns (travel distance between fixations, eye links, etc.). A summary of these studies follows.

Blaauw (1975) studied drivers' eye fixations on two types of road sections (two left curves and one straight road) during the day. The sections were approximately 276 meters long and were two-lane one-way roads bordered, for the most part, by crash barriers. Thus, a limited horizontal field of view existed. On the roads, drivers were instructed to drive in the right lane. Five men, ranging from 22 to 28 years of age, participated.

Cohen and Studach (1977) examined eye fixations of nine students (mean age of 23.5 years), each with more than 20,000 kilometers of driving experience. Eye fixations were examined on a rural road with right and left curves.

Olson, Battle, and Aoki (1989) examined the glances of six men (20 to 34 years old) on straight (two sections) and curved rural roads (three right and three left 90-degree curves), both at night and during the day. Olson and his colleagues defined a fixation as a glance to a feature of the road which included a number of individual fixations in that area. While driving, participants first followed another vehicle and then drove the same route without a lead vehicle . Only the results for driving without a lead vehicle are summarized in the present review. One point to note is that Olson et al. reported the glances as falling into two categories: 1) between 100 and 300 feet in front of the vehicle and 2) greater than 300 feet in front of the vehicle, which they defined as far field.

Rackoff and Rockwell (1975) studied the eye fixations of four college-aged men on a rural two-lane road during the day and at night. Unfortunately, Rackoff and Rockwell do not provide more detail about the road or subjects.

Table 1. Studies that report driver eye-fixation data

Situation/Variable	Researchers
Age	Rackoff (1974) Rackoff and Mourant (1979)
Auxiliary display	Antin, Dingus, Hulse, and Wierwille (1990) Kurokawa and Wierwille (1991) Noy (1990) Pauzie and Marin-Lamellet (1989) Wierwille, Hulse, Fischer, and Dingus (1988) Zwahlen and Debald (1986)
Driver degradation	Kaluger and Smith (1970) Mortimer and Jorgeson (1972) Moskowitz, Ziedman, and Sharma (1976) Rockwell and Weir (1973) Safford (1971)
Experience	Mourant and Rockwell (1972) Renge (1980) Zell (1969)
Interstate highways	Mourant and Rockwell (1970b) Mourant and Rockwell (1972) Mourant, Rockwell, and Rackoff (1969) Rackoff (1974) Rackoff and Mourant (1979) Rackoff and Rockwell (1975) Rockwell, Ernst, and Rulon (1970) Zell (1969)
Lead vehicle	Mourant and Rockwell (1970a) Mourant, Rockwell, and Rackoff (1969) Sivak, Conn, and Olson (1986) Zell (1969)
No traffic	Blaauw (1975) Cohen and Studach (1977) Olson, Battle, and Aoki (1989) Rackoff and Rockwell (1975) Rockwell, Ernst, and Rulon (1970) Shinar, McDowell, and Rockwell (1977) Zwahlen (1982)
Road familiarity	Mourant and Rockwell (1970a) Mourant and Rockwell (1972) Mourant, Rockwell, and Rackoff (1969)
Straight and curved rural two-lane roads	Blaauw (1975) Cohen and Studach (1977) Olson, Battle, and Aoki (1989) Rackoff and Rockwell (1975) Rockwell, Ernst, and Rulon (1970) Shinar, McDowell, and Rockwell (1977) Zwahlen (1982)
Time of day	Olson, Battle, and Aoki (1989) Rackoff and Mourant (1979) Rackoff and Rockwell (1975) Rockwell, Ernst, and Rulon (1970) Zwahlen (1982)

Rockwell, Ernst, and Rulon (1970) investigated eye fixations on a rural two-lane road during the day and at night. The road was 22-feet wide and did not have edge lines. Of particular interest on the road were a straight section and an S-curve, which were both 0.3 miles long. The S-curve had a right curve of 37 degrees and a left curve of 34 degrees. Rockwell et al. stated that two drivers were tested but do not provide any information about them.

Shinar, McDowell, and Rockwell (1977) used a hilly two-lane rural road (34 kilometers long) to investigate the eye fixations of drivers (two female and three male students). Twenty-two curves on the route varied from 0.05 to 0.13 kilometers in length and from 5 to 19 degrees in central curvature. They included three high accident curves (three or more accidents within four years) and 11 non accident curves (zero accidents over the same period). Shinar et al. were interested in the approach and curve zones on the curves as well as two straight road sections.

Zwahlen (1982) collected eye-fixation data on a hilly two-lane rural road for two drivers during the day and for one driver at night. Seven curved sections and three straight sections of road were of interest. Again, no other descriptive information was provided.

A summary of the results of these studies is provided below. (Because Zwahlen's (1982) data could not be compared with those of the other studies, it is not referred to in the next section. Please see the appendix for a description of the results.)

Fixations on Straight Rural Roads During the Day

Percentages of Fixations

On straight roads during the day, approximately 55 percent of eye fixations are on the road (Blaauw, 1975; Olson et al., 1989). Fixation percentages for different road features are shown in figure 1. Olson et al. report that 24 percent of fixations are to the center of the road and approximately 30 percent are directed equally to the right and left edges of the road. Blaauw found a more varied pattern with only 6.1 percent, 6.9 percent, and 8.4 percent of eye fixations directed toward the center line, right edge, and left edge, respectively. According to Blaauw, the highest percentage of fixations on the road are directed toward the left lane (14.7 percent) (which is not the oncoming lane in his study) and the driver's own lane (12.8 percent); the fewest fixations are to the road edge markers (right edge, 2.5 percent and left edge, 3.1 percent). According to Olson et al., fewer fixations (25 percent) are directed toward the far field (greater than 300 feet in front of the vehicle). Blaauw reports a figure of 39 percent fixations toward the sky (an area above and left of the focus of expansion, the point where the lane markers converge with the horizon).

The differences in the data of Olson et al. and Blaauw could be due to the following: (1) the definition of a fixation (Blaauw only reported fixations greater than 100 milliseconds; Olson et al. defined a fixation as one or more fixations within a certain area), (2) the definition of a feature (for example, Blaauw distinguished between edge and edge marker whereas Olson et al. did not), (3) the type of roads (Blaauw used one-way roads while Olson et al. used two-way roads), and (4) the crash barriers Blaauw reports on the side of his road.

Percentages of Time

Olson et al. report that drivers spend a significant portion of their time fixating on the far field (40 percent). (See figure 1.) Drivers spend slightly more time (51 percent) fixating on road features 100 to 300 feet in front of the car: center of road--28 percent, right edge--11 percent, and left edge--12 percent. The data of Rockwell et al. and Rackoff and Rockwell differ slightly from Olson et al.'s. According to the Rockwell et al. data, approximately 66 percent of the time

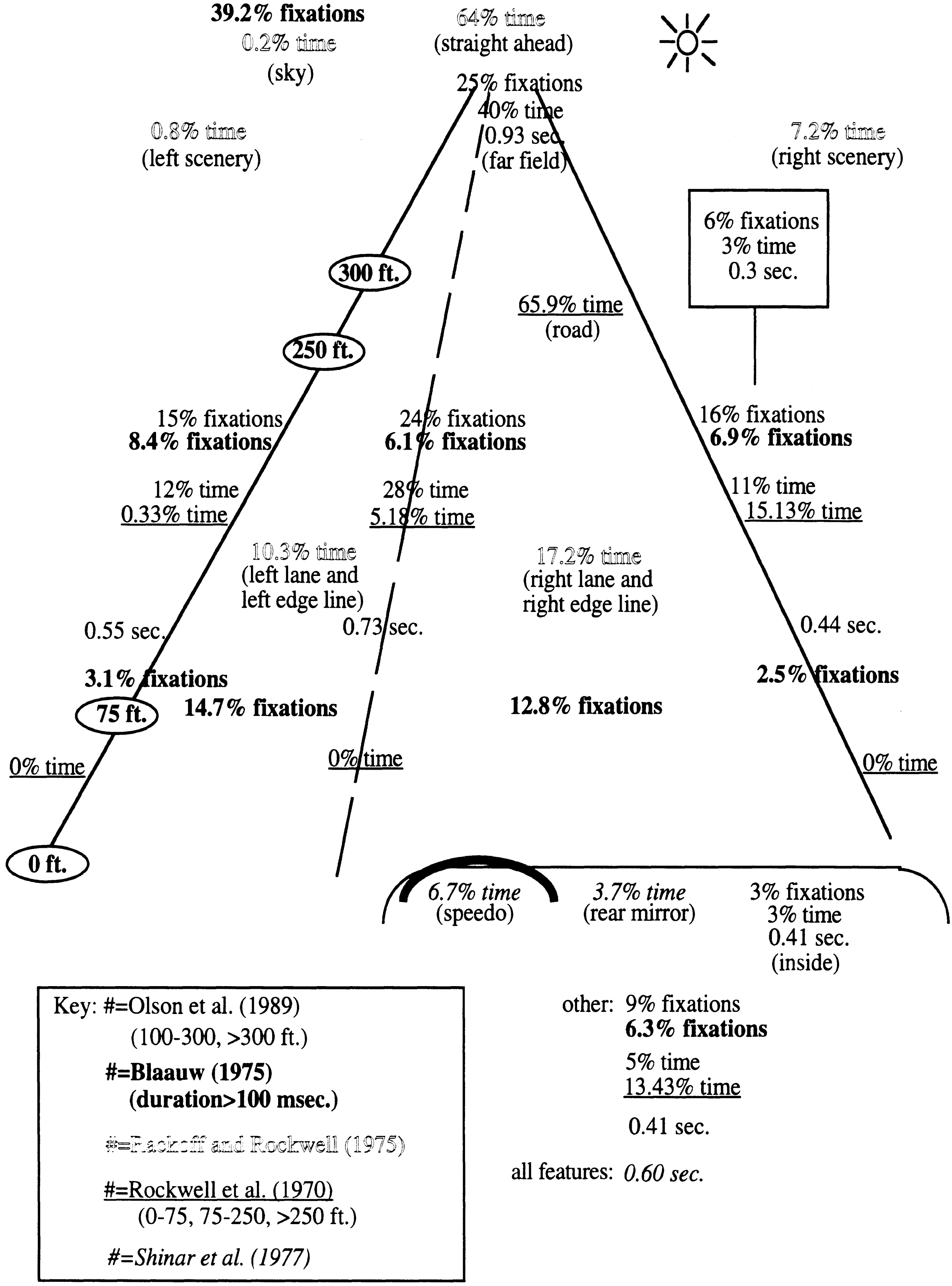


Figure 1. Fixations on straight rural roads during the day

drivers are looking on the road at a distance greater than 250 feet in front of the car. Their data show that at distances from 75 to 250 feet in front of the car drivers look at the road less (approximately 21 percent). Rockwell et al. report that fixations are directed to the right edge 15 percent of the time, to the center line 5 percent of the time, and to the left edge less than 1 percent of the time. They report that drivers do not look at the edges or center line at distances less than 75 feet in front of the car.

Rackoff and Rockwell found that drivers spend most of their time (64 percent) looking straight ahead (above the focus of expansion). Far less time is spent looking at the road (left edge line and left lane, 10.3 percent, and right edge line and right lane, 17.2 percent) and scenery (left, 0.8 percent and right, 7.2 percent). Rackoff and Rockwell found that drivers look at the sky less than 1 percent of the time.

One explanation that could account for the differences in the data of Olson et al. and Rockwell et al. is that, perhaps, in Rockwell et al.'s study drivers fixated a majority of the road features between 250 and 300 feet in front of the car. This would make the percentages of time for the two studies more comparable: 66 percent of the time from Rockwell et al. versus 51 percent of the time from Olson et al. between 100 and 300 feet. Nevertheless, according to the two studies, drivers spend a majority of the time looking at the road: up to 91 percent according to Olson et al. and 87 percent according to Rockwell et al.

Fixation Durations

Fixation durations are also presented in figure 1. Olson et al. report that the longest fixations are to the far field (0.93 seconds) and center of the road (0.73 seconds) while shorter fixations are to the left and right edges (0.55 seconds and 0.44 seconds, respectively). Short fixations are also found inside the car (0.41 seconds) and to other features in the environment (other category, 0.41 seconds) (Olson et al., 1989). Shinar et al. report an average of 0.60 seconds to all road features, which is close to the average duration of Olson et al.'s data (0.58 seconds).

Other Fixation Locations

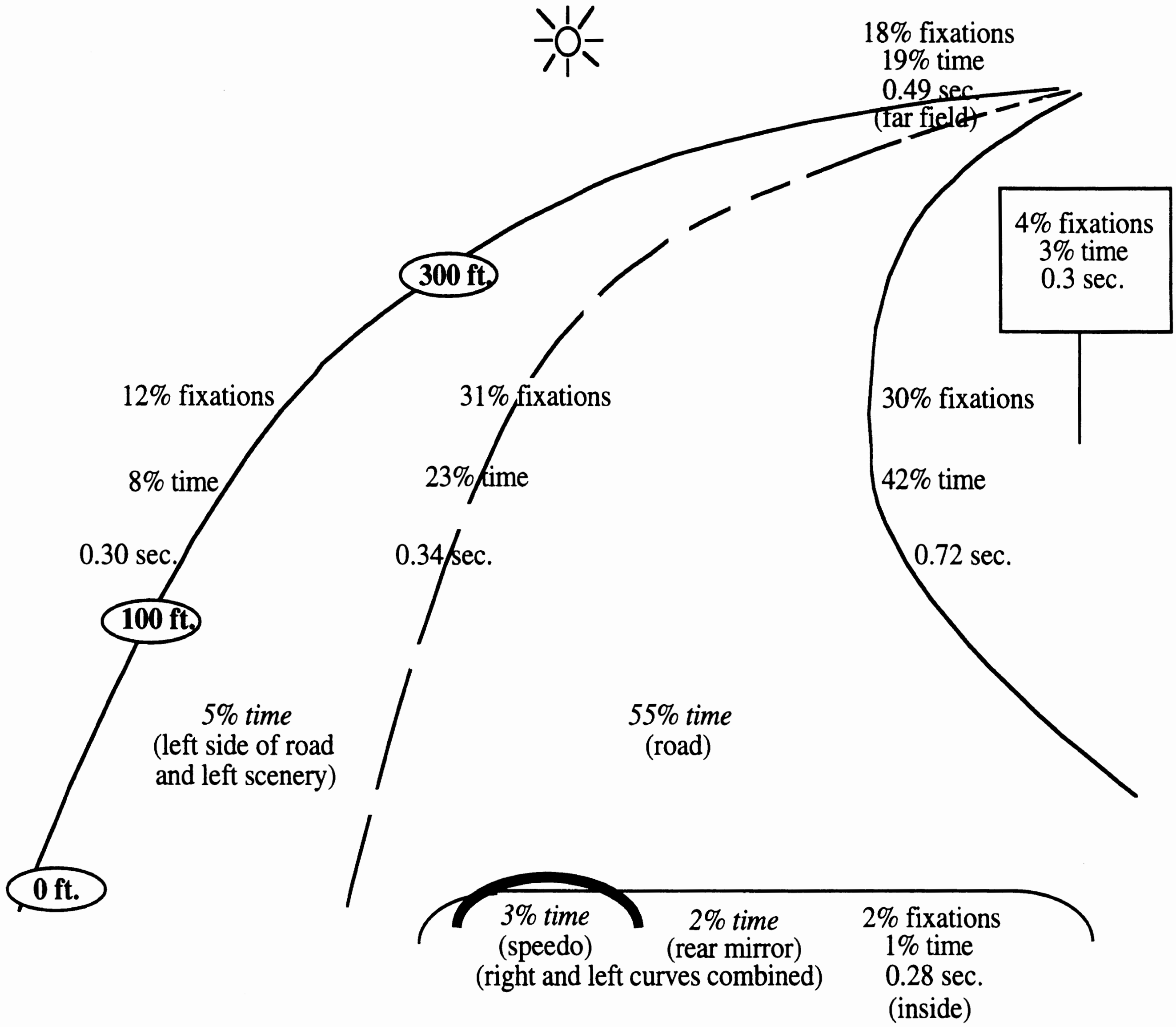
Fixations to signs are few (6 percent), infrequent (3 percent of the time), and short (0.3 seconds) (Olson et al., 1989). Since signs are not used for steering the car on the road but more for reference, attention to them is not expected to be great because drivers simply look at them when they feel it is necessary. The same can be said for glances inside the car. Approximately 7 percent and 4 percent of the time is spent viewing the speedometer and the rear view mirror, respectively (Shinar et al., 1977). Olson et al.'s findings are similar; 3 percent of the time drivers are looking inside the car and these fixations account for 3 percent of the total fixations.

Fixations on Curved Rural Roads During the Day

Percentages of Fixations

On right curves, Olson et al. report that drivers direct most of their fixations toward the center of the road (31 percent) and the right road edge (30 percent). (See figure 2.) The far field attracts 18 percent of the fixations while only 12 percent are directed to the left edge of the road.

On left curves, Olson et al. report that drivers look at the left edge (29 percent fixations) more than the center of the road (20 percent fixations) and the right road edge (13 percent fixations). (See figure 3.) Their data do not agree with Blaauw, however, who reports 2.4 percent, 3.3 percent, and 11.1 percent of fixations to the left edge, center line, and right edge of the road, respectively.



