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16. Abstract

This report describes an investigation of driver eye patterns on straight and curved rural roads. Eight participants (four under 30 years, four over 60 years) drove on a 4.6 mile, two-lane road while wearing an eye mark camera to record eye fixations. While data was collected for the entire route, only four road sections were of interest (one straight section and three left curves (3, 13 and 21 degrees)). In addition to eye fixation data, driving performance measures (speed and lane deviation) were recorded. Analysis of the results indicates that fixations to oncoming cars on the 3 degree curve (103 msec) were shorter than fixations to oncoming cars on the other two curves (588 msec) and the straight section (541 msec). On the straight section, there were more fixations to the far field (59 percent) than on the three curves (3 degree--18 percent; 13 degree--37 percent; 21 degree--28 percent). The probability of fixating on road features also varied with road curvature. On the straight section, the probability of fixating on the far field is 40 percent, whereas on curves it ranges from 10 percent (3 degree curve) to 28 percent (13 degree curve). On curves, the driver is more likely to distribute his/her eye fixations more evenly over the road features. From the driving data, there were no indications of excessive lane deviation or speed. The data from this study will be entered into a simulation model that will describe driver eye fixation patterns, and the model will be validated. The ultimate goal of the simulation 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.

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PREFACE

An on-road study examining eye patterns on straight versus curved roads is currently in progress. Thus far, data for eight participants have been collected and partially analyzed. In addition, a simulation model has been developed to predict driver eye patterns. Data from the on-road study will be entered into the model. In the future, this model can be used to predict fixation patterns rather than collect data on the road.

This report summarizes the data collected for eight participants. It does not include transition probability data or a description of the modeling process. That work is currently in progress.

The work planned for the next year is to complete the on-road study and analyze data for a total of 32 drivers, and to start work on a model validation experiment.

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INTRODUCTION

Driving is primarily a visual task, yet in an engineering sense what people do is not exactly understood. Of particular importance are the perceptual cues used to safely maneuver a vehicle. Under development are many types of new in-vehicle displays (touch screen CRTs for radio and climate control, traffic monitoring systems, etc.). These displays may force the driver's visual attention away from the road for a longer period of time than do traditional displays. Before drivers' eye fixation behavior with advanced displays can be understood, however, there needs to be some baseline data that describes driver eye patterns under "plain old driving" conditions.

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. Of the studies at hand, most of the data are not comparable to each other due to different driver and/or road characteristics or different definitions of road features. Thus, individual research efforts provide limited data and a conglomeration of the data to describe "the big picture" is impossible due to the inconsistencies among the studies.

It is the intent of this research project to start to draw the big picture. Driver eye fixation patterns on straight and curved rural roads will be described in order to provide baseline data of visual behavior in the driving task. Further, the data will be entered into a simulation model that will describe driver eye fixation patterns and the model will be validated.

The model will be developed through the use of data collected as part of this research. Specific data that will be incorporated into the 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 eye fixations?

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

3. How does age affect these patterns?

4. How well does the fixation model describe actual driving behavior?

The ultimate goal of the simulation 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 MOVEMENT LITERATURE

Driver eye movement patterns have been investigated by many researchers in several different situations (see Table 1). While some studies report eye patterns on straight and curved, rural, two-lane roads, others report eye movements on interstate highways. Some investigate situations where the driver follows a lead vehicle, whereas others investigate no traffic situations. 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 observed by several researchers (see Table 1). These researchers have examined drivers' time fixating on different features of the road (right edge, left edge, center line, etc.), percent fixations on features of the road, duration of eye fixations, number of eye 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 movements 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 movements of nine students (mean age of 23.5 years), each with more than 20,000 kilometers of driving experience. Eye movements 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 car. 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 movements 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 eye movement patterns

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 (1970) 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 (1970) 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	Rackoff and Rockwell (1975)

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 movements 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 nonaccident 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 movement data on a rural, hilly, two-lane 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.

Fixations on Straight Rural Roads During the Day

Percent Fixations

For driving on straight roads during the day, approximately 55 percent of eye fixations are on the road (Blaauw, 1975; Olson et al., 1989). Percent fixations for different road features are shown in Figure 1. Olson et al. report that 24 percent of the fixations were to the center line of the road and that approximately 30 percent were directed equally to the right and left edges of the road. Blaauw found a more varied eye 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, most of the eye fixations on the road were 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 were to the road edges (right edge--2.5 percent and left edge--3.1 percent).

The differences in the data of Olson et al. and Blaauw could be due to the following: (1) Olson et al.'s higher percentages for the center line and road edges may be due to their definition of fixation (one or more fixations within a certain area), (2) Blaauw's lower percentage of fixations to road edges could be due to his road type: the crash barriers may have been so obvious that drivers could see them in the periphery and did not actually have to look at them, (3) Blaauw and Olson et al. studied different types of roads (Blaauw used one-way roads, while Olson et al. used two-way roads), and (4) Blaauw only reported fixations greater than 100 milliseconds.

Percent Time

Olson et al. report that drivers spent a significant portion of their time fixating on the far field (40 percent). (See Figure 1.) Drivers spent slightly more time (51 percent) fixating on road features 100 to 300 feet in front of the car: center line--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 (1989). According to the Rockwell et al. data, approximately 66 percent of the time 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