Key: #=Olson et al. (1989)
(100-300, >300 ft.)
#=Shinar et al. (1977)
<u>#=Cohen and Studach (1977)</u>

other: 4% fixations
2% time
0.35 sec.

all features: *0.30 sec.*
<u>0.32 sec.</u>

Figure 2. Fixations on right curved rural roads during the day

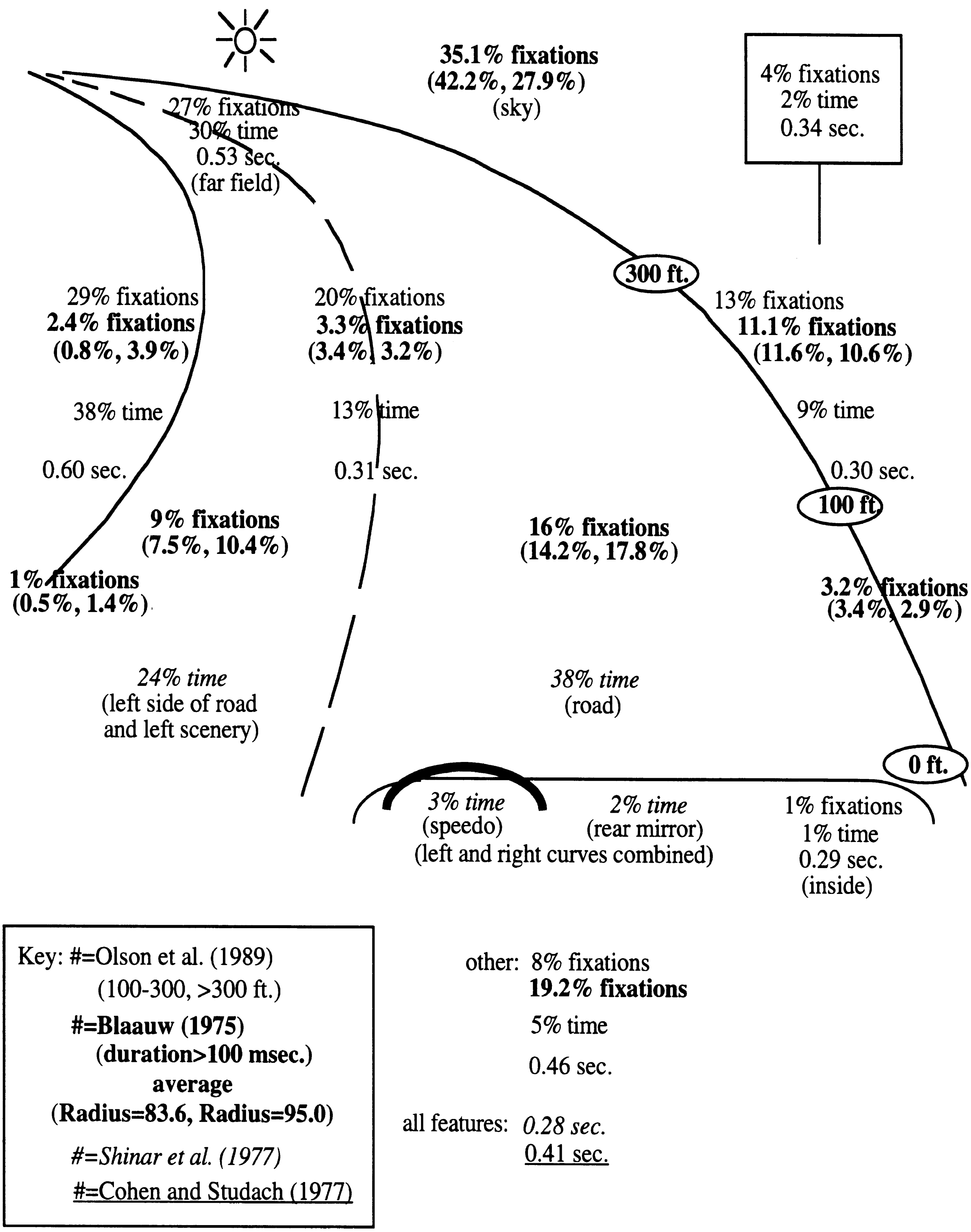


Figure 3. Fixations on left curved rural roads during the day

Blaauw also reports 1 percent of fixations to the left edge marker, 3.2 percent to the right edge marker, 9 percent to the left lane, and 16 percent to the right lane.

Thus, Blaauw's subjects directed more fixations to the right side of the road (30.3 percent) than to the left (12.4 percent). Drivers direct 35.1 percent of their fixations to the sky according to Blaauw and 27 percent of their fixations to the far field according to Olson et al.

The data reported for Blaauw in the preceding paragraph are actually the average of two left curves, one with a radius of 95.0 meters and a sharper curve with a radius of 83.6 meters. The fixation percentages to different road features for the two curves are shown in figure 3. For the sharper curve, fewer fixations are directed to the left side of the road (lane, edge, and marker) and to the right lane while more are directed to the sky. An explanation for more fixations to the sky on a sharper curve is unclear at this time. It may be a function of Blaauw's subjects or type of road.

It is not clear why Blaauw's data indicate so few fixations to the left road edge, marker, and center line when compared with those of Olson et al. Again, perhaps Blaauw's road type could be the cause of the discrepancy between the data because the crash barriers on either side of the road limited the horizontal field of view. It should also be remembered that all of Blaauw's reported fixations are greater than 100 milliseconds.

Percentages of Time

On right curves, Shinar et al. found that drivers look at the road 55 percent of the time, and the left side of the road and left scenery only 5 percent of the time. Olson et al.'s finding of fixations to the left edge of the road 8 percent of the time is similar to Shinar et al.'s 5 percent to the left side of the road and left scenery. Olson et al., however, report slightly more time (73 percent) fixating on the road: right edge--42 percent, center of the road--23 percent, and left edge--8 percent. They also report that drivers look at the far field 19 percent of the time.

On left curves, drivers spend a quarter of the time (24 percent) looking toward the left side of the road and left scenery, but only a third of the time (38 percent) looking at the road (Shinar et al., 1977). Olson et al.'s data contradict this somewhat. They report that drivers look at the left road edge 38 percent of the time and the road 60 percent of the time (right edge--9 percent, center of the road--13 percent, and left edge--38 percent). According to Olson et al., drivers spend a third of the time (30 percent) looking at the far field.

It should be noted that the data of Olson et al. and Shinar et al. may not be very comparable. Shinar et al. refer to the percentage of time spent looking at the *road*, where the features that actually define the road are not specified; do they mean just the lanes or also the edges? Olson et al., on the other hand, specifically refer to the road edges and center of the road.

Fixation Durations

On right curves, the longest fixations are to the right road edge (0.72 seconds) and the far field (0.49 seconds) while shorter fixations are to the center of the road (0.34 seconds) and the left road edge (0.3 seconds) (Olson et al., 1989). Cohen and Studach and Shinar et al. found fixation durations to average around 0.30 seconds. It should be taken into account that these are mean durations and that many of the fixations may be significantly shorter in length. Blaauw reports that approximately 30 percent of fixations on right curves are greater than 0.1 seconds in length.

On left curves, drivers look the longest at the left edge (0.6 seconds) and the far field (0.53 seconds), and the same amount of time at the center of the road (0.31 seconds) and the right road edge (0.3 seconds) (Olson et al., 1989). Cohen and Studach found average fixation durations to be 0.41 seconds while Shinar et al. report an average duration of 0.28 seconds on left curves.

Other Fixation Locations

On both right and left curves, fixations inside the car and to signs were infrequent (1 to 3 percent of the time) and short (approximately 0.30 seconds) (Olson et al, 1989). Drivers glance at the speedometer and rear view mirror 3 percent and 2 percent of the time, respectively (Shinar et al., 1977).

Fixations on Approach Zones to Curves During the Day

As the road geometry changes from a straight road to a curve, changes in eye fixations have been observed (Cohen and Studach, 1977; Shinar et al., 1977). Figures 4 and 5 show fixation data for right and left approach zones, respectively. Directly prior to an approach zone for a right curve (thus, on a fairly straight road), drivers fixate to the right and left lanes equally while on an approach zone for a right curve, more fixations are directed toward the right lane (Cohen and Studach, 1977). Unfortunately, Cohen and Studach do not cite exact numbers.

For both right and left approach zones, drivers spend equal amounts of time (23 percent) viewing the road and scenery (Shinar et al., 1977). In the approach zone, fixation durations are 0.17 seconds long on right curves, but substantially longer (0.36 seconds) on left curves (Shinar et al., 1977).

Summary

On straight roads, drivers spend 21 to 51 percent of the time looking at road features (Olson et al., 1989; Rackoff and Rockwell, 1975; Rockwell et al., 1970). Approximately 55 percent of the fixations are on road features, with a fairly even distribution to the center of the road, lanes, and road edges (Blaauw, 1975; Olson et al., 1989). Fixation durations average 0.60 seconds with longer fixations to the far field (0.93 seconds) and center of the road (0.73 seconds), and shorter fixations to the road edges (right, 0.44 seconds and left, 0.55 seconds) and inside the vehicle (0.41 seconds) (Olson et al., 1989; Shinar et al., 1977).

On approaches to right and left curves, approximately the same amount of time (23 percent) is spent looking at the road and scenery (Shinar et al., 1977). This percentage is comparable to the low end of the range for straight road driving. In the right approach zone to a curve, drivers' fixations are not equally distributed as on a straight road. Rather, more fixations are directed to the right side of the road than the left (Cohen and Studach, 1977). Shorter fixation durations are found on approaches (right, 0.17 seconds and left, 0.36 seconds) than on straight roads (0.59 seconds).

While driving in a curve, drivers direct more of their visual attention to the road and spend more time looking at various road features than they do on straight roads. On right curves, drivers direct more fixations toward the road (73 percent) than they do on left curves (46 to 62 percent) (Blaauw, 1975; Olson et al., 1989). On right curves, the right side of the road is looked at the most (Olson et al., 1989). On left curves the data is more inconclusive. Olson et al. report more fixations to the left side of the road, but Blaauw found more fixations to the right side. While the percentage of time data may be somewhat ambiguous, it could be interpreted that drivers spend more time looking at the road on right curves (55 to 73 percent) than on left curves (38 to 60 percent) (Olson et al., 1989; Shinar et al., 1977). On curves, fixation durations are shorter than on straight roads; average durations are approximately the same on right and left curves (right, 0.3 to 0.47 seconds and left, 0.28 to 0.44 seconds) (Cohen and Studach, 1977; Olson et al., 1989; Shinar et al., 1977). On right curves, drivers look the longest at the right road edge (0.7 seconds) whereas on left curves the longest fixations are to the left edge (0.6 seconds) (Olson et al., 1989).

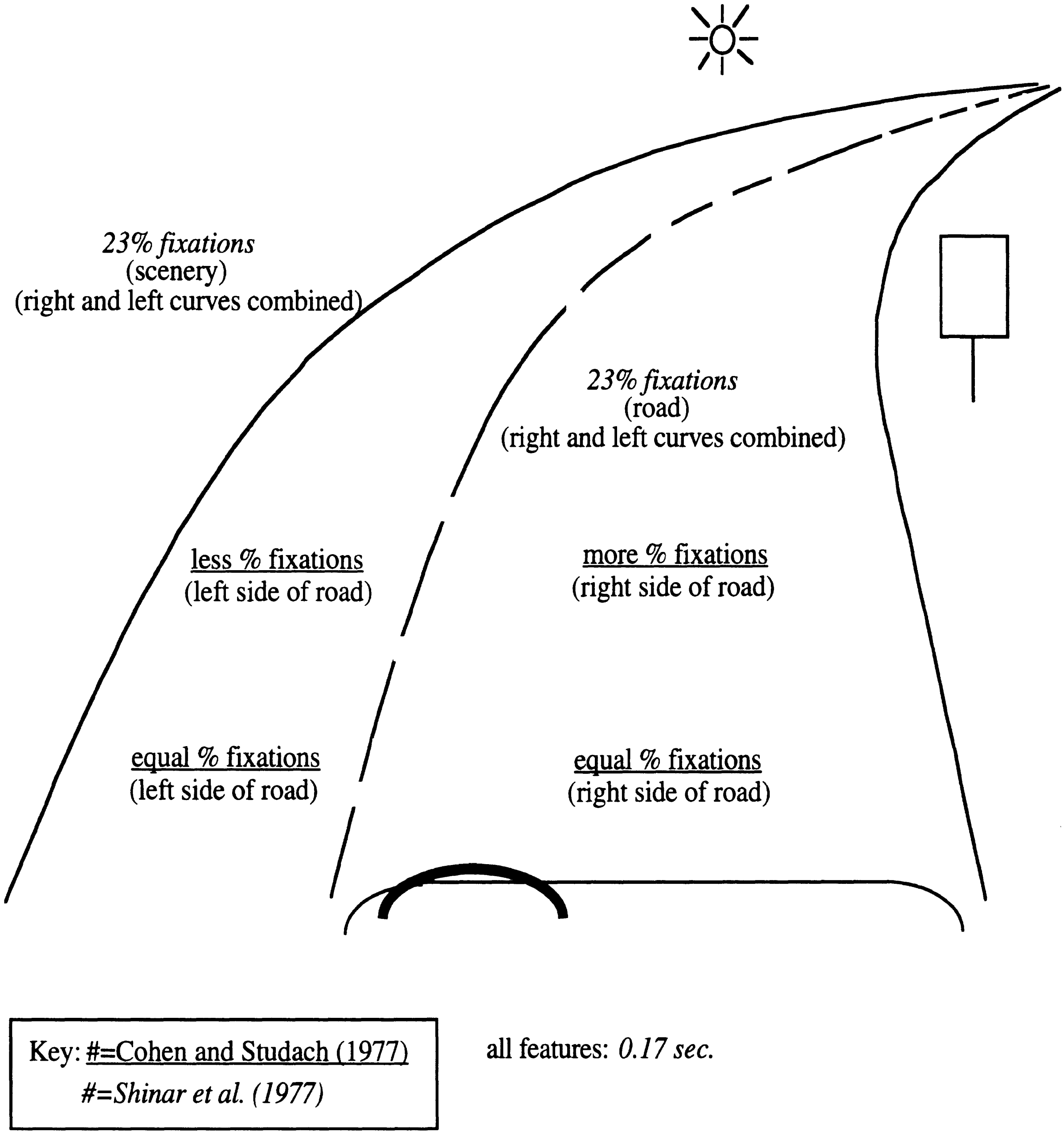
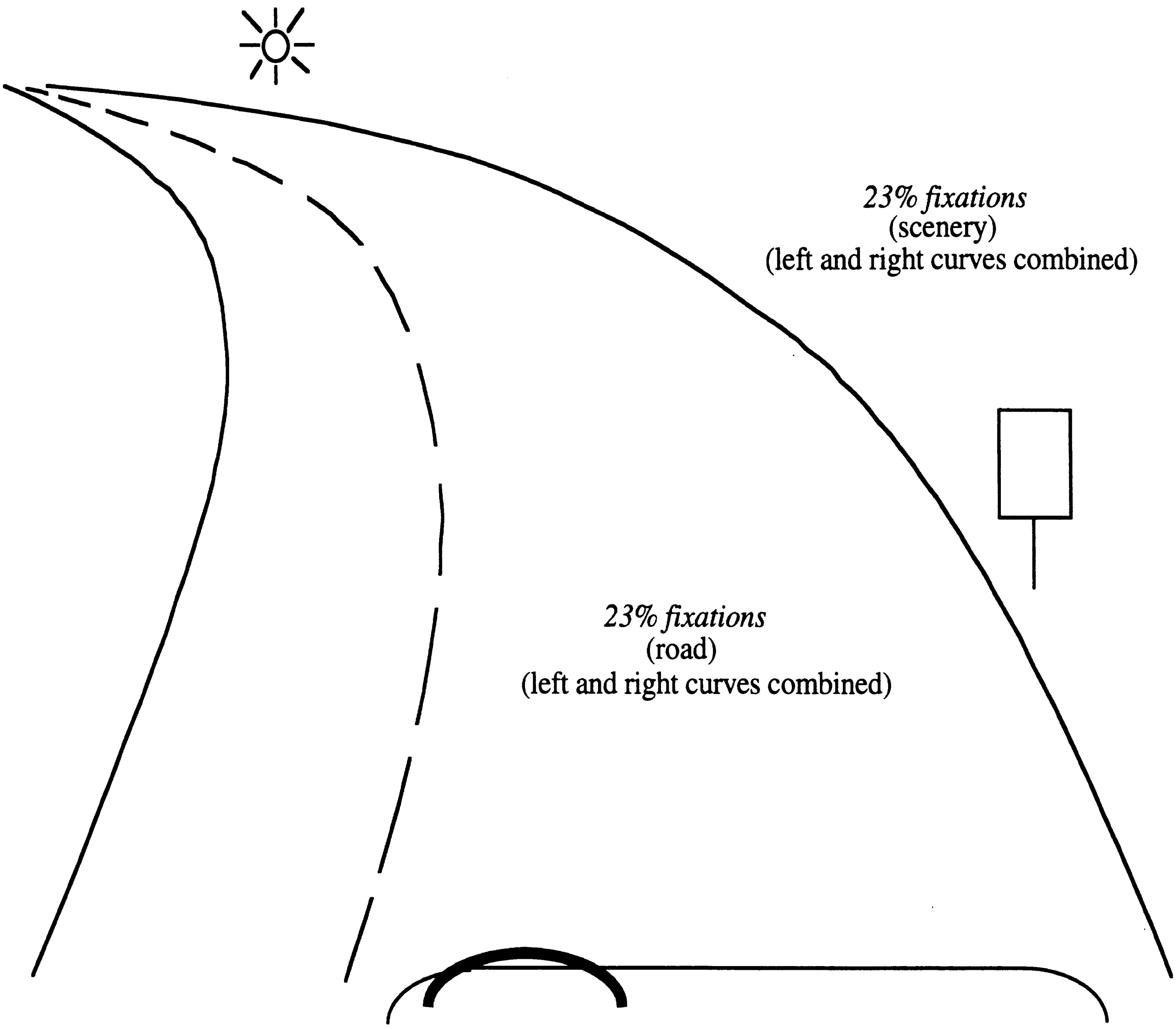


Figure 4. Fixations on a right approach zone during the day



Key: #=*Shinar et al. (1977)*

all features: *0.36 sec.*

Figure 5. Fixations on a left approach zone during the day

From the above discussion, it is evident that road geometry (straight versus curves) affects drivers' eye fixations. When driving on curved roads, drivers direct more fixations toward the road but for less time per fixation than they do on straight roads.

Driver Eye Fixations as a Function of Age

Vision is substantially affected by the aging process. Physical changes occur at 35 to 45 years of age, which lead to reduced power of accommodation (close focusing ability) of the lens and greater sensitivity to glare (Wolf, 1972). Presbyopia, an irreversible age-related visual disability that results from the inability of one's eye to vary its optical characteristics in order to focus objects at different distances, becomes progressively apparent after the mid-40s and peaks between 60 and 70 years of age (Rockwell, Augsburger, Smith, and Freeman, 1988). After age 60, an acceleration of functional loss is observed, there is a considerable decrease in capacity to adapt to darkness and to perceive intermittent stimuli, and there is a measurable shrinkage of the visual field (Wolf, 1972).

Due to changes with age in the visual system, eye-fixation patterns of older drivers may be different from those of younger drivers. Rackoff has examined the eye fixations of drivers as a function of age (Rackoff, 1974; Rackoff and Mourant, 1979). The results are reported below.

Literature Pertaining to Age

It should be noted that the Rackoff and Mourant (1979) study reports a subset of the experiments reported in Rackoff (1974). Because not all of the details of the experiments are provided in Rackoff (1974), the report from 1979 is also used as a reference. One study (Rackoff, 1974) compared younger (nine subjects, 21 to 29 years old) and older drivers (eight subjects, 60 to 70 years old) while in light traffic and car-following situations on a freeway during the day and at night. Rackoff and Mourant also looked at eye patterns of younger (10 subjects, 21 to 29 years old) versus older (13 subjects, 60 to 70 years old) drivers. Testing took place on a freeway both during the day and night with open-road and car-following conditions. In both studies, the younger drivers had 5 to 13 years driving experience and the older drivers had 46 to 60 years of experience on the road.

Fixation Time

Fixation time was defined by Rackoff as consecutive fixations separated by at least one visual degree. The fixation times of older drivers were significantly shorter than those for younger drivers in the night car-following condition only. (See table 2.) The large standard deviations for the day car-following condition indicate that some of the fixations for the younger drivers may be shorter than those of the older drivers.

Table 2. Fixation time for four driving conditions (Rackoff, 1974)

	Fixation Duration (sec.) Mean		Std. Deviation	
Driving Condition	Younger	Older	Younger	Older
Day, Light traffic	1.61	1.52	1.60	1.44
Day, Car-following	3.97	2.41	3.53	2.15**
Night, Light traffic	1.97	1.89	1.80	1.86
Night, Car-following .	5.12	1.99*	2.57	1.82

*differences between younger and older, $p < 0.05$
**differences between younger and older, $p < 0.10$

Time to the Scene Ahead

As shown in table 3, there were no significant differences between younger and older drivers with respect to the time spent looking at the forward scene. Older drivers spent more time looking ahead in the light traffic condition, whereas younger drivers spent more time looking ahead while car-following.

Table 3. Percentage of time spent fixating on the scene ahead (Rackoff, 1974)

Driving Condition	Mean Percent Time	
	Younger	Older
Day, Light traffic	71.6	77.8
Day, Car-following	84.5	78.4
Night, Light traffic	66.0	72.8
Night, Car-following	81.8	79.2

Time Away from the Scene Ahead

Older drivers had significantly shorter fixation durations away from the forward scene compared with the durations of younger drivers in day light traffic and night car-following conditions. (See table 4.) No significant differences were found in the percentage of time that older and younger drivers spent looking away from the forward scene. (See table 5.)

Table 4. Mean time per look away from the scene ahead (Rackoff, 1974)

Driving Condition	Mean Time (sec.)	
	Younger	Older
Day, Light traffic	1.02	0.57*
Day, Car-following	0.91	1.00
Night, Light traffic	1.15	1.15
Night, Car-following	1.29	0.74*

*differences between younger and older, $p < 0.05$
**differences between younger and older, $p < 0.10$

Table 5. Percentage of time looking away from the scene ahead (Rackoff, 1974)

Driving Condition	Mean Percent Time	
	Younger	Older
Day, Light traffic	18.1	11.1
Day, Car-following	8.9	12.7
Night, Light traffic	24.7	20.5
Night, Car-following	17.2	16.3

Eye Travel Distances

Older drivers had longer travel distances during the day while car-following and larger standard deviations for all conditions except open driving and light traffic during the day. (See table 6.) The large standard deviations indicate that some older drivers performed as well as or better than some younger drivers.

Table 6. Eye travel distances for younger and older drivers (Rackoff, 1974; Rackoff and Mourant, 1979)

	Eye Travel Distance (degrees)			
	Mean		Std. Deviation	
Driving Condition	Younger	Older	Younger	Older
Day, Open driving	4.3	4.3	2.6	2.6
Day, Car-following	2.3	3.6*	1.0	1.7**
Day, Light traffic	4.3	4.3	2.6	2.6
Night, Open driving	3.3	3.9	1.4	2.2**
Night, Car-following	3.4	3.7	1.4	2.5*
Night, Light traffic	3.3	3.9	1.4	2.2**

*differences between younger and older, $p < 0.05$
**differences between younger and older, $p < 0.10$

Eye Open Durations

Rackoff and Mourant instructed subjects to close their eyes while driving as often and for as long as they felt comfortable. Lengths of eye open intervals are presented in table 7. For all driving conditions, older drivers had longer eye open durations than did younger drivers. Standard deviations of the durations for older drivers were substantially large at night (significantly larger than for younger drivers), which indicates some performance comparable to that of younger drivers.

Table 7. Eye open durations for younger and older drivers (Rackoff and Mourant, 1979)

	Eye Open Duration (sec.)			
	Mean		Std. Deviation	
Driving Condition	Younger	Older	Younger	Older
Day, Open driving	0.7	1.6*	0.4	0.9
Day, Car-following	0.7	2.0*	0.5	1.2
Night, Open driving	1.4	2.5*	1.1	2.0**
Night, Car-following	1.6	3.5*	1.2	2.6*

*differences between younger and older, $p < 0.05$
**differences between younger and older, $p < 0.10$

Other Results

Older and younger drivers did not differ in their fixations to the speedometer, but there were some differences in side mirror and rear mirror fixations. (See table 8.) Older drivers spent less time looking at the side mirror, a fact that is reflected in two measures: percentage of time and number of looks per minute. One reason for this may be that some of the older drivers may have had experience driving earlier models of vehicles which did not have side mirrors. According to Rackoff, older drivers never looked at the rear mirror.

Table 8. Data for in-vehicle fixations (Rackoff, 1974)

	Speedometer		Side Mirror		Rear Mirror	
Dependent Measure	Younger	Older	Younger	Older	Younger	Older
Percent Time	4.5	3.4	3.3	1.3**	1.8	0.0*
Mean Time/Look (sec.)	0.9	1.2	1.0	1.3	-----	-----
Look Rate***	3.0	2.0	-----	-----	1.0	0.0**
# Looks/Minute	-----	-----	1.9	0.6*	-----	-----

*differences between younger and older, $p < 0.05$
**differences between younger and older, $p < 0.10$
***# looks per trial time

Summary

No differences between older and younger drivers were found with respect to time spent looking toward or away from the forward scene. However, older drivers had shorter fixation times when looking away from the scene ahead during the day in light traffic and at night while car-following. Older drivers also had longer eye open durations for all the driving conditions and longer eye travel distances for car-following during the day. Finally, older drivers looked in the side mirror less than younger drivers and never looked in the rear mirror.

While major differences in the eye fixations of younger and older drivers may not be present, the above data suggest that, in some situations, older drivers do pay more attention to the road. These data, however, do not indicate whether there are differences in where older versus younger drivers look on the road. Also, the fixation time data reported here do not provide researchers with comparable duration time data due to Rackoff's definition of fixation time. In order to quantify differences in eye-fixation patterns between older and younger drivers, further research needs to be carried out.

Models of Driver Behavior

Models of various aspects of the driving task have been developed. Preview models describe the driver's responses while operating a vehicle (Miller, 1967; Sheridan, 1966). These models characterize the human controller during operations that require previewing input prior to making overt responses. Preview models of driving can be helpful in studying the effects of preview on driving performance. Models characterizing steering behavior have been proposed by a number of researchers (Crossman and Szostak, 1968; Donges, 1978; Godthelp, 1984; McLean and Hoffman, 1973; McRuer, Allen, Weir, and Klein, 1977). These models typically include a description of navigation, guidance, and/or control operations using parameters such as heading, path angle, lateral position, and steering-wheel angle. While some models describe the occurrence of operations in series (Crossman and Szostak, 1968), others model them in parallel (Donges, 1978).

Models that describe drivers' behavior in terms of attentional demand, workload, and eye fixations have also been developed. Attentional demand has been characterized by Senders, Kristofferson, Levison, Dietrich, and Ward (1967), as well as Wierwille, Hulse, Fischer, and Dingus (1988). While Senders et al. derive attentional demand from occlusion interval data, Wierwille et al. relate attentional demand to aspects of the road such as curvature, sight distance, road width, and lane width. McDonald (1973) proposed a model for predicting driver workload based on the tracking involved in driving, as well as discrete tasks such as reading signs. Cohen and Hirsig (1980) developed a model to sequentially predict drivers' future fixation targets and, in additional research (Cohen and Hirsig, 1983), theorized that drivers move their eyes toward a target to minimize the discrepancy between the actual environment and the drivers' concepts of the environment.

These models are described in detail below.

Models of Attentional Demand

Senders, Kristofferson, Levison, Dietrich, and Ward (1967)

Senders and his colleagues developed what they call an "uncertainty model" of the driving situation. This model describes the cumulative uncertainty of the driver between looks at the road, and it characterizes attentional demand as pertaining to the road, traffic situation, and the velocity of travel. Their theoretical premise is that "drivers drive to a limit that is determined by that point when the driver's information processing capacity, either real or imagined, is matched by the information generation rate of the road, either real or estimated" (page 3).

The driver's uncertainty at the end of the occlusion interval is described by the following equation:

$$U(T_d) = H \bullet D[1-e^{-(V/D+1/F)T_d}] + K_n V^2 (T_d)^{3/2} <= U_c$$

where $H \bullet D[1-e^{-(V/D+1/F)T_d}]$ = the amount of information in storage at the end of the occlusion interval,

- H = the information density of the road
- D = the weighting constant (miles)
- V = vehicle velocity (miles/second)
- F = the time constant (seconds) for the rate of forgetting
- T_d = the time at the end of the occlusion interval

- K_n = a constant (includes the power density spectrum and other scaling factors)
- $V^2(T_d)^{3/2}$ = the driver's uncertainty concerning the lateral displacement of the vehicle
- U_c = the driver's criterion level (bits)

Experimentally, Senders et al. studied the attentional demand of drivers by using a visual occlusion method. Drivers wore a helmet with a translucent shield attached to the front that could be lowered and raised using a pneumatic cylinder. Subjects could either control their speed when there were fixed viewing and occlusion times or could control the length of the occlusion interval when there were fixed velocity and viewing times. The purpose of the experiments was to validate the model of driver uncertainty and, thus, to provide data on the relationship between road characteristics, road viewing times, interlook times, and speed.

Two experiments (one and four) investigated drivers' speeds with constant viewing and occlusion times. Experiment one was performed on an interstate highway that had large radii of curvature (straight roads) and wide lanes that did not require precise steering. The section of highway driven was new and unopened, thus no traffic was encountered while driving. Experiment four, performed at a motorsport park, consisted of 1.6 miles of well paved, banked roadway with ten turns varying in radii from straight to hair pin.

In experiment one, subjects made three runs on the interstate highway, each with different viewing times (0.25, 0.50, and 1.0 seconds) and various occlusion times (1.0 to 9.0 seconds). Drivers adjusted their speed while driving. While only the data of two subjects are provided, Senders et al. report that all data fit the following trend: as occlusion time increased, the maximum velocity decreased. The data for the two subjects are shown in table 9.

Values of model parameters were obtained for the drivers. The drivers' criterion levels, U_c, are shown in table 10. The drivers' criterion levels varied as viewing time increased: subject one accumulated more uncertainty as viewing time increased, subject three less uncertainty, and the uncertainty of subject two remained relatively consistent. It should also be noted that the amount of uncertainty drivers were willing to accumulate varied between drivers.

Table 9. Mean speed with fixed viewing and occlusion times on an interstate highway (Senders et al., 1967)

	Mean Speed (mph)	
	Viewing Time (sec.)	
Occlusion Time (sec.)	0.5	0.25
1.0	--	50
1.5	60	45
2.0	--	38
2.5	47	33
3.0	60	21
4.0	46	19
6.0	17	13
7.5	13	6
9.0	5	5

Table 10. Values of U_c (driver criterion level) for experiment one (Senders et al., 1967)

	Driver Criterion Level (U_c)		
	Viewing Time (sec.)		
Subject	0.25	0.50	1.00
1	3.13	3.76	5.22
2	0.99	1.07	1.13
3	7.16	5.96	4.29
4	--	4.93	--
5	--	6.99	--

In experiment four, runs were made on a test track with a viewing time of 0.5 seconds and five occlusion times (0.5, 1.0, 1.5, 2.0, and 3.0 seconds). As in experiment one, there was a consistent reduction in speed as occlusion time increased (specific numbers are not reported in the paper). As reported by Senders et al., the speeds drivers attained with occlusion times between 1.0 and 3.0 seconds were "markedly" lower than those in experiment one on the highway. They attributed these lower speeds to the increased information density of the road on the test track.

Experiments two and three involved measuring occlusion times chosen by the driver when speed and viewing time (0.5 seconds) were fixed. Experiment two took place on the interstate highway and experiment three was performed on the test track.

In experiment two, mean occlusion times for three subjects were determined for speeds ranging from 22 to 60 miles per hour. This was done by allowing the driver to accelerate to a preset speed. The data are shown in table 11. As speed decreased, occlusion time slowly increased. Comparing these results to those of experiment one where drivers voluntarily set their speed with fixed occlusion time intervals, one can see that the occlusion times are substantially lower.

Table 11. Mean occlusion time as a function of speed for experiment three (Senders et al., 1967)

Speed (mph)	Occlusion Time (sec.) Subject One	Two	Three	Mean
60	1.48	1.84	--	1.84
50	1.66	2.50	2.21	2.12
40	1.75	2.82	2.42	2.33
30	2.10	3.19	3.25	2.85
25	2.26	3.95	3.57	3.26
22	2.60	3.98	3.64	3.41

Experiment three was similar to experiment two except that it was performed at the test track. Subjects drove at three different speeds (22, 25, and 30 miles per hour) and occlusion times were measured. While occlusion times were not reported, other data are cited in the report. Senders et al. report that the higher the speed, the shorter the time interval between observations. Table 12 shows that as speed decreased from 30 to 22 miles per hour, the total number of looks decreased slightly and the distance traveled between observations increased slightly.

Table 12. Data from experiment three (Senders et al., 1967)

Speed (mph)	Number of Looks	Distance (feet)
30	74.5	90.3
25	73.5	94.9
22	70.5	101.0

In conclusion, driver behavior has been examined on two different types of roads (interstate highway and test track) using two different approaches (fixed viewing and occlusion times, and fixed viewing times and speed). Through experimentation, Senders et al. have verified the adequacy of the driver uncertainty model through comparison of model parameter values and observed data. Thus, the model of Senders et al., in conjunction with the visual occlusion technique, can be used to predict the attentional demand of the road where attentional demand is based on the information density of the road, vehicle velocity, rate of forgetting, and parameters of the occlusion interval. The model, however, can not describe the characteristics of the road at which the driver is looking.

Wierwille, Hulse, Fischer, and Dingus (1988)

Another model of attentional demand has been proposed by Wierwille, Hulse, Fischer, and Dingus who investigated drivers' eye fixations while using a moving map display (Etak). The participants included 12 men and 12 women divided into three age groups (18 to 30 years, 31 to 44 years, and 45 years and older). Drivers navigated over two routes (seven and eight miles long) that consisted of roads requiring three levels of attentional demand (low, medium, and high). Attentional demand was manipulated by varying sight distance, curvature, lane restriction (distance of closest object to roadway), and road width. Specifically, Wierwille et al. defined the parameters as follows:

Sight Distance: $A = 20 \log_2 (500/S_d)$

where S_d = the sight distance in meters

If $S_d > 500$m, then A was set equal to 0
If $S_d < 15.6$m, then A was set equal to 100

Curvature: $B = R^{-1} (100/R^{-1} max)$

where R^{-1} = the inverse radius of curvature, and
$R^{-1}max$ = the maximum value across the experiment

$R^{-1} = [2p (DQ)]/360X$

where DQ = the change in direction in degrees between the beginning and end of the curve, and
X = the arc length along the curve in meters

R^{-1} max was set at 0.054/meter

Lane Width: $C = 40 S_o + 100$

where S_o = the distance of the closest obstruction (telephone pole, ditch, etc.) to the road in meters

If $S_o > 2.5$m, then C was set equal to 0

Road Width: $D = -36.5 R_w + 267$

where R_w = the road width (2 lanes) in meters

If $R_w > 7.3$m, then D was set equal to 0
If $R_w < 4.7$m, then D was set equal to 100

Attentional demand was determined through a weighted equation of the four parameters defined above. The equation is:

Attentional Demand = 0.4 A + 0.3 B + 0.2 C + 0.1 D

where attentional demand is between 0 and 100.

Sight distance was weighted most heavily, followed by curvature, lane width, and finally road width. Thus, sight distance is most important in determining attentional demand as shown by its weighting factor, and road width is least important. Ratings of low demand were less than 14.9, medium ratings were between 15.0 and 29.9, and high ratings were greater than 29.9. It should be noted that, in their report, Wierwille et al. do not provide any explanations for how the equations for the four parameters were developed or the rationale for the weighting of the parameters in the equation for attentional demand.

Wierwille et al. used this equation to obtain objective ratings of the roadway segments of interest. This objective rating, then, was simply used as an independent variable in on-road experiments. Experienced drivers also subjectively rated the attentional demand of the roadway segments.

Wierwille et al. found a relatively high correlation (0.72) between objective and subjective attentional-demand assessments. Because both the overall objective and subjective ratings were closely related to sight distance in the objective assessment equation, Wierwille et al. conclude that this dependence contributes to the high correlation between the two assessments of attentional demand. Thus, it appears that attentional demand can be predicted based on the characteristics of the roadway that Wierwille et al. defined, namely sight distance, road curvature, lane width, and road width.

Driver Workload

McDonald (1973)

As part of his dissertation work, McDonald developed a model that can predict the workload of a driver on various road segments. Two submodels, tracking workload and discrete workload, are combined to produce a total workload model. The tracking workload submodel predicts the workload of the driver through roadway design features. Tracking workload is determined in terms of percent occupied for each length of road with different design features. McDonald performed experiments that led to plots of percent occupied versus speed for a range of right and left curves. If the road in question is similar to the road McDonald studied, then percent occupied can simply be taken from these figures. If the road in question is different from McDonald's road, then the simulation mode of the tracking submodel must be utilized. Using this simulation, the predicted stress equals the number of corrections per second made by the vehicle multiplied by the time to detect and initiate the correction of an error. The product of this submodel is a time line that indicates the length of time the driver will experience the design feature and its associated tracking workload.