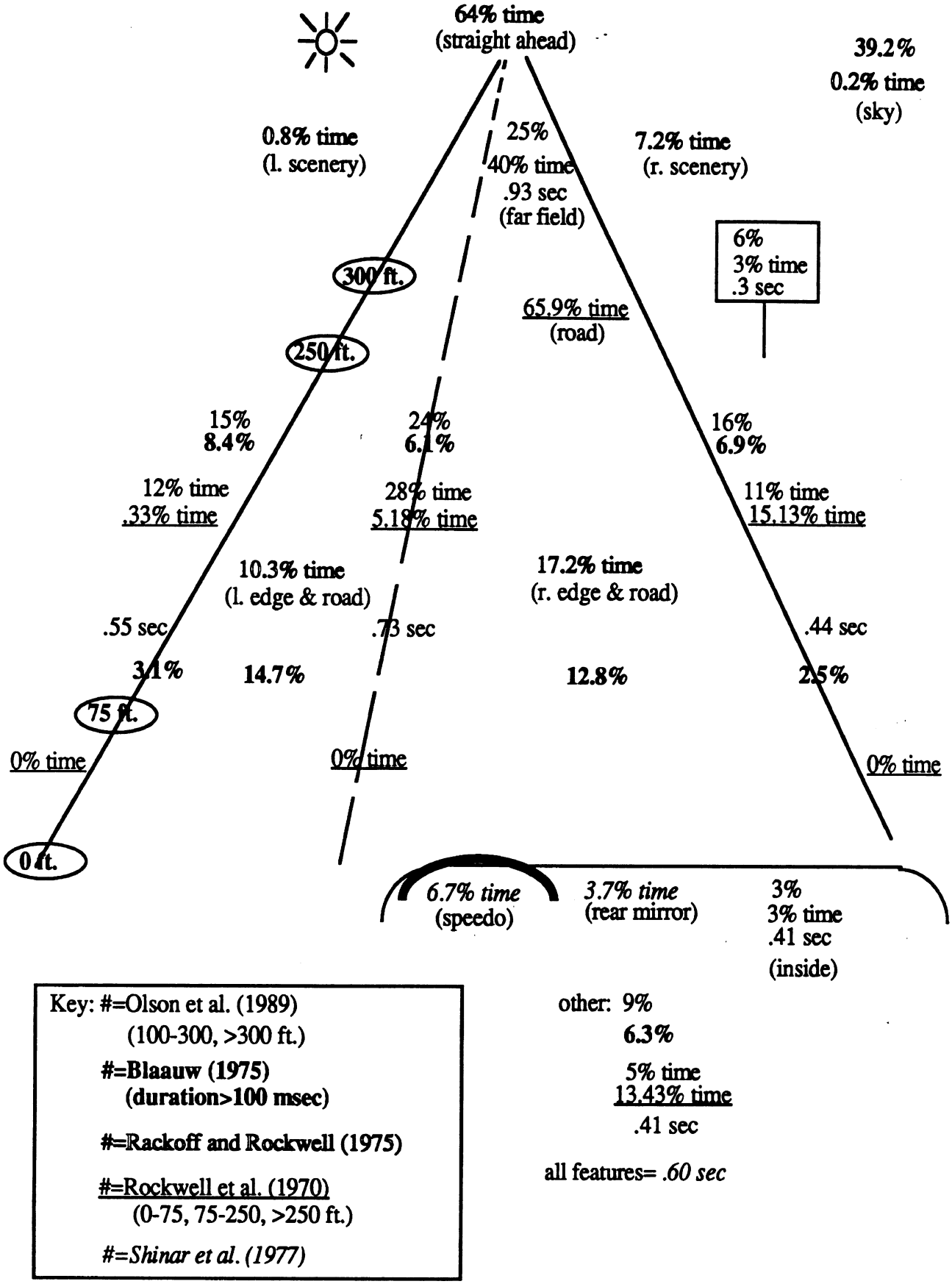


Figure 1. Fixations on a straight, rural road during the day

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

One explanation 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 to 300 feet in front of the car, which might make their 66 percent figure more comparable to Olson et al.'s 51 percent between 100 to 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 were to the far field (0.93 seconds) and center of the road (0.73 seconds) while shorter fixations were to the left and right edges (0.55 seconds and 0.44 seconds, respectively). Short fixations were 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 were 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 have to. 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

Percent Fixations

On right curves, Olson et al. report that drivers direct most of their fixations at the center line (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 of the road (29 percent fixations) more than the center line (20 percent fixations) and 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 side, center line, and right side of the road, respectively. Blaauw also reports 1 percent of fixations to be to the left road edge line, 3.2 percent to the right road edge, 9 percent to the left lane, and 16 percent to the right lane. Thus, Blaauw's subjects clearly 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