The discrete workload submodel predicts the stress associated with nontracking tasks, such as the time to read road signs. Discrete workload or stress is calculated through the critical path method. According to this method, the earliest time of initiation and the latest time of completion are used to calculate the time available for reading the sign. The stress from reading the sign equals the time required to read the sign divided by the time available. Since there may be more than one sign in view at a time, stress equals the total stress from the number of signs that are in view for a given period. Discrete stress is converted to percent occupied by the regression equation,

$$Y = 14.8 + 43X$$

where X = discrete stress for operation at average speed.

For operation at maximum speed, multiply discrete stress by 100. A time line is produced that indicates the discrete workload imposed on the driver during the time traveled through a section of roadway.

A total workload threshold can be determined for each second by using the tracking workload time line and the regression equation, $T = 61 + 0.48X$, where T is between 0 and 100 percent. If the total workload (tracking and discrete) is greater than the workload threshold for any second of roadway, then the driver is overloaded.

McDonald's model takes visual characteristics of the road into account in determining workload. The tracking submodel involves a subject centering a target between two lines on a display, which involves visual perception and appropriate control movements. The discrete submodel involves nontracking tasks, but McDonald is vague as to what these are. He does, however, give an example of directional signs in two cases. It can not be assumed, however, that sign reading simply imposes a visual workload. A cognitive workload may also be imposed since the driver has to interpret the sign and make a decision. Thus, McDonald considers the visual load of the driver in predicting workload, but his model does not take into account the load associated with individual features of the road. While McDonald claims his model predicts workload, it appears that it is predicting visual load rather than mental workload imposed on the driver.

Driver Eye-Fixation Behavior

Cohen and Hirsig (1980)

Cohen and Hirsig developed a discrete-time process model that sequentially predicts drivers' future fixation targets. To describe the location of eye fixations, the driving path is divided into the following four categories:

- focus of expansion - "the furthest place where the driver could still determine his advance path of driving (surrounded by an area of approximately 2 degrees around it, which corresponds to the extension of central vision)" (page 84)
- path of driving - "limited in a lateral direction by the road's (real or imaginary) middle lane line and the sidewalk on the right. In a longitudinal direction the path of driving was limited by the road's focus of expansion" (page 85)
- left of the road - the area to the left of the driver's own path of driving, including the left of the real or imaginary middle lane line
- right of the road - the area to the right of the driver's own path of driving

In the model, these four categories are used to describe the varying importance of the road elements, and are denoted as environmental variables $W_{ij}(N)$ (where $j = 1$ to 4), which are summarized in an environment vector, $\underline{W}_i(N)$.

The prediction model is formulated by

$$\hat{\underline{X}}_i(N=1) = \underline{X}_i(N=1)$$

$$\hat{\underline{X}}_i(N+1) = f_i\left[\underline{X}_i(N-I), \underline{W}_i(N+K)\right]$$

where $\hat{\underline{X}}_i$, denotes a prediction for $\underline{X}_i$, an eye fixation

f_i = the simplest set of functions that allow an accurate approximation of F_i, a time invariant mathematical steady relationship
I = the time interval
W_i = the relative importance of the driving path over a long distance
K = the number of environment vectors lying ahead

$\underline{X}_i$, an eye fixation, can be defined as

$$X_{ij}(N) = X_{ij}(N) - X_{ij}(N-1);\ j = 1, 2, 3$$

where $X_{ij}(N)$ is a state variable that is a component of the state vector, $\underline{X}_i(N)$
$X_{i1}(N)$ = the X-coordinate of the Nth eye fixation
$X_{i2}(N)$ = the Y-coordinate of the Nth eye fixation
$X_{i3}(N)$ = the duration of the Nth eye fixation

$X_{i4}(N)$, $X_{i5}(N)$, and $X_{i6}(N)$ describe the deviations of X_{i1}, X_{i2}, and X_{i3} in successive observations

Thus, the model provides a prediction for the next eye fixation given the momentary and previous eye fixations and a number of environment vectors lying ahead.

Cohen and Hirsig collected two sets of independent data for three women and four men (all 24 to 35 years old, mean = 29 years) to test and validate the model. The first set of data was used to establish individual, time-discrete process models. The second set of data was used to validate the individual models. The route consisted of an infrequently used suburban road with a slight curve to the left. The route was characterized by a pedestrian crossing at the beginning, a bus stop on each side of the road, and an intersection with a pedestrian crossing at the end. The presence of traffic and pedestrians occurred naturally; they were not controlled variables.

For six of the subjects (one subject had too few fixations to validate his model), correct predictions ranged from 37 percent to 57 percent. Prediction errors were due to difficulty in distinguishing between fixations toward the focus of expansion and toward the path of driving. Combining these two categories led to a much higher rate of correct predictions (45 to 88 percent).

While investigating driver eye fixations further, Cohen and Hirsig made modifications to the aforementioned model. In place of four environmental variables (focus of expansion, path of driving, left of the road, and right of the road) that describe the driving path, the four most important targets in the forward scene are identified, one of these always being the focus of expansion. Criteria for selection of the targets are that they are required to change the vehicle's movement parameters or they compromise the safety of the driving situation.

A second modification involved a model of information processing that postulated that "continuous information input is required in driving in order to avoid any discrepancy between the objective traffic conditions and its cognitive representation, i.e., the driver's schema" (page 154). Thus, at any given time, a driver has a current schema, but also has to integrate new features into this schema, leading to an elaborated schema. The current schema is a function of the last three targets of fixation, which are weighted by the fixations' respective durations. The elaborate schema is a function of the environmental variables and three subject variables: the motorist's input control, guidance information, and interindividual variability, which are weighting factors. A mathematical description of the model can be found in Cohen and Hirsig (1980).

Again, two sets of independent data were collected to test and validate the model. Eight subjects (all 23 to 42 years old, mean = 30 years) drove on a narrow road (width = 3 meters with cars parked on it), which resulted in a great amount of lateral control information to process by the driver. Because of a short sight distance and the possibility of traffic and pedestrians, the driver also had to obtain guidance information. After analyzing the results, Cohen and Hirsig found that the model accurately described and predicted 50 percent of the fixations.

In summary, Cohen and Hirsig have formulated models that predict fixations based on past information input, features of the road, and subject variables. While the first model that was discussed predicts the next fixation as pertaining to a general category of road elements, the second model predicts the spatial location of the next fixation.

Cohen and Hirsig (1983)

Because the models described above were not perfect in predicting driver's fixations, Cohen and Hirsig continued to theorize on driver's eye-fixation behavior. In describing eye-fixation behavior, they have assumed that the environment's objective characteristics (distal stimuli) are closely related to its subjective representation (proximal stimuli), a theory similar to that formulated as part of the second model mentioned above. In other words, when driving down a road, a driver continuously picks up new information and, in doing so, approximates the proximal to the distal stimuli, while maintaining a minimum discrepancy between them. This discrepancy, they theorize, is an essential variable governing the movement of the eye toward its next fixation location.

The distal stimuli (C_s), the concept the driver should have, is defined as

$$C_s = \sum_{I=1}^{13} (W_I * D_I * \partial_I) / DS$$

where W_I = the environmental variables
∂_I = the center of the sector
I = the sector of the visual field

D_I is not defined by Cohen and Hirsig

DS = the sum of all weighted factors and is defined as

$$DS = \sum_{I=1}^{13} W_I * P_I$$

where P_I = the subject's coding factors

The proximal stimuli (C), the driver's concept of the environment, is defined as a function of the lateral angle which was observed during the last second. The discrepancy between the proximal and distal stimuli for an Nth observational interval is denoted as error signal ER (N).

Eye-fixation data were collected for eight subjects (23 to 42 years old) on a narrow road with high information density and a short maximum forward view. Two sets of data were collected for each subject, one in each direction.

An analysis of the data revealed that any deviation between the proximal and distal stimuli were corrected due to new relevant input as modulated by the error signal and its derivatives. Thus, "drivers' eye-fixation behavior can be characterized as a part of a control model which stresses a good correspondence between the internal representation of the environment and its objective characteristics. Any non-tolerable discrepancy between the two variables is reduced due to a postulated error signal" (page 37).

Summary

Various models have been proposed which describe driving behavior. Both preview and steering control models provide knowledge of the capabilities and limitations of the driver-vehicle system. Models of attentional demand and workload provide an overall rating for a particular type of road. Finally, models of driver eye-fixation behavior predict eye fixations on roads with moderately high information density.

RESEARCH OBJECTIVE

While there are a number of studies that have examined driver fixation patterns on rural roads, much research in this area still needs to be performed in order to provide baseline data for the driving task. The following are some shortcomings of the reviewed literature:

1. The definition of a fixation may vary from researcher to researcher. For example, Olson et al. (1989) really studied glances to areas of the road (a number of individual fixations), but called these glances fixations in their report.

2. Many of the studies that investigated fixations on curved roads never mentioned the specific radius of curvature. Thus, it is not known whether eye fixations vary with curvature and, if they do, the relationship is unknown.

3. Many of the studies performed on rural roads do not report details of the subjects, such as age and experience. Both of these variables have been shown to affect driving performance and eye-fixation patterns.

4. Individual researchers may have different definitions of road features or other places where the driver looks. For example, when left lane is reported, is that simply the lane or does it include the center line or road edge marker? Also, some researchers break the road up into sections (i.e., less than 75 feet in front of the car, 75 to 250 feet in front of the car, etc.) while others do not.

5. Eye patterns of older drivers on rural roads have not been studied.

6. No transition probability data have been reported in previous studies.

7. No models have tried to predict driver eye fixations on rural roads.

All of the above comments make the studies in the literature very hard to compare. Further, baseline data on driver eye fixations can not be determined from the studies in the literature due to lack of older driver data on rural roads, as well as the other shortcomings mentioned.

In this study, driver eye-fixation data on straight and curved rural roads were collected to provide baseline data for the driving task. Subsequently, these data will be utilized to develop theoretical and computer simulation models that will describe and predict driver eye-fixation patterns.

EXPERIMENT PROTOCOL

An on-road experiment examining eye fixations on straight versus curved rural roads was performed. The experiment involved 39 licensed drivers traveling on roads in Ann Arbor, Salem, and Northfield Townships, just north of Ann Arbor, Michigan. Drivers wore an eye-mark camera that recorded where they were looking in the forward visual scene.

The following questions were addressed in this experiment:

1. For daytime driving on straight rural roads, what are driver eye patterns and transition probabilities between road features (e.g., right edge marker, left edge marker, center line), car mirrors, and in-vehicle features?

2. What is the relationship between degree of curvature and driver eye fixations?

3. How does age affect driver eye fixations?

Experiment Design

The experiment design is a 4 x 2 x 2 mixed factorial. (See figure 6.) Road curvature (four levels, straight and three different degrees of curvature) was a within-subjects variable, while age (two levels, younger and older) and gender (two levels, men and women) were between-subjects variables. Dependent measures of interest were eye-fixation durations and locations (the feature fixated).

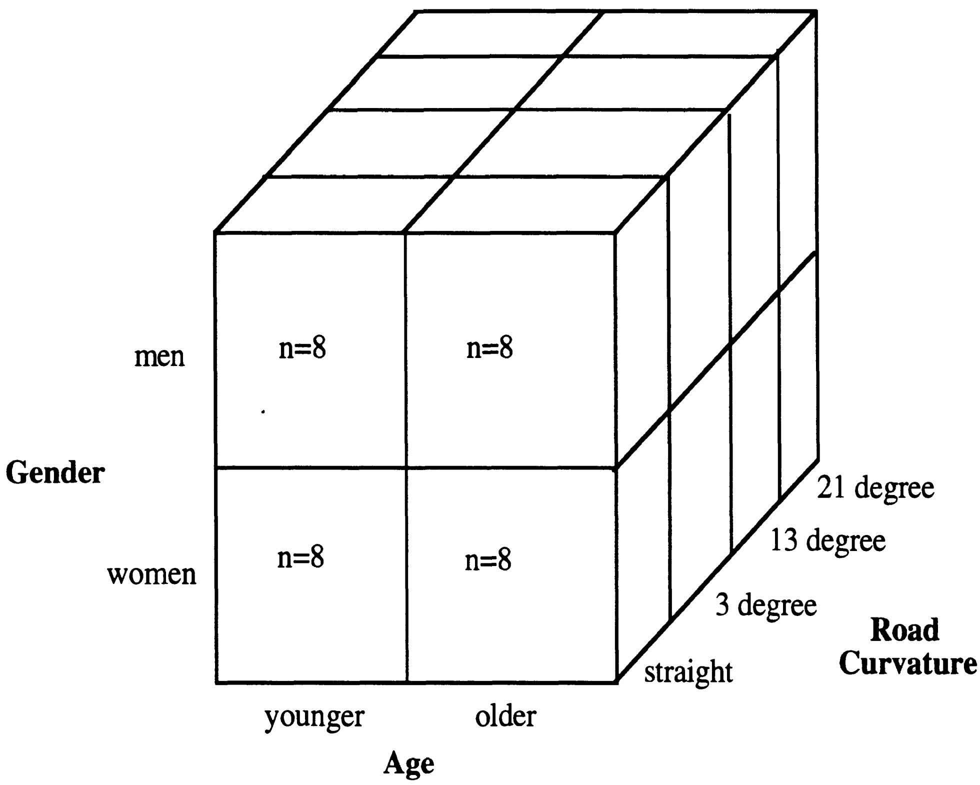


Figure 6. Experiment design

Test Participants

A total of 39 licensed drivers participated in this experiment. Because there was difficulty in calibrating the eye-mark recorder for some individuals, acceptable data were obtained for 32 drivers, the desired number. As indicated in figure 6, participants were divided into younger (ages 18 to 33 years, mean = 24 years) and older (ages 62 to 77 years, mean = 68 years) age groups, with an equal number of men and women in each group. Participants were recruited from the university community or had served in previous University of Michigan Transportation Research Institute (UMTRI) studies.

All participants reported driving on a daily basis and mostly in daylight conditions. None of the participants were familiar with the test site.

Road Characteristics

Eye-fixation data were collected on Seven Mile Road, a rural two-lane road with a center dividing line, which is 10 miles north of Ann Arbor, Michigan. The section driven on is 4.6 miles long and has 15 curves ranging from 1 degree 24 minutes to 21 degrees in curvature (based on measurements from the local county road commission). Figure 7 shows the road and the location of the segments of interest. Three left curves (3 degrees, 13 degrees, and 21 degrees) were selected for detailed study due to their range of curvature. The straight segment was selected because it is flat and the sight distance is large. Figures 8 through 11 show pictures of the straight segment and three curves that were studied in detail. Each curve is shown from the perspective of the driver as he/she starts to enter the curve.

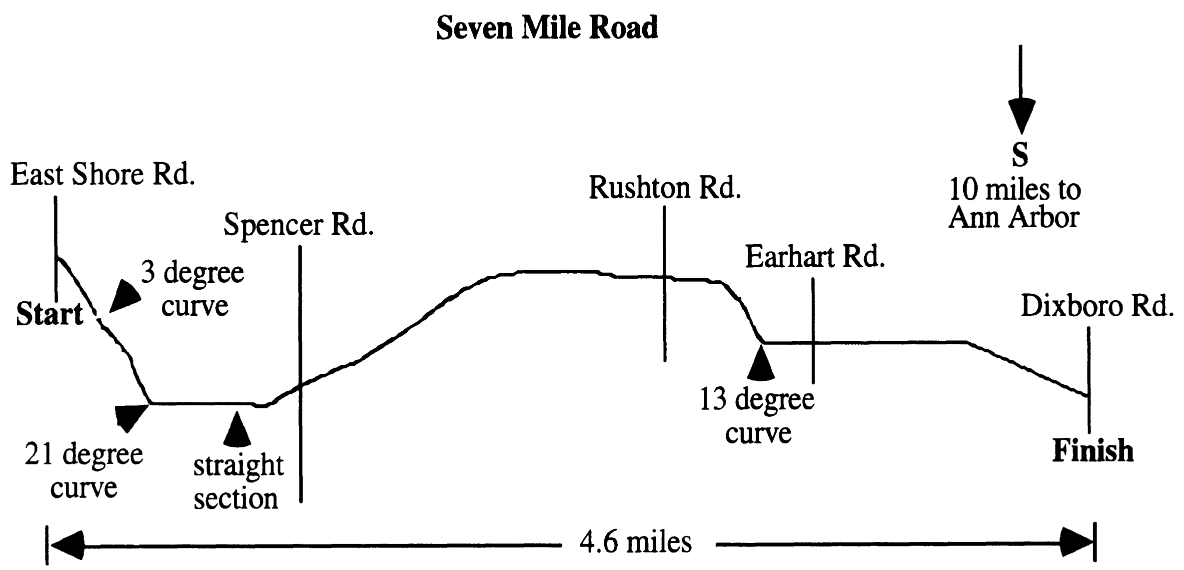


Figure 7. Section of Seven Mile Road used for data collection

Figure 8. Straight road segment

Figure 9. Three degree curve

Figure 10. Thirteen degree curve

Figure 11. Twenty-one degree curve

Characteristics of the road segments are shown in table 13. Confounded with radius of curvature are lane width, length of curve, and posted speed. Lane widths among the road segments vary by approximately 2 feet. The length of the curves vary from 310 to 393 feet. Eye fixations on only the actual curve segments were examined, not on the approach or exit zones of the curves. The curve segments of road were determined by looking at the engineering plans of the road which specified the P.C. (point of curvature) and P.T. (point of tangency) of each curve. The length of the straight segment of road approximates the average of the curve lengths. The speed limit on the road was posted at 50 miles per hour; none of the curves was posted for a reduced speed.

Table 13. Characteristics of road segments

	Road Segment			
	Straight	Curve 1	Curve 2	Curve 3
Curvature (degrees)	0	3	13	21
Lane width	10'1"	11'	10'2"	9'11"
Length	350'	310'	346'	393'

Test Equipment and Materials

Test Vehicle

The test vehicle was a 1991 Honda Accord station wagon with automatic transmission. For a more complete description of the vehicle, please see Sweet and Green (1993).