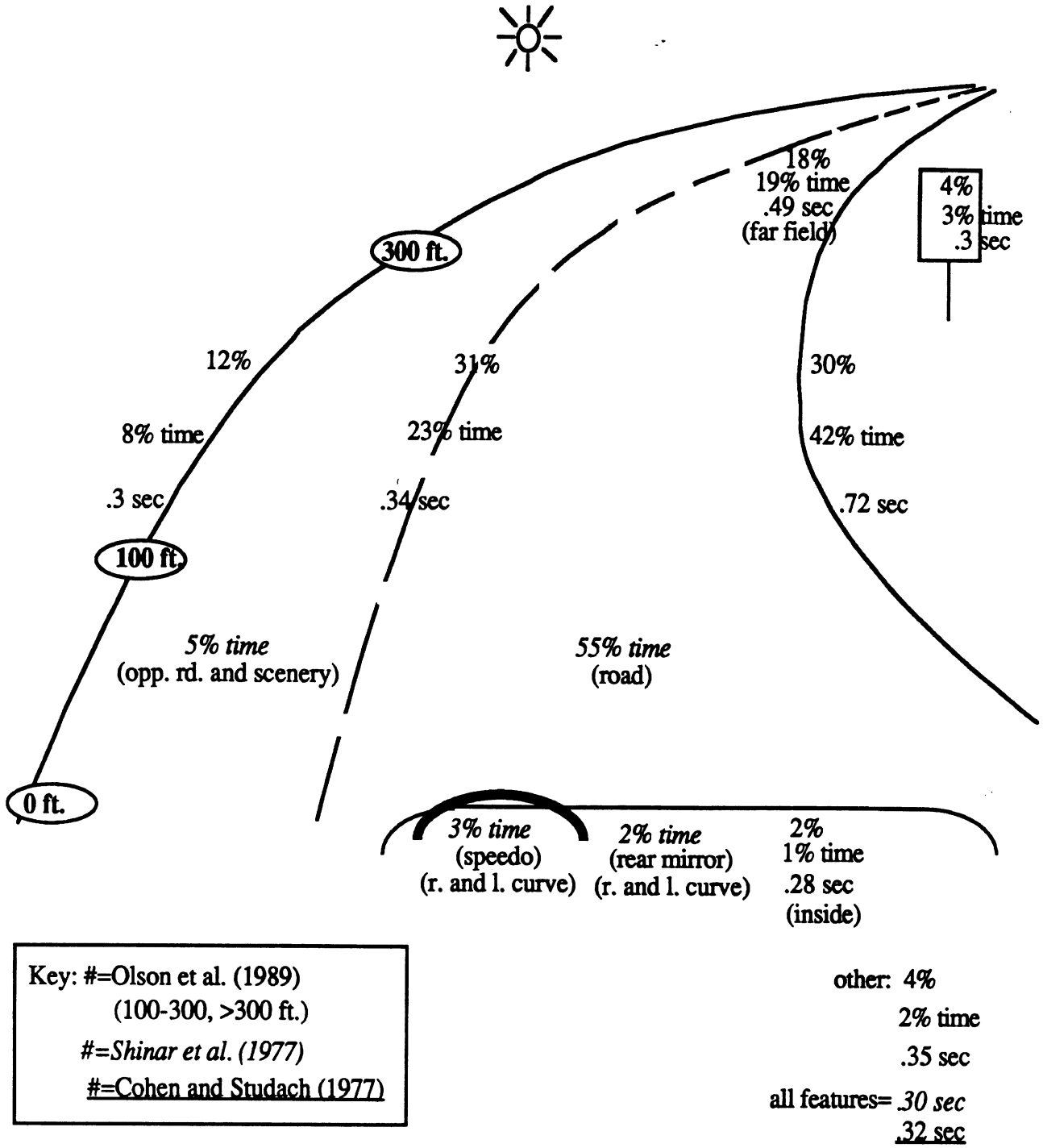
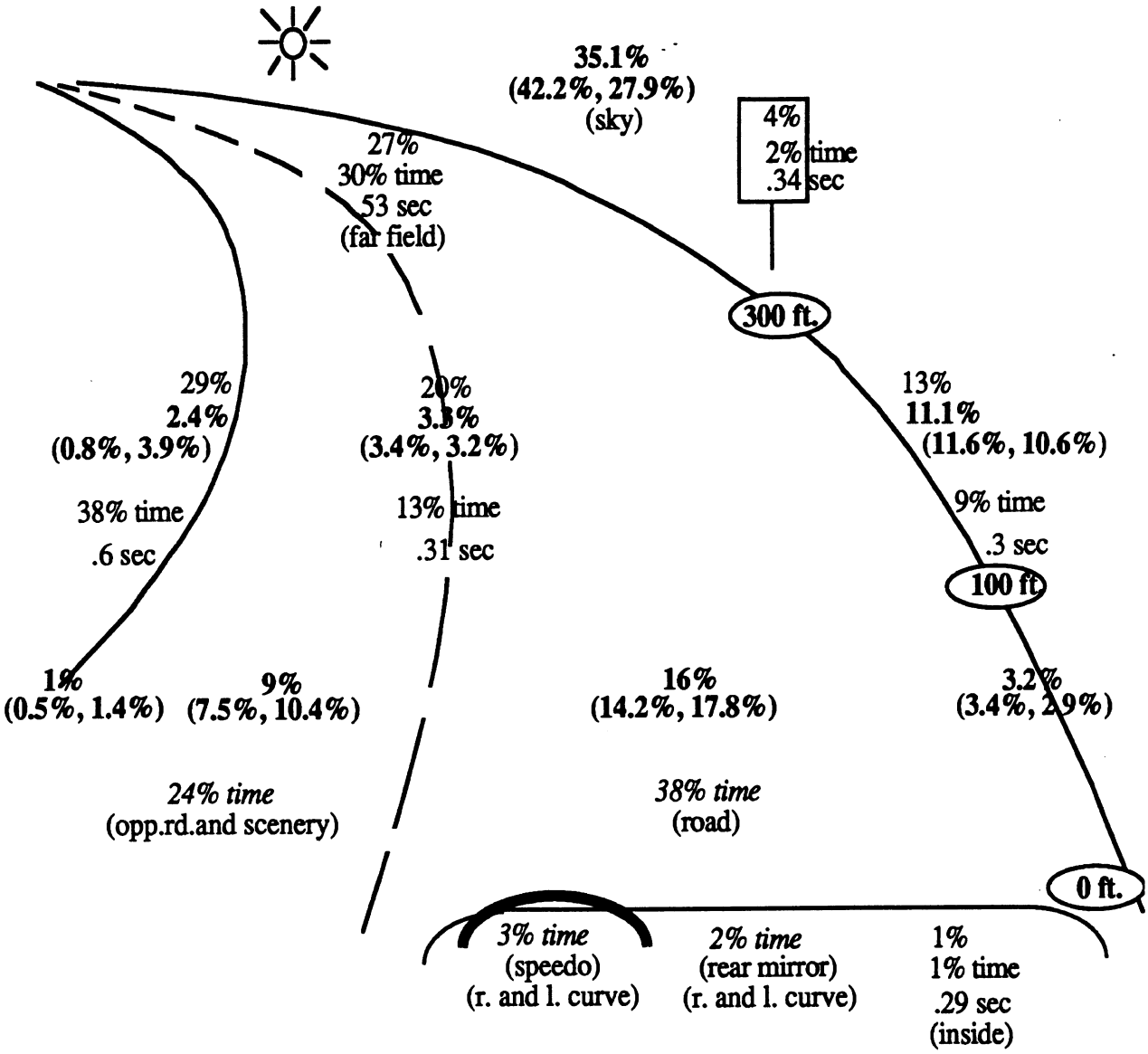


Figure 2. Fixations on a right curved, rural road during the day



Key: #=Olson et al. (1989)
(100-300, >300 ft.)
#=Blaauw (1975)
(duration>100 msec)
average
(R=83.6, R=95.0)
#=Shinar et al. (1977)
#=Cohen and Studach (1977)

other: 8%
19.2%
5% time
.46 sec

all features= *.28 sec*
.41 sec

Figure 3. Fixations on a left curved, rural road during the day

according to Blaauw and 27 percent of 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 percent fixations to different road features for the two curve types 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 and center line. 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.

Percent Time

On right curves, Shinar et al. found that drivers look at the right lane 55 percent of the time and the opposite road and 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 opposite road and scenery. Olson et al., however, report slightly more time being spent fixating on the road--42 percent of the time to the right edge and 23 percent of the time to the center line. They report that drivers also look at the far field 19 percent of the time.

Drivers spend over a third of the time (38 percent) looking at the right lane but only a quarter of the time (24 percent) on the left lane and scenery to the left side of the road on left curves (Shinar et al., 1977). Olson et al.'s data contradicts this somewhat. They report that drivers look at the left road edge 38 percent of the time and the right lane 24 percent of the time at the most (if one considers looking at the center line (13 percent time) and the right edge (9 percent time) part of the right lane). According to Olson et al., drivers spend a third of their time (30 percent) looking at the far field.