Eye-Mark Recorder

An NAC eye-mark recorder (model V) was used to track drivers' eye fixations. (See figure 12.) The recorder superimposes the position of the eye gaze on the driver's forward view. The eye position, commonly referred to as the *eye spot* or *eye mark*, is obtained through the corneal reflection technique in which a spot of infrared light is reflected from the cornea onto a series of mirrors and prisms and then recorded on video by cameras mounted on stalks to each side of the driver's head. The horizontal and vertical ranges of the NAC are 60 degrees and 45 degrees, respectively. The camera recording the forward scene is mounted on top of the headpiece, on the driver's forehead. The eye mark is represented as a square on the videotaped road scene.

For this experiment, eye fixations were recorded from the right eye. Thus, the left camera unit was removed to increase the peripheral field of view on the left side and the imbalance that resulted from this was partially corrected by a counterweight. Other modifications to the headpiece included custom padding to increase comfort and stability, as well as the bundling of wires from the individual head-camera units (the right eye camera, the scene camera, and the LED power) to allow freer head movement.

Test Procedure

Before collecting data on the road, the experimenter provided an overview of the study and obtained the subject's consent to participate.

The experiment was performed on the road previously described. The subject drove to the test site in order to become familiar with the vehicle. Upon arrival at the test site, the experimenter turned on the equipment while the subject filled out a biographical form. Next, the experimenter briefed the subject on the route to drive. Subjects were instructed to drive as they normally do, but not to exceed the speed limit. The eye-mark recorder was fitted on the subject and calibration was performed. Prior to data collection, the subject drove for approximately 2 miles while wearing the eye-mark recorder in order to become comfortable with the experimental procedure. Finally, the subject drove on the 9.2-mile test route wearing the eye-mark recorder. Data were collected for the entire route, but analyzed only for the road segments of interest. At the end of the route, the eye-mark recorder was removed and the subject drove back to UMTRI. The experiment concluded with an assessment of far visual acuity and an interview in which the subject reviewed the videotape and explained any reasons for looking at certain features of the road or in the vehicle.

Figure 12. The NAC model V headpiece

It was important that participants did not alter their normal eye patterns while driving. Therefore, drivers were told that the apparatus they were wearing measured characteristics of the eye, but were not directly told that eye fixations were of interest. Subjects were told the true purpose of the experiment upon the completion of the study.

Each session lasted 1.5 to 2 hours.

RESULTS

Data Reduction

The experimenter used landmarks on the side of the road (mailboxes, posted signs, etc.) to define the beginning and end of each road segment during data collection. In most cases, these landmarks were clearly visible on the videotapes. As a secondary means of identification, the beginning and end of the segments were auditorily coded on the videotapes.

Software for Data Reduction

Eye-fixation data from the videotapes were reduced using a computer program in HyperCard. The analyzer first defined the tape sections to be analyzed, in this case, the four road segments. Then, the analyzer went through the videotape frame by frame and noted the fixation location of the eye mark. At the end of this analysis, a listing of the frame numbers and the fixation locations was provided. A second HyperCard program converted this data into fixation locations and *durations*. Output from this program listed, in sequence, the number of frames of the fixation, the duration of the fixation, and the fixation location. Consequently, transition data is also present.

Another HyperCard program sorted the previous output file and, in columnar format, displayed the fixation durations of the road and car features for each subject. From this data file, mean fixation durations for each feature and fixation probabilities were obtained.

Hardware for Data Reduction

Eye-mark data reduction was performed on a Macintosh computer connected to an NEC PC-VCR and monitor. Superimposed on the monitor was a grid divided into 1 degree sections, which was used to determine the spatial travel distance of the eye mark.

Definition of an Eye Fixation

The following criteria were used to define a new eye fixation:

1. Spatial travel distance was at least 1 degree from the previous frame or the first frame of the fixation.

2. The duration was greater than 50 milliseconds (Carpenter and Just, 1976; Gould, 1976).

Definitions of Features

Fifteen categories of features were identified after examination of the data. These included features of the road (left edge, right edge, center line, right lane, and left lane), in the vehicle (instrument panel and mirrors), and in the environment (oncoming car, far field, right scenery, and left scenery). Two additional categories were used to define fixations, other and unknown. The category "other" referred to fixations toward infrequently occurring objects such as pedestrians and animals. The category "unknown" was used when the eye mark was not evident on the videotape. This generally occurred when the driver moved his or her eyes so far to the left or right that the light was not reflected on the cornea. The general locations of these features on the straight and curved road segments are shown in figures 13 and 14, respectively.

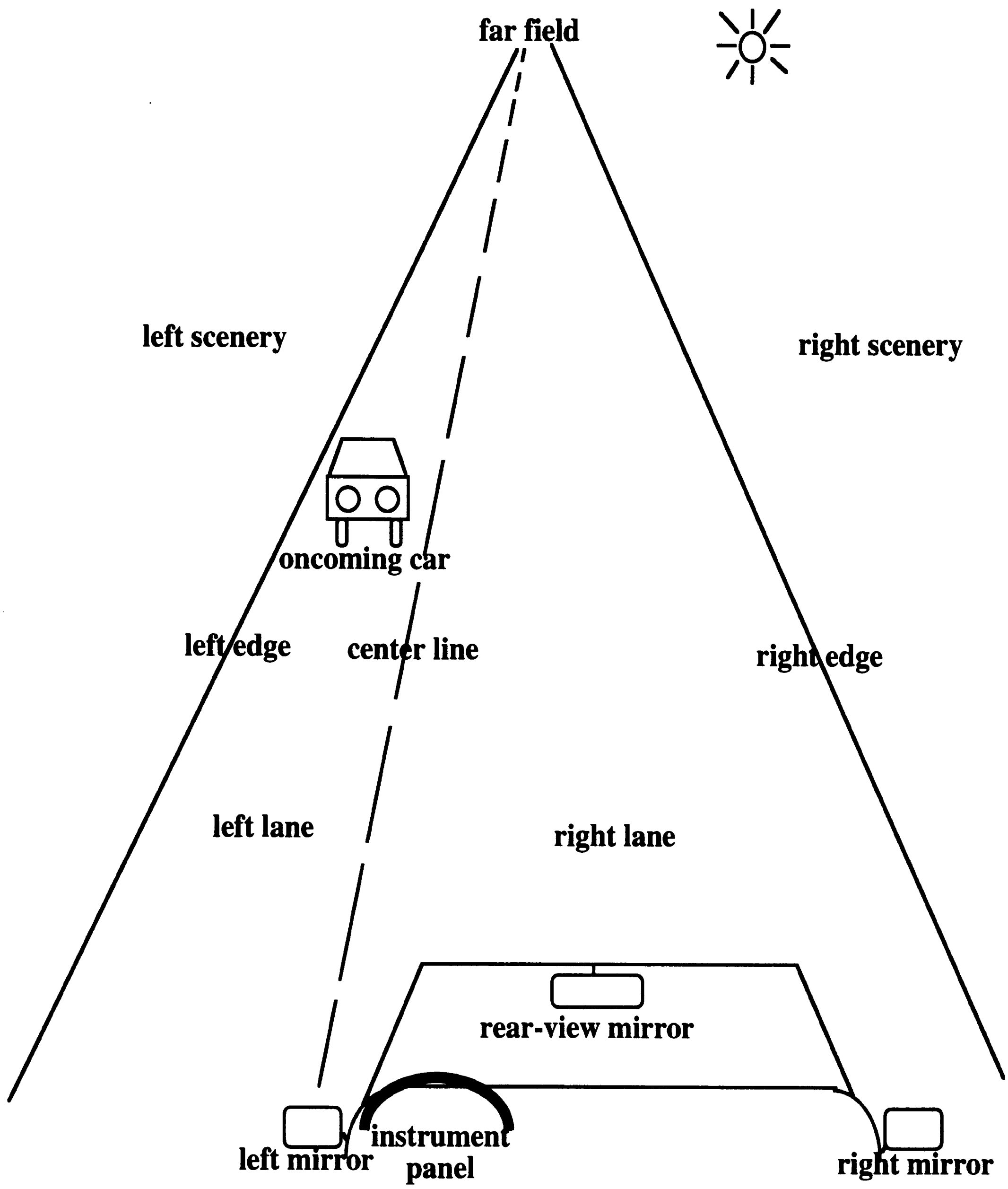


Figure 13. Locations of features on the straight road segment

For the curves, the definition of far field differed from that of the straight segment. The far field was defined as the area straight ahead above the road, far down the road and included an area between a horizontal line through the left edge of the road and a diagonal line through the right edge of the road. (See figure 14.) Also, two additional features were defined on the curves, left and right far fields. The left far field was the area far down the road to the left of an imaginary horizontal line through the left edge of the road. (See figure 14.) The right far field was defined as the area straight ahead, far down the road.

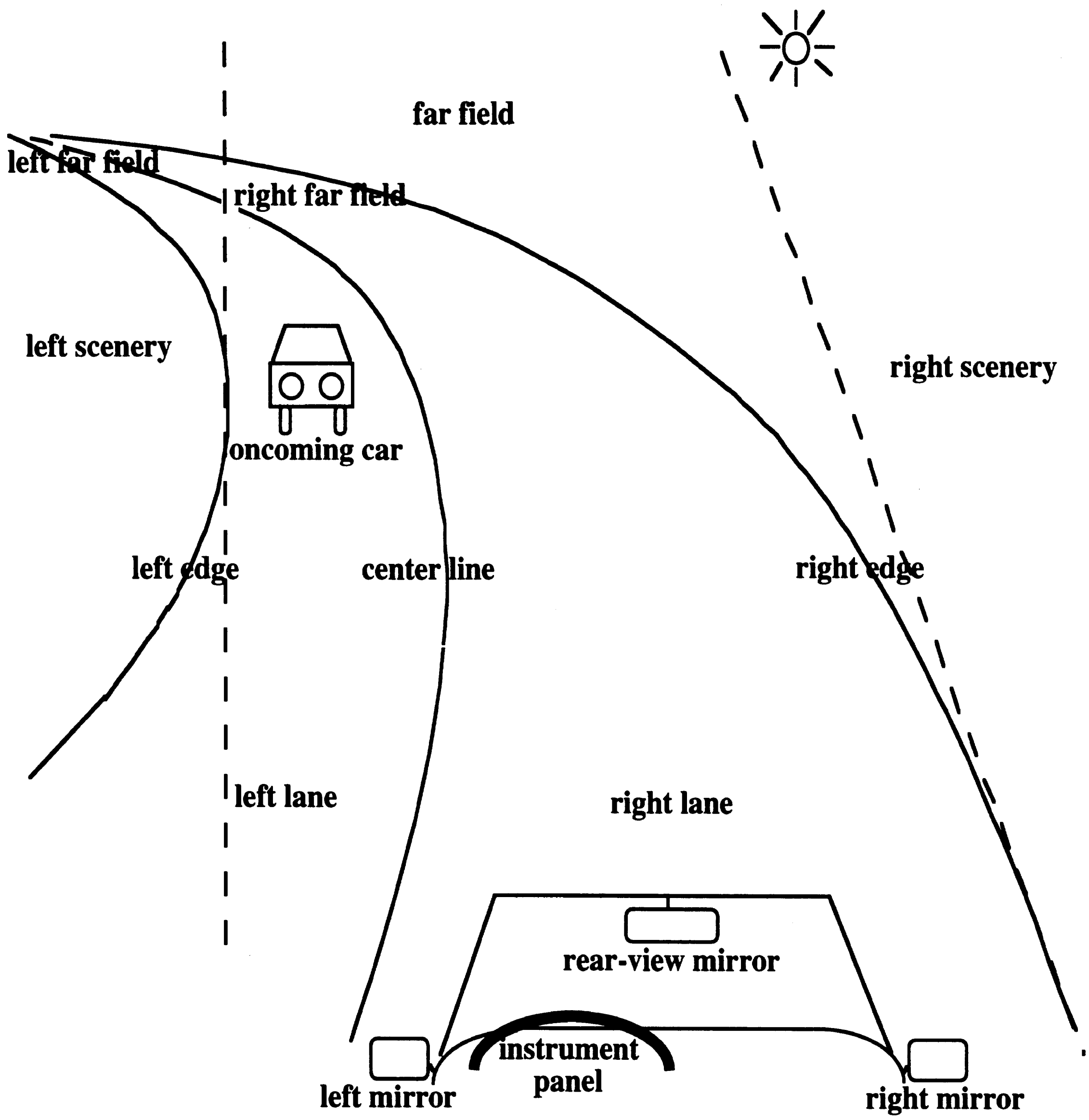


Figure 14. Locations of features on the curved road segments

Definitions of the features on the straight and curved road segments are provided in tables 14 and 15, respectively.

Table 14. Definitions of features for the straight road segment

Far Field	the area around the focus of expansion where the end of the road meets the horizon, it appears that everything in the visual scene is expanding from this area roughly +/- 4 degrees horizontally and +/- 2 degrees vertically
Left Scenery	the area to the left side of the road that does not include the far field, the left road edge, or signs
Right Scenery	the area to the right side of the road that does not include the far field, the right road edge, or signs
Oncoming Car	a car approaching from the opposite direction
Left Edge	the area around the left edge line of the road roughly +/- 1 degree horizontally
Right Edge	the area around the right edge line of the road roughly +/- 1 degree horizontally
Center Line	the area around the center line of the road roughly +/- 1 degree horizontally
Left Lane	the left lane that does not include the areas around the left edge line and center line
Right Lane	the right lane that does not include the areas around the right edge line and center line
Left Mirror	the area around the left mirror
Right Mirror	the area around the right mirror
Rear-View Mirror	the area around the rear-view mirror
Instrument Panel	the area around the instrument panel the eye mark could be + 8-10 degrees vertically (around the top of the steering wheel)
Out-of-View	the eye mark is not evident on the monitor
Other	reserved for novel features such as pedestrians, mailboxes, etc. or fixations above the far field directed toward the sky

Table 15. Definitions of features for the curves (different from those of the straight segment)

Far Field	the area straight ahead above the road, far down the road; between a horizontal line through the left edge of the road and a diagonal line through the right edge of the road
Left Far Field	the area far down the road to the left of an imaginary horizontal line through the left edge of the road
Right Far Field	the area straight ahead on the road, far down the road
Left Scenery	the area to the left side of the road that does not include the left far field, the left road edge, or signs
Right Scenery	the area to the right side of the road that does not include the far field, the right road edge, or signs

Eye-Fixation Data

Percentages of Fixations

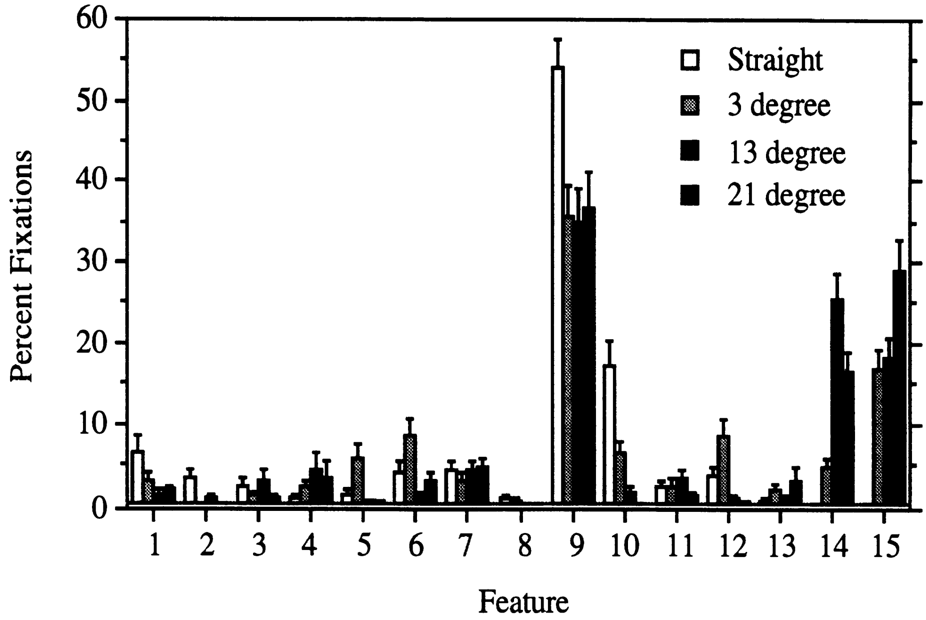
The data for percentages of fixations were entered into a data base and a repeated measures analysis of variance (ANOVA) was run using the statistical program SuperANOVA on a Macintosh computer. The independent variables were age, gender, road curvature, and road/car feature. The features included the road edges (right and left), center line, lanes (right and left), scenery (right and left), far field (right and left), oncoming cars, instrument panel, mirrors, unknown, and other.

The main effect of feature ($F[14, 392] = 117.561$, $p < 0.0001$) and the curvature by feature interaction ($F[42, 1176] = 11.968$, $p < 0.0001$) were significant. To determine how the fixation percentages for each feature varied as a function of road curvature, post hoc pairwise comparisons for curvature were performed at each level of feature. To correct for positively biased *F*-tests which result from repeated measures designs, the Greenhouse-Geisser correction procedure was employed to adjust the degrees of freedom used to obtain critical values from the *F*-table. Significant differences were found for six features: center line, far field, right scenery, right lane, left far field, and right far field.

The curvature by feature interaction in figure 15 shows that differences in fixation percentages between the straight segment and the three curves were found for only two features, far field and right scenery. For both of these features, fixation percentages were higher on the straight segment (far field, 54 percent and right scenery, 17 percent) than on the curves (average: far field, 36 percent and right scenery, 3 percent).

Fixation percentages on the 3 degree curve differed from those on the 13 degree and 21 degree curves for two features, center line and right lane. For both of these features, fixation percentages were higher on the 3 degree curve (center line, 9 percent and right lane, 9 percent) than on the 13 degree and 21 degree curves (average: center line, 2 percent and right lane, 0 percent). There were also higher fixation percentages to the right scenery on the 3 degree curve (6 percent) than on the 21 degree curve (0 percent).

Fixation percentages to the left far field differed for all three curves (3 degree--5 percent, 13 degree--26 percent, and 21 degree--16 percent) while fixation percentages to the right far field were higher on the 21 degree curve (29 percent) than on the other two curves (average: 18 percent).