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 line (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.

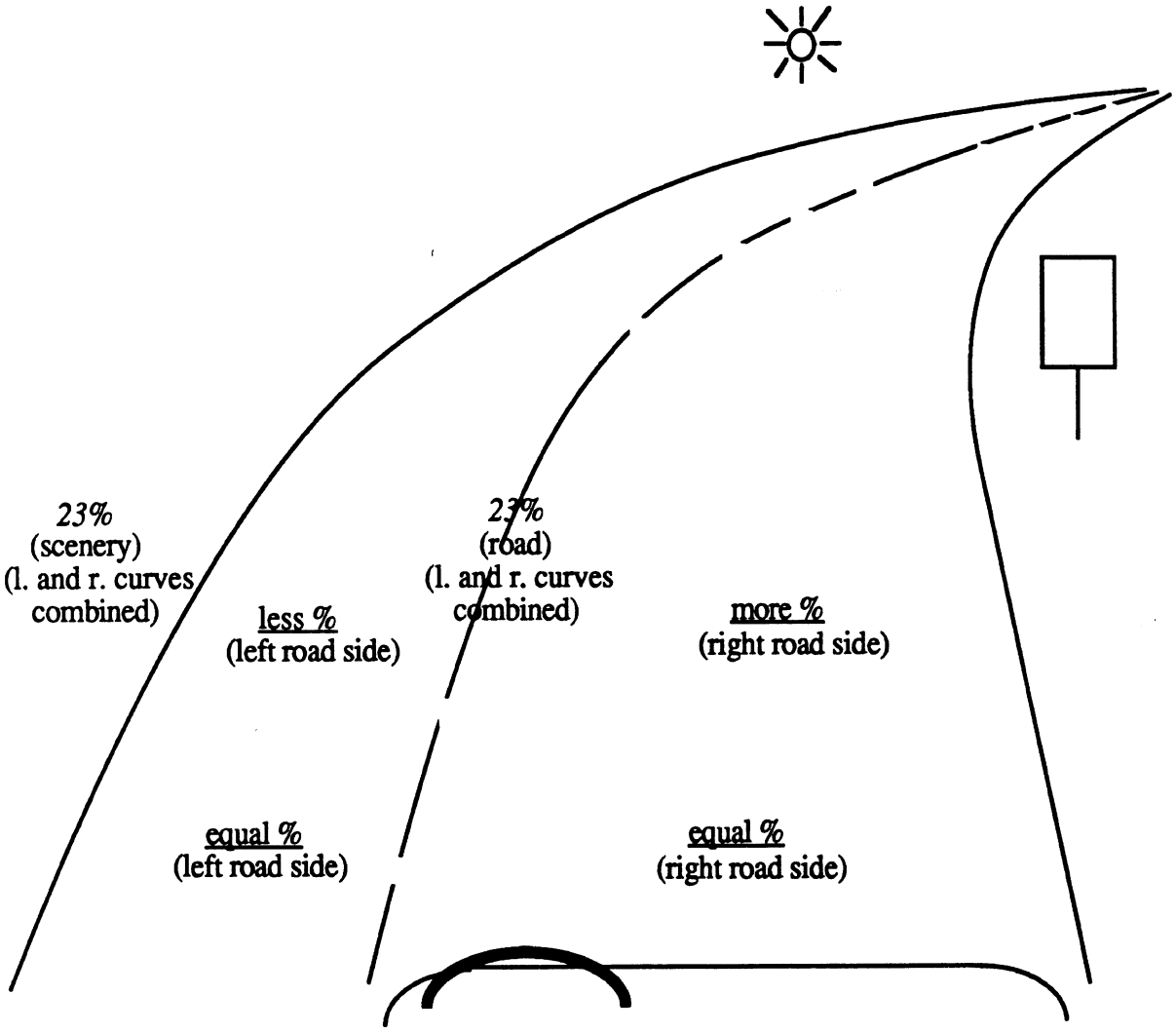
On left curves, drivers looked the longest at the left edge (0.6 seconds) and the far field (0.53 seconds), and the same amount of time at the center line (0.31 seconds) and the right road edge (0.3 seconds) (Olson et al., 1989). Cohen and Studach found average fixation durations to be 0.41 seconds while 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 2 percent of the time) and short (approximately 0.30 seconds) (Olson et al, 1989). Drivers glanced 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.



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

all features= *.17 sec*

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

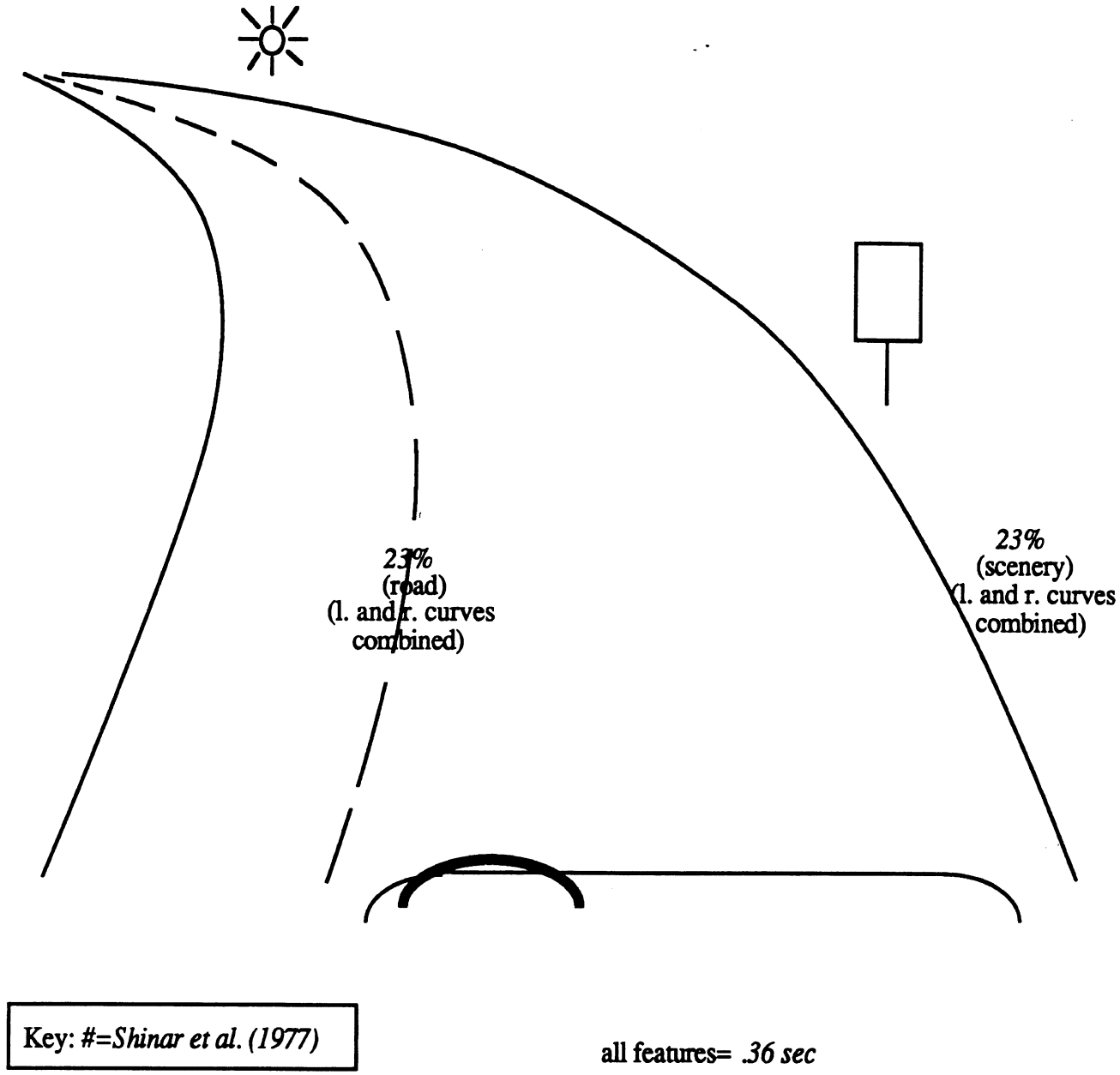


Figure 5. Fixations on a left approach zone during the day

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 line, lanes, and road edges (Blaauw, 1975; Olson et al., 1989). Fixation durations average 0.59 seconds with longer fixations to the far field (0.93 seconds) and road center (0.73 seconds) and

shorter fixations to the road edges (right--0.44 seconds, left--0.55 seconds) and inside the vehicle (0.41 seconds) (Olson et al., 1989; Shinar et al., 1977).

On right and left curve approaches, 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; 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 (43 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 ambiguous. Olson et al. report more fixations to the left side of the road but Blaauw found more fixations to the right side. On right curves, drivers spend more time looking at the right side of the road (55 to 65 percent) than the left side (8 percent), but on left curves they spend equal time on both sides of the road (24 to 38 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--0.3-0.47 seconds; left--0.28-0.44 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 longest fixations are to the left edge (0.6 seconds) (Olson et al., 1989).

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. On both straight and curved roads, drivers spend approximately the same amount of time looking at the road.

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 movement 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 referred to. 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 younger drivers for 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 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 for the light traffic condition, whereas younger drivers spent more time looking ahead while car-following.

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

	Mean Percent Time	
Driving Condition	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 Scene Ahead

Older drivers had significantly shorter durations of fixations 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 scene ahead (Rackoff, 1974)

	Mean Time (sec)	
Driving Condition	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. Percent time away from scene ahead (Rackoff, 1974)

	Mean Percent Time	
Driving Condition	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 versus 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 versus 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: percent time and number of looks per minute. 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 movement 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 movements 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 road 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 discussed 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:

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

where $H \cdot D[1-e^{-(V/D+1/F)T_d}]$ = 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 which 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 a different viewing time (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 is given, 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 is shown in Table 9.

Values of model parameters were obtained for the drivers. The drivers' criterion levels, U_c, are shown in Table 10. U_c varied as viewing time increased: subject one accumulated more uncertainty as viewing time increased, subject three less uncertainty, and 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 given 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 is 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)

	Occlusion Time (sec)			
Speed	Subject			
(mph)	1	2	3	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 what 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 movements 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 varying degrees 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 is 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} is the inverse radius of curvature,
and R^{-1}max is the maximum value across the experiment.

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

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

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

Lane Width: $C = 40\ S_0 + 100$

where S_0 is the distance of the closest obstruction (telephone pole, ditch, etc.) to the road in meters.

If $S_0 > 2.5$m, then C was set equal to 0.

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

where R_w is 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,

$$Y = 14.8 + 43 X$$

where X = percent workload tracking 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 $T = 61 + 0.48X$. 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 Movement 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

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

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

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 percent 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 m 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 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 movement behavior. In describing eye movement 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
D_I is not defined by Cohen and Hirsig

∂_I = the center of the sector
I = the sector of the visual field
DS = the sum of all weighted factors and is defined as

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

where P_I is 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 was 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 movement 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 to 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. Models of driver eye movement 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 looked at 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, what the relationship is.

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 up the road 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 movements 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 was studied to provide baseline data for the driving task. Subsequently, this data will be entered into a simulation model that will describe driver eye fixation patterns, and the model will be validated.

EXPERIMENT PROTOCOL

An on-road experiment examining eye patterns on straight versus curved roads was performed. The experiment involved 15 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 between road features (e.g., right edge marker, left edge marker, center line), car mirrors, and in-vehicle eye fixations?
2. What is the relationship between degree of curvature and the distribution of driver eye fixations?
3. How does age affect these patterns?

Experiment Design

The experiment design is a 4 x 2 x 2 mixed factorial. (See Figure 6.) Road curvature (four levels--straight, 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 data and driving performance. Eye fixation data collected included eye fixation location (feature) and duration. Driving performance measures were lane deviation and speed.