Feature:	1 = instrument panel	9 = far field
	2 = mirrors	10 = right scenery
	3 = oncoming car	11 = left scenery
	4 = left edge	12 = right lane
	5 = right edge	13 = left lane
	6 = center line	14 = left far field
	7 = unknown	15 = right far field
	8 = other	

Figure 15. Fixation percentages to features for the four road segments (Error bars indicate the standard error of the mean.)

Probability of Fixating on a Feature

The fixation percentage data can be transformed to also represent the probability of a driver fixating on the features of the road. For example, 54 percent of the fixations directed to the far field indicate that the probability of fixating on the far field is 0.54. Thus, the probability of fixating on different road and car features was obtained by the equation:

$$\text{fixation probability to feature A} = \frac{\text{\# fixations to feature A}}{\text{total \# fixations}}$$

Probabilities of fixating on different features for the road segments of interest are shown in figures 16 through 19. All of the road segments are similar in that the probability of fixating far down the road at the far field is higher (straight--0.54, 3 degree--0.36, 13 degree--0.35, and 21 degree--0.37) than the probability of fixating on any other feature (for all segments: range from 0.00 to 0.09).

On the straight segment, it is interesting to note that the probability of fixating on the right scenery is 0.17, substantially higher than the probability of fixating on any other feature (range from 0.01 to 0.04), and higher than the sum of the road features (edges, center line, and lanes, 0.11).

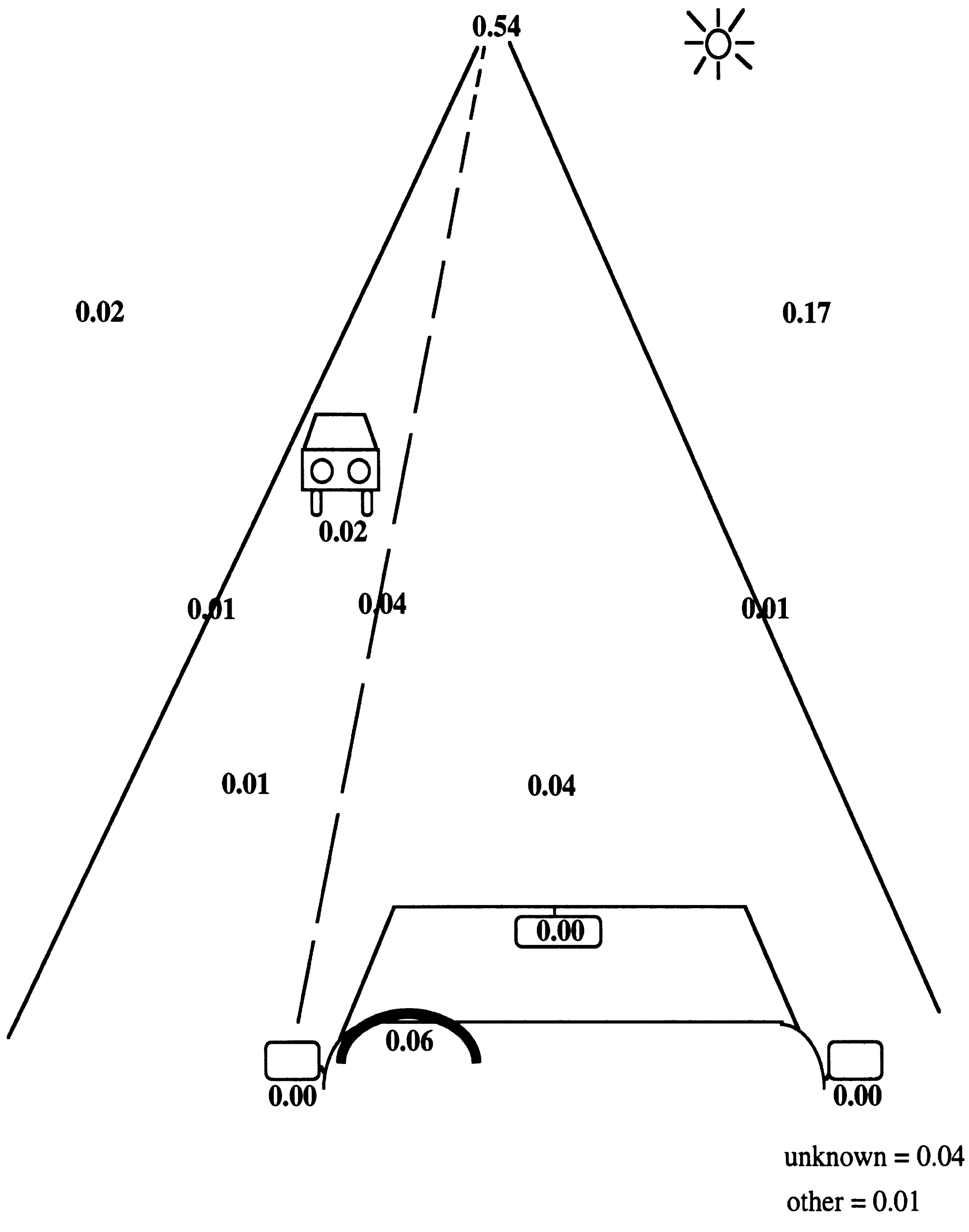


Figure 16. Probability of fixating on features on the straight road segment

On the 3 degree curve, the probability of fixating on road features (edges, center line, and lanes, 0.27) is higher than on any other road segment. Further, the probability of fixating on the right far field (defined as far down the road) is 0.17 and, as stated previously, the probability of fixating on the far field (defined as straight ahead above the road) is 0.36. Fixations on the 3 degree curve are more evenly distributed among the far field and road features than on the other road segments.

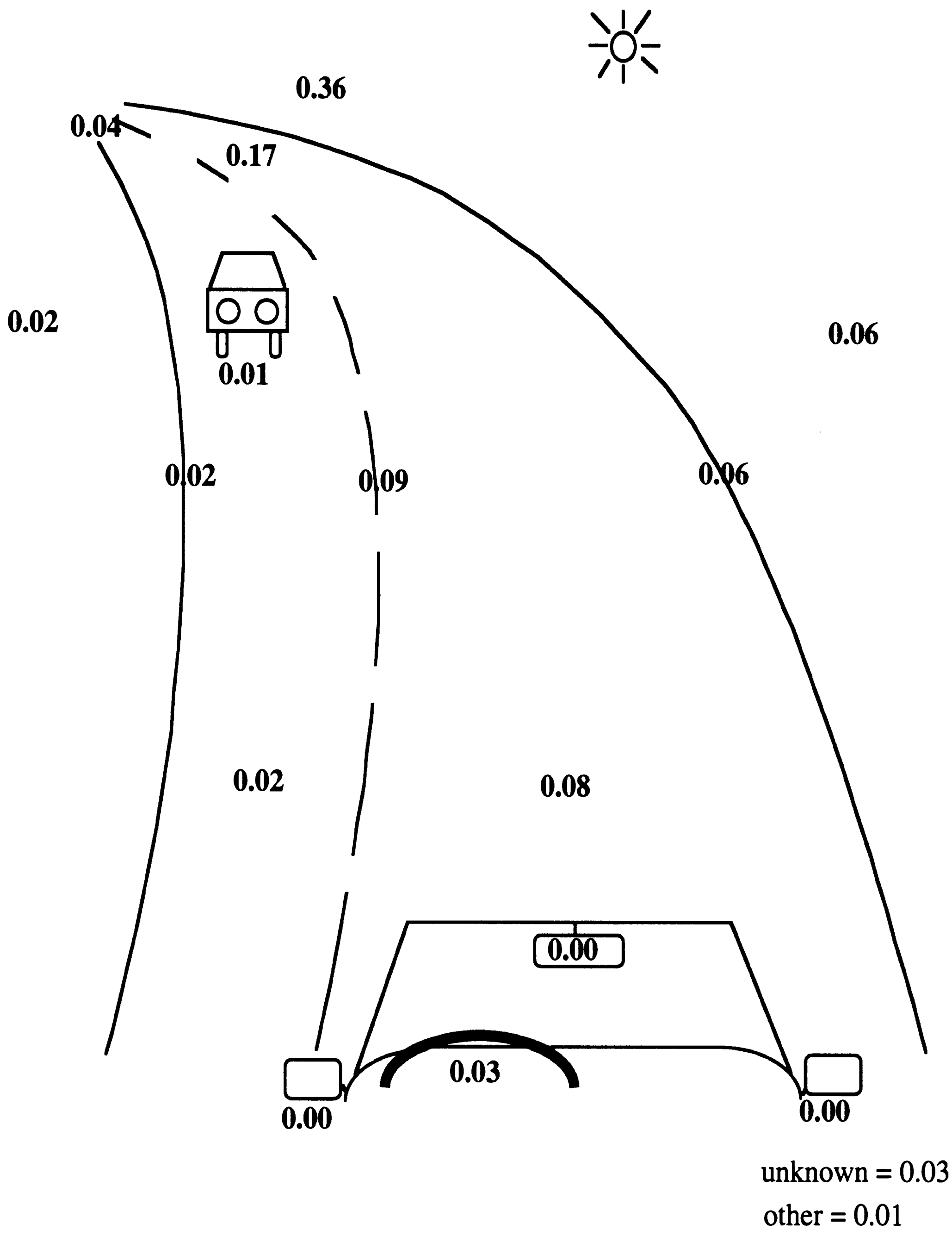


Figure 17. Probability of fixating on features on the 3 degree curve

Fixation probabilities on the 13 degree and 21 degree curves are similar. The probability of fixating on the far field (defined as straight ahead above the road) is higher (13 degree, 0.35 and 21 degree, 0.37) than the probability of fixating on any other feature. Also, the probability of fixating on the left far field (defined as far down the curve) (13 degree, 0.26 and 21 degree, 0.16) and the right far field (defined as far down the road on a curve) (13 degree, 0.18 and 21 degree, 0.29) is relatively high. Finally, there is a higher probability of fixating on the left side of the road (left edge and left lane) (13 degree, 0.05 and 21 degree, 0.06) than on the right side (right edge and right lane) (13 degree, 0.01 and 21 degree, 0.00).

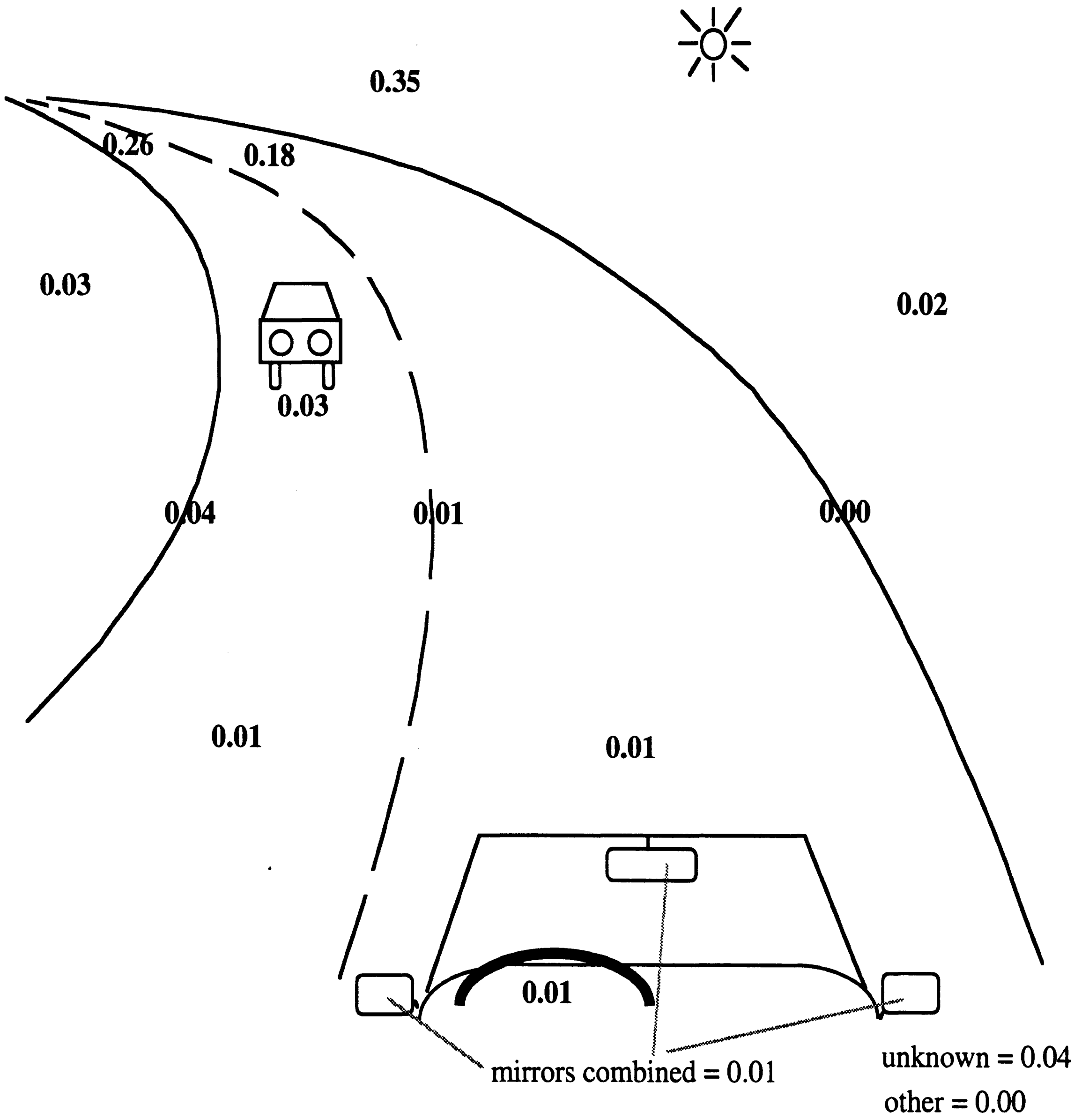


Figure 18. Probability of fixating on features on the 13 degree curve

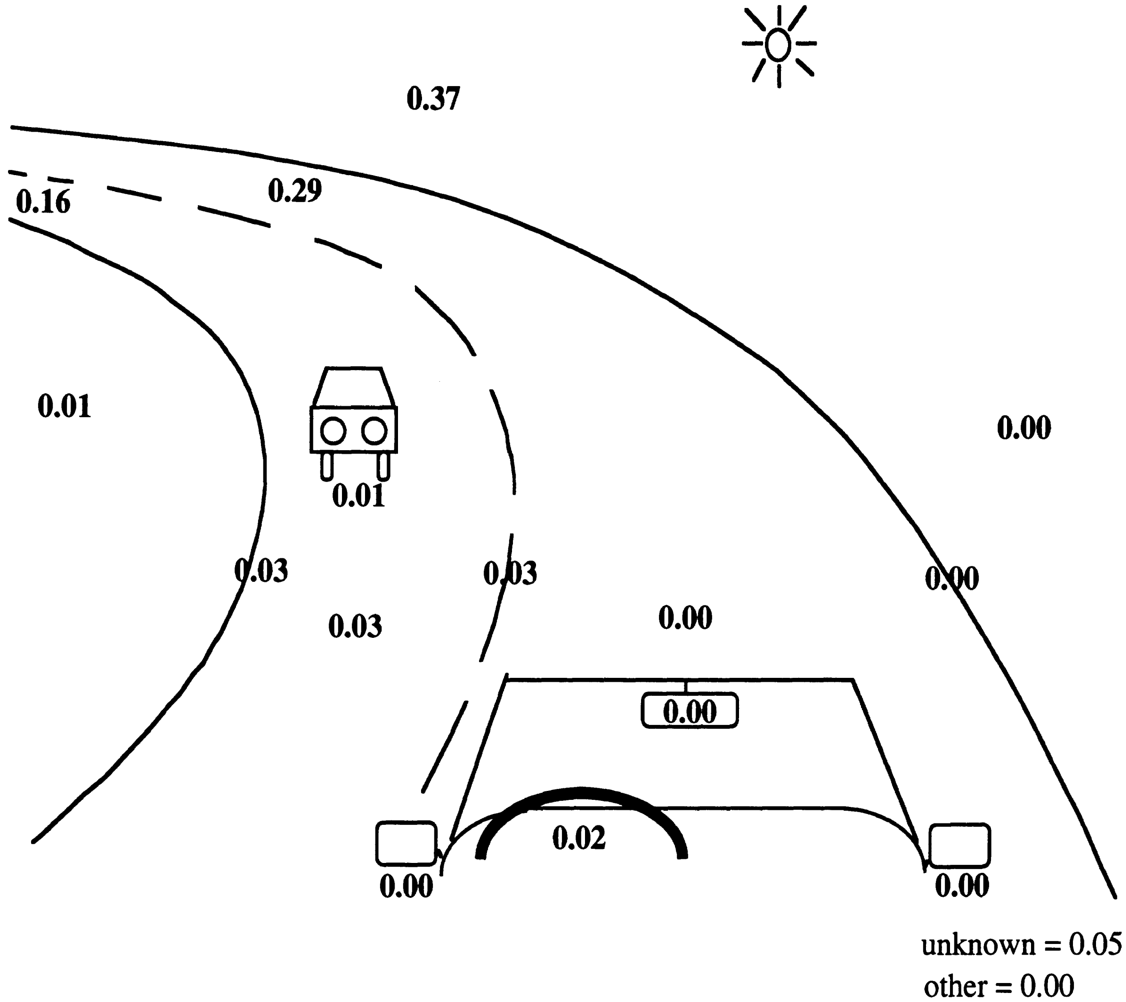


Figure 19. Probability of fixating on features on the 21 degree curve

Number of Fixations

The number of fixations made by subjects were entered into a data base and a repeated measures analysis of variance (ANOVA) was run using the statistical program SuperANOVA on a Macintosh computer. The independent variables were age, gender, and road curvature.

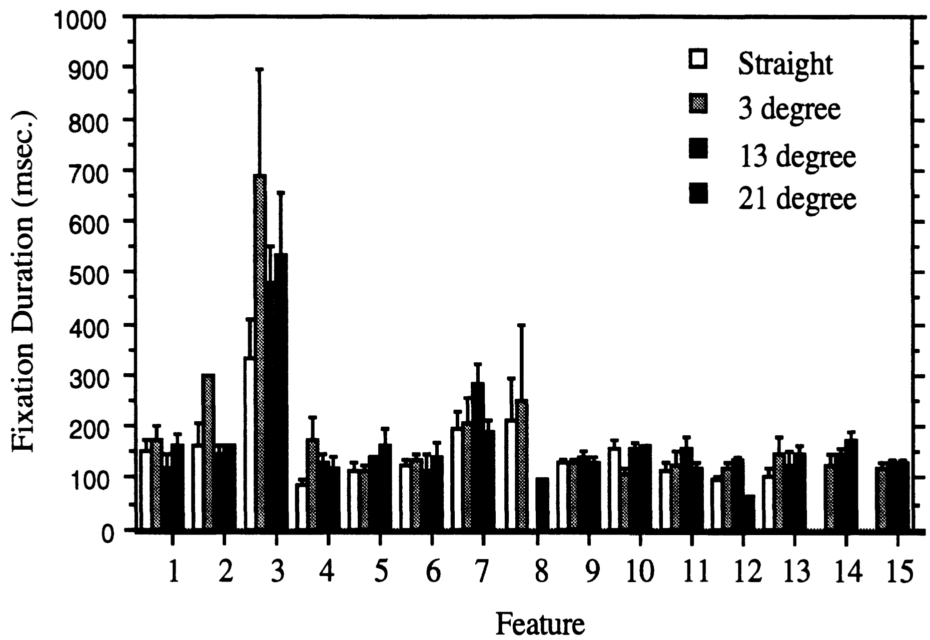
The main effects of age ($F[1, 28] = 13.067$, $p < 0.0012$) and road curvature ($F[3, 84] = 34.214$, $p < 0.0001$) were significant. To determine how the number of fixations varied as a function of road curvature, post hoc pairwise comparisons for curvature were performed. To correct for positively biased F-tests which result from repeated measures designs, the Greenhouse-Geisser correction procedure was employed to adjust the degrees of freedom used to obtain critical values from the F-table.

More fixations were made on the 21 degree curve (41) than on the 13 degree curve (34). The fewest fixations were made on the straight road segment and the 3 degree curve (average: 28), which were significantly lower than the number of fixations on the 13 degree curve. In addition, older drivers had more fixations (36) overall than younger drivers (30).

Fixation Durations

There were many missing values for the duration data because fixation durations were considered for only those features that were fixated upon. Thus, if the left road edge was not fixated by a subject on the straight road segment, then no fixation duration could be obtained. Because of the substantial number of missing values, a statistical test was not applied. A descriptive summary is provided, however.

The overall mean fixation duration was 158 milliseconds. Fixation durations were longest on the 13 degree curve (169 milliseconds) and shortest on the straight segment (149 milliseconds), with durations of 154 milliseconds and 159 milliseconds on the 3 and 21 degree curves, respectively. Fixation durations were longer for younger (174 milliseconds) than older drivers (145 milliseconds). Figure 20 shows the fixation durations for features on the four road segments. Fixations were longer to oncoming cars (506 milliseconds) than to any other feature (146 milliseconds). It should be noted that drivers seemed to track oncoming cars once they fixated on them; this pursuit movement was considered as one fixation since there was no obvious break in the eye-fixation behavior. Fixations to oncoming cars were longest on the 3 degree curve (688 milliseconds) and shortest on the straight segment (331 milliseconds).



Feature:	1 = instrument panel	9 = far field
	2 = mirrors	10 = right scenery
	3 = oncoming car	11 = left scenery
	4 = left edge	12 = right lane
	5 = right edge	13 = left lane
	6 = center line	14 = left far field
	7 = unknown	15 = right far field
	8 = other	

Figure 20. Fixation durations for features for the four road segments (Error bars indicate the standard error of the mean.)

CONCLUSIONS

The results of this study indicate that there were some differences in driver eye fixations depending on the curvature of the road. On the straight road segment, drivers directed significantly more fixations toward the right scenery than they did on the curves. This may indicate that, on straight road segments, drivers can direct more of their visual attention to features that do not necessarily relate to the task of maintaining the longitudinal and lateral position of the vehicle.

Higher fixation percentages to the center line, right lane, and right scenery were found on the 3 degree curve than on the 21 degree curve. On the 21 degree curve, all of the fixations tended to be on the left side of the road or straight ahead above the road, far down the road. In addition, drivers made more fixations on the 21 degree curve than on any other road segment. These results indicate that a sharper curve demands more attention for vehicle control than do straight road segments or less gradual curves and, on a sharp curve, drivers tend to look in the direction of the curve.

On all of the road segments, drivers tended to fixate as far down the road as they could. Thus, on the straight road segment, drivers looked at the far field and, on the left curves, drivers looked at the far field, as well as the left and right far fields.

Fixation durations were fairly consistent among different road curvatures and features, except for the straight segment where fixations to oncoming cars were brief when compared with fixations on the curves. While the probability of the occurrence of an oncoming vehicle was very low on the particular rural road used for the study, it should be noted that when there was an oncoming vehicle, drivers tended to look at it and, in fact, to track it for a substantial length of time. The shorter durations to oncoming vehicles on the straight segment than on the curves indicate that either drivers did not look at these vehicles as soon as they were in the forward view or that they stopped looking at them sooner than they did on the curves. A reanalysis of the videotapes will be necessary in order to determine the explanation for this outcome.

Finally, the location of driver eye fixations was not influenced by driver age. Younger drivers, however, had slightly longer but fewer fixations than older drivers.

Comparison of Data from the Present Study to those from the Literature

The fixation percentage data and fixation durations obtained from the present study were compared to data from previous research described in the section of this report entitled "Eye-Fixation Literature." On straight roads, fixation percentages to two features are similar: center line (present study, 4 percent fixations and Blaauw (1975), 6.1 percent fixations) and instrument panel (present study, 6 percent fixations and Olson et al. (1989), 3 percent fixations inside). Many of the fixation percentages vary considerably, however. In the present study, only 11 percent of the fixations were to road features whereas Blaauw (1975) and Olson et al. (1989) found approximately 55 percent of the fixations to features on the road. Fifty-four percent of the fixations were found to the far field in the present study whereas Olson et al. (1989) found 25 percent of the fixations to this area. These differences may be attributable to variations in the definitions of features among the studies.

Mean fixation durations on the straight segment in the present study were 149 milliseconds whereas Shinar et al. (1977) report a mean of 600 milliseconds. Perhaps, the large discrepancy in these fixation durations can be attributed to differences in the definition of a fixation between the present author and Shinar et al. (1977). It should be noted that Shinar et al. (1977) do not state their definition of a fixation.

For left curves, a comparison of the data from the present study and previous research revealed that there are similar fixation percentages for three features: left edge (present study, 2 to 4 percent fixations for the three curves and Blaauw (1975), 3.4 percent fixations), center line (present study, 1 to 3 percent fixations for the 3 and 21 degree curves and Blaauw (1975), 3.3 percent fixations), and instrument panel (present study, 1 to 3 percent fixations for the three curves and Olson et al. (1989), 1 percent fixations inside). Similar to the straight road comparison data reported above, there were more fixations to the far field (57 to 82 percent fixations for the three curves) and less to road features (7 to 27 percent fixations for the three curves) in the present study whereas the previous research indicates otherwise: far field (Olson et al., 27 percent fixations) and road features (Blaauw, 46 percent fixations and Olson et al., 62 percent fixations). In the present study, fixation durations on left curves ranged from 154 to 169 milliseconds for the three curves whereas Shinar et al. (1977) (0.28 seconds), Cohen and Studach (1977) (0.41 seconds), and Olson et al. (1989) (0.30 to 0.60 seconds) report longer durations. As stated above, the differences in the data may be due to variations in the definitions of features and fixations among the studies.

Future Directions

The data from this study will be analyzed further to determine the probability of transitioning from one feature to another. This will provide a more complete description of driver eye-fixation behavior on straight and curved rural roads. In addition, the site distances of the curves will be defined in order to determine how this factor may influence driver eye fixations.

Finally, theoretical and computer modeling efforts to describe and predict driver eye fixations will be completed.

REFERENCES

Antin, J.F., Dingus, T.A., Hulse, M.C., and Wierwille, W.W. (1990). An evaluation of the effectiveness and efficiency of an automobile moving-map navigational display. *International Journal of Man-Machine Studies, 33*(5), 581-594.

Blaauw, G.J. (1975). Drivers' scanning behaviour on some curved and straight road sections. *First International Congress on Vision and Road Safety.* Paris, France: Linas-Montlhery.

Blaauw, G.J., and Riemersma, J.B.J. (1975). *Interpretation of roadway designs by an analysis of drivers' visual scanning and driving behaviour on straight and curved roadway sections* (Technical Report No. IZF 1975-C5). The Netherlands: Institute for Perception.

Carpenter, P.A., and Just, M.A. (1976). Linguistic influences on picture scanning. In R.A. Monty and J.W. Senders (Eds.), *Eye movements and psychological processes.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Cohen, A.S., and Hirsig, R. (1980). *Feedforward programming of car drivers' eye movement behavior: A system theoretical approach* (Final Technical Report, Volume II). Zurich: Swiss Federal Institute of Technology, Department of Behavioral Science.

Cohen, A.S., and Hirsig, R. (1983). *Development of a general model of the car drivers' eye movement sequences and effects of subject and environmental variables* (Technical Report). Zurich: Swiss Federal Institute of Technology, Department of Behavioral Science.

Cohen, A.S., and Studach, H. (1977). Eye movements while driving cars around curves. *Perceptual and Motor Skills, 44*(3), 683-689.

Crossman, E.R.F.W., and Szostak, M. (1968, March). *Man-machine models for car-steering.* Paper presented at the Fourth NASA/University Conference on Manual Control, Ann Arbor, MI.

Donges, E. (1978). A two-level model of driver steering behavior. *Human Factors, 20*(6), 691-707.

Fry, G.A. (1968). The use of the eyes in steering a car on straight and curved roads. *American Journal of Optometry, 45*(6), 374-391.

Gatchell, S.M. (1977). *Power boat operators' visual behavior patterns.* Unpublished doctoral dissertation, University of Michigan, Ann Arbor, MI.

Godthelp, J. (1984). *Preview control: open and closed loop automobile steering at curve entrance* (Technical Report IZF 1984-33). The Netherlands: Institute for Perception.

Gordon, D.A. (1966). Perceptual basis of vehicular guidance. *Public Roads, 34*(3), 53-68.

Gould, J.D. (1976). Looking at pictures. In R.A. Monty and J.W. Senders (Eds.), *Eye movements and psychological processes.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Kaluger, N.A., and Smith, G.L. (1970). Driver eye-movement patterns under conditions of prolonged driving and sleep deprivation. *Highway Research Record*, 336, 92-106.

Kurokawa, K., and Wierwille, W.W. (1991). Effects of instrument panel clutter and control labelling on visual demand and task performance. In *Society of Information Display International Symposium Digest, XXIII*.

McDonald, L.B. (1973). *A model for predicting driver workload in the freeway environment: A feasibility study*. Unpublished doctoral dissertation, Texas A & M University, College Station, TX.

McLean, J.R., and Hoffman, E.R. (1973). The effects of restricted preview on driver steering control and performance. *Human Factors, 15*(4), 421-430.

McRuer, D.T., Allen, R.W., Weir, D.H., and Klein, R.H. (1977). New results in driver steering control models. *Human Factors, 19*(4), 381-397.

Miller, R.A. (1967). *A preview control model with one or two fast time scale loops* (DSR 70283-4). Cambridge, MA: Massachusetts Institute of Technology, Department of Mechanical Engineering, Engineering Projects Laboratory.

Mortimer, R.G., and Jorgeson, C.M. (1972). Eye fixations of drivers as affected by highway and traffic characteristics and moderate doses of alcohol. In *Proceedings of the Human Factors Society 16th Annual Meeting* (pp. 86-92). Santa Monica, CA: Human Factors Society.

Moskowitz, H., Ziedman, K., and Sharma, S. (1976). Visual search behavior while viewing driving scenes under the influence of alcohol and marijuana. *Human Factors, 18*(5), 417-432.

Mourant, R.R., and Rockwell, T.H. (1970a). Mapping eye-movement patterns to the visual scene in driving: an exploratory study. *Human Factors, 12*(1), 81-87.

Mourant, R.R., and Rockwell, T.H. (1970b). Visual information seeking of novice drivers. *1970 International Automobile Safety Conference Compendium*. New York, NY: Society of Automotive Engineers.

Mourant, R.R., and Rockwell, T.H. (1972). Strategies of visual search by novice and experienced drivers. *Human Factors, 14*(4), 325-335.

Mourant, R.R., Rockwell, T.H., and Rackoff, N.J. (1969). Drivers' eye movements and visual workload. *Highway Research Record,* 292, 1-10.

Noy, Y.I. (1990, February). *Attention and performance while driving with auxiliary in-vehicle displays* (Technical Report TP 10727 (E)). Ottawa, Canada: Road Safety and Motor Vehicle Regulation, Transport Canada.

Olson, P.L., Battle, D.S., Aoki, T. (1989). *Driver eye fixations under different operating conditions* (Technical Report UMTRI-89-3). Ann Arbor: University of Michigan Transportation Research Institute.

Pauzie, A., and Marin-Lamellet, C. (1989). Analysis of aging drivers' behaviors navigating with in-vehicle visual display systems. In *Proceedings of the First Vehicle Navigation and Information Systems Conference (VNIS '89)* (pp. 61-67). New York, NY: IEEE.

Rackoff, N. (1974). *An investigation of age related changes in drivers' visual search patterns and driving performance and the relation to tests of basic functional capacities*. Unpublished doctoral dissertation, Ohio State University, Columbus, OH.

Rackoff, N.J., and Mourant, R.R. (1979). Driving performance of the elderly. *Accident Analysis & Prevention, 11*, 247-253.

Rackoff, N.J., and Rockwell, T.H. (1975). Driver search and scan patterns in night driving. *Transportation Research Board Special Report 156*, 53-63.

Renge, K. (1980). The effects of driving experience on a driver's visual attention-An analysis of objects looked at: using the 'verbal report' method. *International Association of Traffic Safety Sciences Research, 4*, 95-106.

Rockwell, T.H. (1972). Eye-movement analysis of visual information acquisition in driving: An overview. *Sixth Conference of the Australian Road Research Board.* Canberra, Australia: ACT.

Rockwell, T.H., Augsburger, A., Smith, S.W., and Freeman, S. (1988). The older driver-A challenge to the design of automotive electronic displays. In *Proceedings of the Human Factors Society 32nd Annual Meeting* (pp. 583-587). Santa Monica, CA: Human Factors Society.

Rockwell, T.H., Ernst, R.L., and Rulon, M.J. (1970). Visual information acquisition by the night driver. In *Visual Requirement in Night Driving* (pp. 23-31). Washington, D.C.: National Research Board.

Rockwell, T.H., and Weir, F.W. (1973). The effects of carbon monoxide intoxication on human performance in laboratory and driving tasks. In *Proceedings of the First International Conference on Driver Behavior*, Zurich, Switzerland.

Safford, Jr., R.R. (1971). *Visual spare capacity in automobile driving and its sensitivity to carboxyhemoglobin.* Unpublished doctoral dissertation, Ohio State University, Columbus, OH.

Senders, J.N. (1966, June). Communication: A reanalysis of the pilot eye-movement data. *IEEE Transactions on Human Factors in Electronics, HFE-7*(2).

Senders, J.W., Kristofferson, A.B., Levison, W.H., Dietrich, C.W., and Ward, J.L. (1967). *Attentional demand of automobile driving* (Technical Report No. 1482). Cambridge, MA: Bolt, Beranek, and Newman, Inc.

Serafin, C. (1993). *Preliminary examination of driver eye fixations on rural roads: Insight into safe driving behavior* (Technical Report UMTRI-93-29). Ann Arbor: University of Michigan Transportation Research Institute.

Sheridan, T.B. (1966). Three models of preview control. *IEEE Transactions on Human Factors in Electronics, HFE-7*(2), 91-102.

Shinar, D., McDowell, E.D., and Rockwell, T.H. (1977). Eye movements in curve negotiation. *Human Factors, 19*(1), 63-71.

Sivak, M., Conn, L.S., and Olson, P.L. (1986). Driver eye fixations and the optimal locations for automobile brake lights. *Journal of Safety Research, 17*, 13-22.

Sweet, R., and Green, P. (1993, January-February). UMTRI's instrumented car. *UMTRI Research Review, 23*(4). Ann Arbor: University of Michigan Transportation Research Institute.

Wierwille, W.W., Hulse, M.C., Fischer, T.J., and Dingus, T.A. (1988, January). *Effects of variations in driving task attentional demand on in-car navigation system usage* (Technical Report CR-88/02/OS). Warren, MI: General Motors Research Laboratories.

Wolf, E. (1972). Studies on the shrinkage of the visual field with age. *Highway Research Record*, 164, 1-7.

Zell, J.K. (1969). *Driver eye movements as a function of driving experience* (Technical Report IE-16). Columbus: Systems Research Group, Ohio State University.

Zwahlen, H.T. (1982). Driver eye scanning on curves and on straight sections on rural highways. In *Proceedings of the Human Factors Society 26th Annual Meeting* (p. 227). Santa Monica, CA: Human Factors Society.

Zwahlen, H.T., and Debald, D.P. (1986). Safety aspects of sophisticated in-vehicle information displays and controls. In *Proceedings of the Human Factors Society 30th Annual Meeting* (pp. 256-260). Santa Monica, CA: Human Factors Society.

APPENDIX

This appendix contains a table that summarizes the eye movement literature reviewed in this report: studies that examined driving on straight and curved rural roads during the day, as well as age.