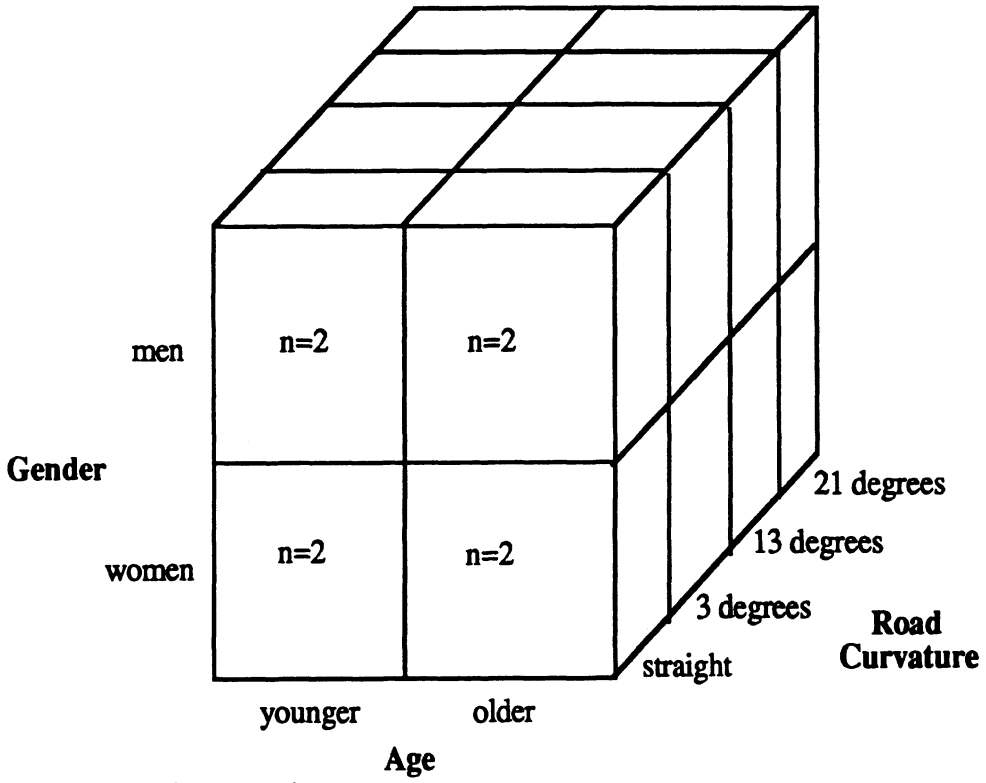


Figure 6. Experiment design

Test Participants

A total of eight licensed drivers participated in this experiment. As indicated in Figure 6, participants were divided into younger (ages 23 to 28, mean=25 years) and older (ages 61 to 71, mean=65 years) age groups, with an equal number of men and women in each group. While 15 drivers were tested initially, only data from eight participants could be analyzed due to equipment and calibration problems. Participants were recruited from the university community or had served in previous University of Michigan Transportation Research Institute (UMTRI) studies.

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

Road Selection

The road used was a rural, two-lane road with a center dividing line. The section driven on was 4.6 miles long and had 15 curves ranging from 1 degree 30 minutes to 21 degrees in curvature (based on measurements from the Washtenaw County Road Commission). One straight section and three left curves (3 degrees, 13 degrees, and 21 degrees) were examined in detail. Figure 7 shows the road and the sections of interest. Three left curves (3 degrees, 13 degrees, and 21 degrees) were selected due to their range of curvature. The straight section was selected because it is flat and the sight distance is large.

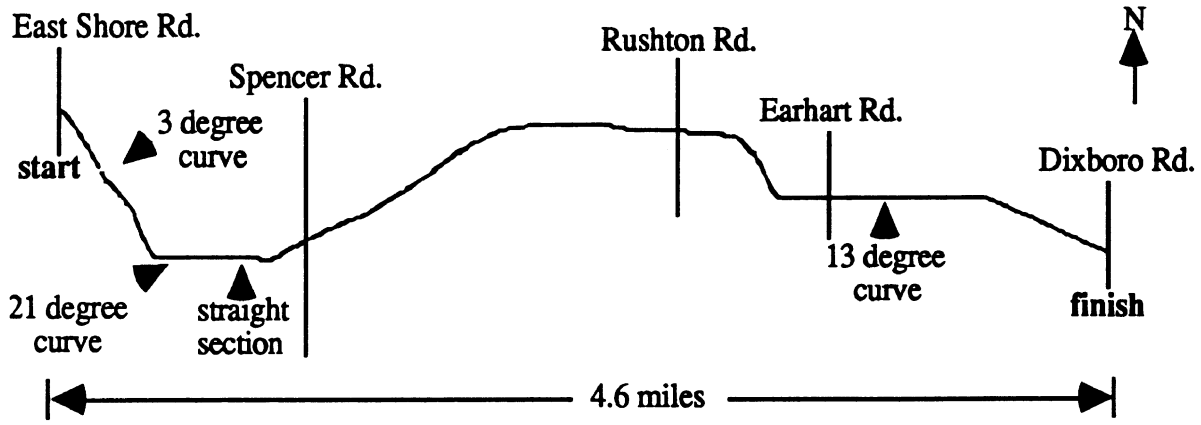


Figure 7. Road section used for data collection

Characteristics of the road segments are shown in Table 13. Confounded with radius of curvature were lane width, length of curve, and posted speed. Lane widths among the road sections varied by approximately 2 feet. The length of the curves varied from 550 feet to 840 feet. Only the curve, per se, was examined, not the approach or exit zones. The length of the straight section of road was close to the curve lengths. The curves were driven at the posted speed. (The posted speed on the road was 50 miles per hour; none of the curves was posted for a reduced speed limit.)

Table 13. Road segment characteristics

	Road Segment			
	Curve 1	Curve 2	Curve 3	Straight
Curvature (degrees)	3	21	13	0
Lane width	11'	9'11"	10'2"	10'1"
Length	550'	840'	600'	660'

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 movements. 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. The eye spot is represented as a square on the videotaped road scene.

Equipment for Collection of Driving Performance Measures

Lane position was recorded using a custom-made lane tracker. The lane tracker consists of a small video camera housed in the left side mirror of the vehicle. The camera points down and forward providing a view of the left lane marker of the road. Computer software detects the lane markings in every third frame and stores the lane deviation measurement to the nearest inch at a rate of 10 Hz.

Speed was determined by the engine and transmission controller, which uses a sensor that pulses every quarter turn of the left front wheel.

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. Subjects 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 camera was fitted on the subject and calibration was performed. Finally, the subject drove on the 10-mile test route with the eye mark camera. Data were collected for the entire route, but analyzed only for the road segments of interest. At the end of the route, the eye camera was removed from the driver's head and the subject drove back to UMTRI. The experiment concluded with an assessment of far visual acuity and a postexperimental interview. In the interview, the subject reviewed the videotape and explained any reasons for looking at certain features of the road or the car.