Partial Summary of Eye Movement Research

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Blaauw (1975) same as Blaauw and Riemersma (1975)	on-road	one-way lane, crash barriers on each side, 2 left curves, 1 straight sect., no road signs, max vel=80kph, each section is 276m long, day	n=5, male, 22-28 years, licensed for 3 years, 30,000 km	road-straight -left curves Radius=83.6 m Radius=95 m 3 trials	eye movements	horizontal and vertical eye positions with respect to vanishing points, horizontal and vertical distributions of eye positions with respect to vanishing points, % fixations to objects	assume left marker is left edge line but could be crash barrier, one-way road has 2-lanes, drivers drove in right lane
Results:	**% Fixations (dur. time>100 msec.)** Radius=83.6m:Radius=95m:straight left edge-0.8:3.9:8.4 left marker-0.5:1.4:3.1 left lane-7.5:10.4:14.7 center marker-3.4:3.2:6.1 right lane-14.2:17.8:12.8 right marker-3.4:2.9:2.5 right edge-11.6:10.6:6.9 sky-42.2:27.9:39.2 other-16.4:21.9:6.3						
Cohen & Studach (1977) Exp. 1	on-road	rural, day/night not stated	n=9, mean age=23.5, >20k km driven, gender not stated	curve-right -left driver-experienced -inexperienced	eye movements -duration -horizontal amplitude	fixation duration and horizontal amplitude as a function of road	
Results:	**Fixation Durations** 0.41 sec.-experienced, left curve 0.32 sec.-experienced, right curve (sig) 0.46 sec.-inexperienced, left curve 0.52 sec.-inexperienced, right curve (not sig)			**Horizontal Amplitude** experienced-left > right curve inexperienced-not sig			
Exp. 2	on-road	type of road and day/night not stated	n=6, mean age=24, experienced and inexperienced gender not stated	road-right curve approach (2 sections)	fixation duration, fixation point on road -right, left, middle	# fixations and fixation duration as a function of road	
Results:	**Fixation Durations** road sections-sig subjects-sig		**# Fixations** nearer curve-right > left side farther from curve-not sig				

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Olson, Battle, & Aoki (1989)	on-road	rural: 1 mile long, straight-1/4 mile 3 90 deg turns, center line but no edge lines, day and night	n=6, males, 20-34 years	road-straight -right curves -left curves ambient illumination -day -night lead vehicle-yes, no	fixations-number -durations on 8 visual field features	% total time on features, % total fixations on features, and mean time/fixation as a function of road	far field>300 feet ahead, left edge, center, right edge are 100-300 feet ahead, ld=lead, nld=no lead d=day, n=night l=left, crv=curve

Results:

% Time	% Total Fixations	Fixation Duration (sec.)
•straight-lead(day/night):no lead(day/night)	•straight-lead(day/night):no lead(day/night)	•straight-lead(day/night):no lead(day/night)
left edge-9/13:12/2	left edge-14/6:15/8	left edge-0.4/0.72:0.55/0.4
center-13/8:28/81	center-18/13:24/53	center-0.4/0.75:0.73/2.1
right edge-10/5:11/8	right edge-14/15:16/16	right edge-0.45/0.43:0.44/0.58
lead car-54/81	lead car-37/52	lead car-0.9/1.95
far field-2/1:40/2	far field-2/1:25/2	far field-0.29/0.2:0.93/0.35
signs-1/2:3/6	signs-2/3:6/9	signs-0.29/0.43:0.3/0.6
inside-2/0:3/1	inside-2/0:3/1	inside-0.53/0:0.41/0.75
other-10/1:5/1	other-13/10:9/10	other-0.56/0.43:0.41/0.6
•right curve-ld(d/n):no ld(d/n):l.crv-ld:nld	•right curve-ld(d/n):no ld(d/n):l.crv-ld:nld	•right curve-lead(day/night):no lead(day/night):left curve-ld:nld
left edge-11/2:8/1:27/20:38/35	left edge-9/5:12/2:21/20:29/31	left edge-0.72/0.35:0.3/0.25:0.53/0.8:0.6/1.3
center-18/18:23/27:8/23:13/56	center-20/28:31/49:11/27:20/48	center-0.34/0.59:0.34/0.85:0.28/0.41:0.31/1.25
right edge-37/43:42/60:11/3:9/5	right edge-24/30:30/41:11/12:13/11	right edge-0.71/1.12:0.72/1.7:0.6/0.29:0.3/0.78
lead car-28/35:x/x:38/48:x/x	lead car-29/31:x/x:33/40:x/x	lead car-0.48/1.0:x/x:0.51/2.0:x/x
far field-5/2:19/2:10/0:30/3	far field-7/2:18/3:13/1:27/6	far field-0.3/0.66:0.49/0.49:0.33/0.2:0.53/0.63
signs-2/0:3/2:1/1:2/1	signs-2/1:4/2:3/2:4/1	signs-0.37/0.29:0.3/0.34:0.23/0.34:0.34/0.3
inside-0/0:1/0:0/0:1/0	inside-1/2:2/1:0/0:1/0	inside-0.28/0:0.28/0:0.37/0:0.29/0
other-5/1:2/1:6/1:5/1	other-10/2:4/1:10/1:8/3	other-0.35/0.25:0.35/0.59:0.5/0.37:0.46/0.21

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Rackoff (1974)	on-road	freeway, normal speed, day and night	young: n=9, 21-29 years, 5-13 years drive experience, 13k avg annual mileage old: n=8, 60-70 years, 46-60 years drive experience, 14k avg annual mileage	ambient illumination -day -night driving condition -open road -car following -light traffic age-young -old	fine eye movements -fixation time -travel distance -concentration index -mean time per area -% trial time in scene ahead -time per look in scene ahead -% time away from scene ahead (not out-of-view) -looks away from scene ahead -time per look away from scene ahead (not out-of-view) -activity index	large eye movements -% trial time at speedo -time per look at speedo -look rate at speedo -% trial time looking at outside mirror -time per look at outside mirror -look rate at outside mirror -% trial time looking at inside mirror -time per look at inside mirror -look rate at inside mirror -% total time out-of-view t-tests	concentration index-% in view time in 3 degree x 3 degree most populous area, activity index-(mean travel distance x # trials)/trial time, look rate-# looks/trial time, measures were sensitive to the experimental conditions, measures were significantly influenced by independent variables, fixation time-consecutive fixations separated by at least one visual degree, unit for time is seconds, deg=degree
Results:	**Fixation Time (old:young)** (mean, standard deviation) day, light traffic-1.52:1.61,1.44:1.60 day, car following-2.41:3.97,2.15:3.53 night, light traffic-1.89:1.97,1.86:1.80 night, car following-1.99:5.12,1.82:2.57 **Travel Distance (deg) (old:young)** (mean, standard deviation) day, light traffic-4.32:4.31,2.64:2.61 day, car following-3.63:2.32,1.69:1.02 night, light traffic-3.94:3.26,2.16:1.38 night, car following-3.72:3.41,2.52:1.39 **Std. Dev. Look Time Away from Scene Ahead (old:young)** day, light traffic-0.62:1.34 day, car following-0.93:0.69 night, light traffic-1.46:0.74 night, car following-0.74:1.54 **Activity Index (old:young)** day, light traffic-2.29:2.22 day, car following-1.21:1.01 night, light traffic-2.15:1.54 night, car following-2.43:1.02			**Concentration Index (old:young)** day, light traffic-74.7:70.5 day, car following-75.9:85.8 night, light traffic-65.6:69.8 night, car following-73.0:77.5 **Mean Time/Area (old:young)** day, light traffic-1.90:1.99 day, car following-2.14:1.52 night, light traffic-2.61:2.09 night, car following-3.08:2.50 **% Time to Scene Ahead (old:young)** day, light traffic-77.8:71.6 day, car following-78.4:84.5 night, light traffic-72.8:66.0 night, car following-79.2:81.8 **Mean Time per In-View Look Away from Scene Ahead (old:young)** day, light traffic-0.57:1.02 day, car following-1.00:0.91 night, light traffic-1.15:1.15 night, car following-0.74:1.29		**Speedo-day, light traffic (old:young)** % time-3.41:4.50 mean time/look-1.20:0.91 std. dev. time-0.37:0.36 look rate-2.0:3.0 **Side Mirror-day, light traffic (old:young)** % time-1.3:3.27 mean time/look-1.27:1.03 # looks/minute-0.57:1.92 **Rear Mirror-day, light traffic (old:young)** % time-0.0:1.80 look rate-0.0:1.00 **% time out-of-view (old:young)** 8.00:14.95 (including blinks) **Time Ahead (old:young)** (mean, standard deviation) day, light traffic-3.17:3.11,2.88:2.58 day, car following-5.31:10.12,5.19:3.42 night, light traffic-4.58:3.29,4.24:2.46 night, car following-4.71:10.27,4.21:4.75 **% Time In-View Away from Scene Ahead (old:young)** day, light traffic-11.1:18.1 day, car following-12.7:8.9	night, light traffic-20.5:24.7 night, car following-16.3:17.2

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Rackoff & Mourant (1979)	on-road	freeway, day and night	young: n=10, 21-29 years, 5-13 years drive experience old: n=13, 60-70 years, 46-60 years drive experience both avg 13-14 thousand km/yr	age-old -young driving condition -open road -car following ambient illumination -day -night	eye movements -voluntary occlusion -mean travel distance velocity		older drivers made longer eye travels than young for day car following condition, older drivers had larger std. dev. of eye travels than young for all driving tasks except day open driving condition, older drivers had longer eye open time than young for all driving tasks, older drivers had larger std. dev. than young for night tasks
Results:	**Mean Eye Travel Distance (degrees)** (day(young:old),night(young:old)) open-4.3:4.3,3.3:3.9 car fol-2.3:3.6,3.4:3.7 **Standard Deviation Eye Travel Distance (degrees)** open-2.6:2.6,1.4:2.2 car fol-1.0:1.7,1.4:2.5				**Mean Eye Open Duration (sec.)** (day(young:old),night(young:old)) open-0.7:1.6,1.4:2.5 car fol-0.7:2.0,1.6:3.5 **Standard Deviation Eye Open Duration (sec.)** open-0.4:0.9,1.1:2.0 car fol-0.5:1.2,1.2:2.6		
Rackoff & Rockwell (1975)	on-road	4-lane divided rural freeway without illumination, 4-lane urban freeway with illumination, rural 2-lane road, day and night	n=4, male, in college	road -4-lane divided rural freeway without illumination, -4-lane urban freeway with illumination, -rural 2-lane road ambient illumination -day -night	eye movements -mean horizontal and vertical location -mean travel distance -CI=concentration index, time spent in most populous 3 x 3 degree grid square -% time to objects -mean time per look		eye movement pattern shifted down and to left from day to night by about one visual degree, eye movements more spatially disperse at night than day on unlighted freeway, road right-right edge line and right road surface in front of driver, road left-left edge line and left road surface in front of driver
Results:	**% Time (day:night)** (freeway without illumination,freeway with illumination,rural road) road right-0.3:7.7,9.6:15.4,17.2:5.9 road left-1.1:37.8,16.1:20.2,10.3:4.6 scenery right-2.4:0.3,2.8:3.7,7.2:1.2 scenery left-3.2:8.3,11.8:0,0.8:1.7 straight ahead-92.6:42.7,57.5:60.7,64:83 sky-0.4:3.3,2.1:0,0.2:3.6 oncoming headlights-0:16,0:0.8,x:x						

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Rockwell, Ernst, & Rulon (1970)	on-road	rural: 2-lane, 22 feet wide, no edge lines, straight section and S curve are 0.3 miles, left turn-34 deg, right trn-37 deg 4-lane divided highway: unlighted, straight, 0.8 miles, edge lines, day and night	n=2, nothing else stated	road-straight -S curve speed-40 mph -60 mph time-day -night	eye movements	% time as a function of all independent variables, % time in transit as a function of all independent variables	considerable variability in drivers' eye movements from one replication to the next, individual drivers exhibit different visual patterns on same highway, c=close, greater than 75 feet in front of vehicle, f=far, 75-250 feet in front of vehicle, road=greater than 250 feet in front of vehicle, s1=subject 1, s2=subject 2

Results:	**% Time (subject 1:subject 2)**	**% Time in transit (subject 1:subject 2)**	**% Time in transit (s1:s2)**	**% Time (s1:s2)**
	•rural straight-day/night	•rural straight-day/night	•4-lane highway-day/night	•4-lane highway-day/night
	1. c. left edge-0:0/0:0	(2-3)-0:0/0:0	(2-3)-0:0/0:.95	c. left edge-0:0/0:0
	2. c. center line-0:0/0:.25	(2-5)-0:0/0:.25	(2-5)-0:0/0:.3	c. center line-0:0/0:5.3
	3. c. right edge-0:0/2:0	(2-6)-0:0/0:0	(2-6)-0:0/0:.1	c. right edge-0:0/0:12.7
	4. f. left edge-.65:0/0:0	(3-4)-0:0/0:0	(3-4)-0:0/0:.1	f. left edge-0:2.7/.15:.15
	5. f. center line-9.05:1.3/0.4:2.38	(3-5)-0:0/0:0	(3-5)-0:0/0:.7	f. center line-0:.35/4.8:13.9
	6. f. right edge-12.9:17.35/61.6:37.5	(3-6)-0:0/2.5:0	(3-6)-0:0/0:.4	f.rghtedge-1.2:0.35/10.15:18.2
	7. road-71.05:60.75/5.7:53	(4-5)-0.2:0/0:0	(4-5)-0.2:0/.08:0	road-79.3:23.5/20.2:34
	other-6.35:20.5/29.4:6.9	(4-6)-0:0/0:0	(4-6)-0:0/0:0	other-19.45:73.05/65:15.75
	•rural S curve-day/night	(4-7)-0:0/0:0	(4-7)-0:.85/.08:0	**% Time (40mph:60mph)**
	c. left edge-0:0/0:0	(5-6)0.2:0.25/0:0.25	(5-6)0:.1/.5:1.1	•4-lane highway-day/night
	c. center line-0:0/0:.0	(5-7)-2.4:0.5/0:.7	(5-7)-0:0.1/.6:.2	c. left edge-0:0/0:0
	c. right edge-0:4.55/.9:.8	(6-7)-3.65:3.55/0:2.65	(6-7)-.65:.25/.3:.95	c center line-0:0/8:.0
	f. left edge-10:0/.15:2.55	out<=>in-10.05:12.5/13.5:7.55	out<=>in-9.1:5.3/9.9:10.85	c. right edge-0:0/4.5:0
	f. center line-3.2:0/.25:8.5	•rural S curve-day/night	**% Time in Transit (40:60)**	f. left edge-0:5/0:0
	f. right edge-11.95:3.6/35.2:16.15	(2-3)-0:0/0:0	•4-lane highway-day/night	f. center line-0:0/6.7:0
	road-29.8:9.85/24.65:45.75	(2-5)-0:0/0:0	(2-3)-0:0/.4:0	f. right edge-0:0/60.8:21.7
	other-42.9:8.2/36.6:26.25	(2-6)-0:0/0:0	(2-5)-0:0/.6:0	road-0:63.1/0:41.6
		(3-4)-0:0/0:0	(2-6)-0:0/1.1:0	other-100:31.9/20:36.7
		(3-5)-0:0/0:0	(3-4)-0:0/0:0	
		(3-6)-0:.15/.65:.15	(3-5)-0:0/.4:0	
		(4-5)-.65:0/.15:.15	(3-6)-0:0/1.3:0	
		(4-6)-.15:0/0:0	(4-5)-0:0/0:0	
		(4-7)-.25:0/0:.45 (5-7)-.25:0/.4:2.7	(4-6)-0:0/0:0	(5-7)-0:0/0:0
		(5-6)-.4:0/.25:.25 (6-7)-1.45:0/2.2:2.0	(4-7)-0:1.8/0:0	(6-7)-0:0/0:1.7
		out<=>in-10.05:4.95/11.55:11.15	(5-6)0:0/.2:0	out<=>in-0:8.1/10.3:6.8

Partial Summary of Eye Movement Research

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Shinar, McDowell, & Rockwell (1977)	on-road	rural: 2-lane, hilly, 34 km, 22 curves-3 high accident and 11 no accident, curves .05-.13 km long and 5-19 degrees, day/night not stated	n=5, 3 male, 2 female	road-straight -curve curve zone -approach -curve curve direction -right -left accident rate -high -low	eye movements -fixation duration -travel distance between successive fixations -fixation location concentration index times -fixations on objects in visual field -blinking -mirror looking	ANOVA	results provide empirical support for theoretical arguments of Gordon (1966) and Fry (1968), straight rd-drivers concentrate on focus of expansion, curve road-drivers concentrate on road ahead and road edge, curve negotiation starts well in advance of the curve, concentration index-fixation time in 3 degree square area of highest fixation density divided by total fixation time

Results:

Fixation Durations	**% of Time**	**% Time on Speedo (sig)**
•sig-high accident v no accident curves	•approach zone	6.7%-straight
0.48 sec. v 0.39 sec.	23%-road	3%-curve
•sig-curves & approach v straight	23%-scenery	**% Time- Rear Mirror (sig)**
0.41 sec. v 0.60 sec.	•curve zone (sig)	3.7%-straight
•right:left (sec.)	27%-scenery	2%-curve
approach, high accident-0.17:0.49	23%-road	
approach, low accident-0.17:0.23	•right v left curve (sig)	
curve, high accident-0.40:0.28	road-55% v 38%	
curve, low accident-0.19:0.27	opposite road,scenery-5% v 24%	
Fixation Locations	**Blink % of Time**	
•right v left curve (sig)	•straight v approach & curve (sig)	
3.6 degrees to right v 0.3 degrees to left	4.1% v 1.8 %	
•approach zone	**Travel Distance Between Fixations**	
1.7 degrees to right, 1.2 degrees above	•approach & curve v straight (sig)	
focus of expansion (foe)	3.1 degrees v 2.6 degrees	
•straight	**Concentration Index (sig)**	
1.6 degrees to right, 0.7 degrees above foe	0.62 v 0.27 (straight v curve & approach)	

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Zwahlen (1982)	on-road	rural: 2-lane, hilly, 8 miles, 7 curved and 3 straight sections, day and night	n=2 (day), n=1(night), nothing else stated	road-straight -right curves -left curves curve zone -approach -curve -leave radius of curve ambient illumination -day -night	eye movements -fixation duration -# fixations	x-y eye fixation density maps, spatial and temporal scanning summary measures as a function of curve and ambient illumination, x-y center of gravity for fixation for curve zone, % total time, % total fixations as a function of conditions	curve approach and negotiation is demanding, night-short foveal preview distance and short preview times, roadway geometry influences fixation x-y centers of gravity and dispersions
Results:	**Fixations/100 feet** curve-3.56 straight-2.21 **Fixation Locations** right curve-right edge line left curve-center line, left edge line **Fixation Durations (sec.)** night-0.46 day-0.39			•x-y center of gravity-eye scanning behavior influenced by curve 300-400 feet before curve begins •fixation patterns-night more concentrated on road ahead than during day			