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.

Each session lasted 1.5 to 2 hours.

RESULTS

Data Reduction

To ensure that the data examined were the same for each subject, the experimenter used landmarks on the side of the road (mailboxes, posted signs, etc.) to define each road segment of interest. These landmarks were clearly visible on the videotape.

Software for Data Reduction

Eye fixation data from the videotapes were reduced using a computer program in HyperCard. The analyzer first defines the tape sections to be analyzed. (In this case, the four road sections.) Then, the analyzer goes through frame-by-frame and notes the fixation location of the eye spot. At the end of this analysis, a listing of the frame numbers and the fixation locations is provided. A second HyperCard program converts this data into fixation locations and *durations*. Output from this program lists, 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 sorts the previous output file and, in columnar format, displays 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 are 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 spot.

Definition of an Eye Fixation

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

1. Spatial travel distance was greater than 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 road features were identified after examination of the data. These included features on the road (left edge, right edge, center line, right lane, and left lane), in the vehicle (instrument panel and left mirror), and in the environment (oncoming car, far field, left far field, right 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 occuring objects such as pedestrians and wild 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 8 and 9, respectively. For the straight section, the categories, right far field and left far field, are not applicable. Fixations were either to the far field, which was defined as the

focus of expansion, or to right or left scenery, which were defined as fixations to the right or left sides of the road.

On curves, the definitions of far field, and left and right scenery, differed from those of the straight section. On curves, the far field was defined as the area straight ahead, just above the road, as illustrated in Figure 9. The left far field was the area far down the road to the left of an imaginary line drawn through the left edge of the road (see Figure 9). The right far field was defined as the area far down the road straight ahead.

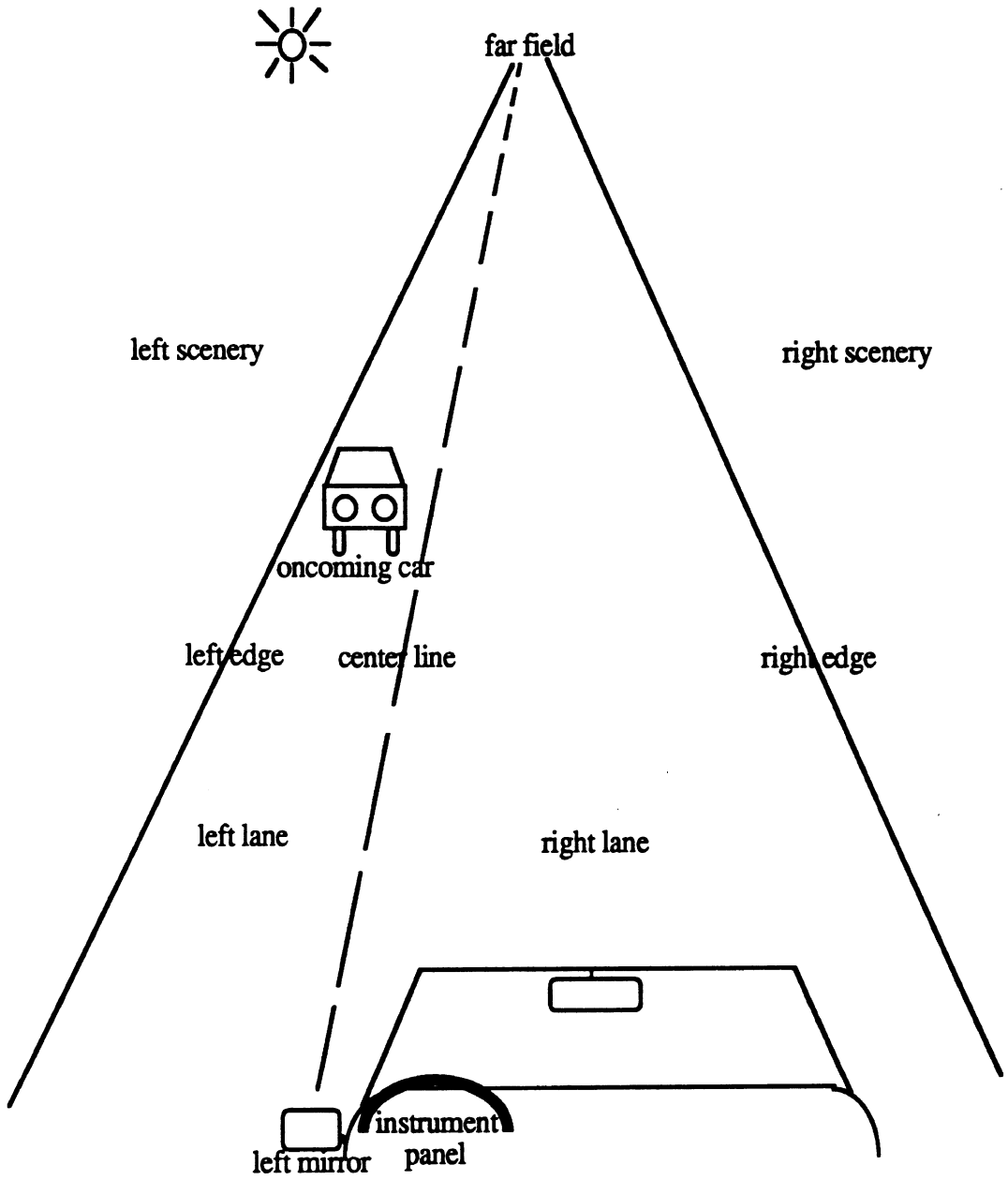


Figure 8. Locations of road features on the straight road segment

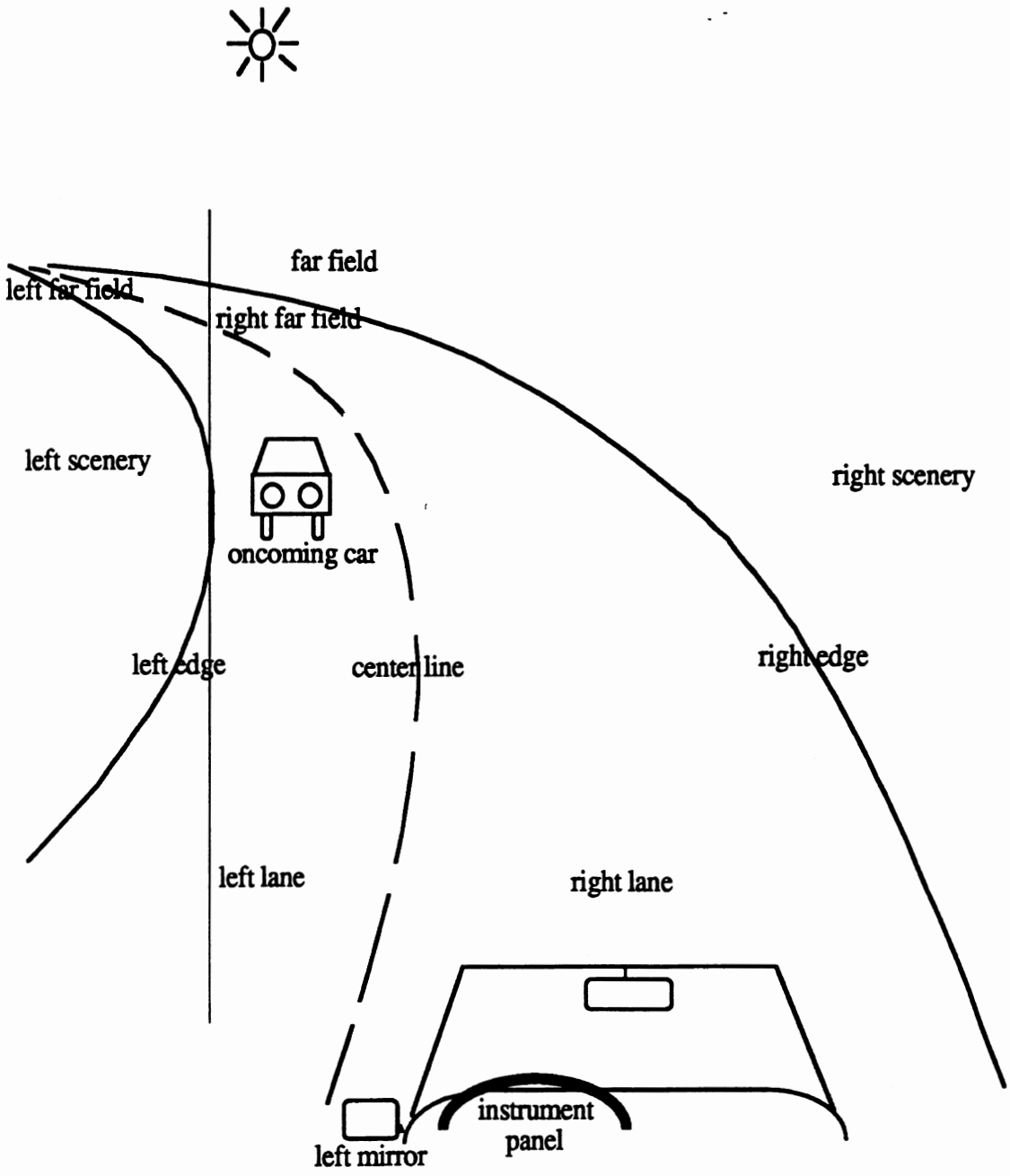


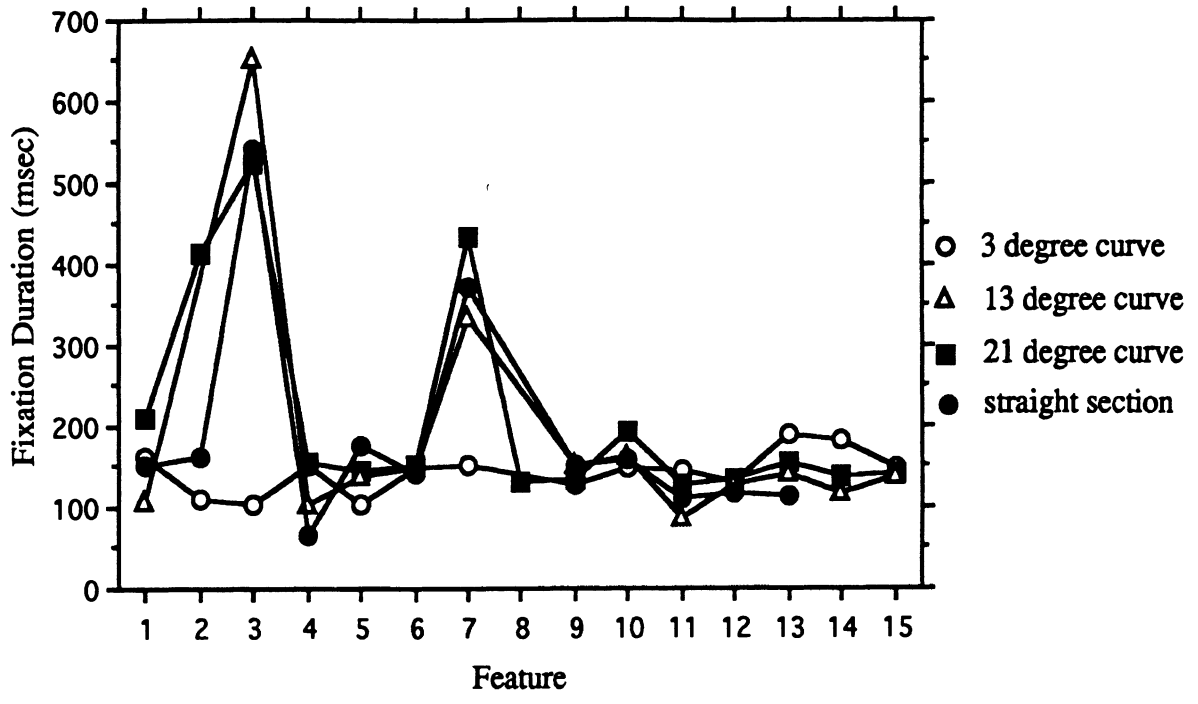
Figure 9. Locations of road features on the curved road segments

Eye Fixation Data

MANOVA

A multivariate analysis of variance (MANOVA) was run using fixation duration and percent fixations (fixation probability) to various road/car features as the dependent variables. The independent variables were age, gender, road geometry, and road and car features. The features included the road edges (right and left), center line, lanes (right and left), scenery (right and left), far field, oncoming cars, instrument panel, and left mirror.

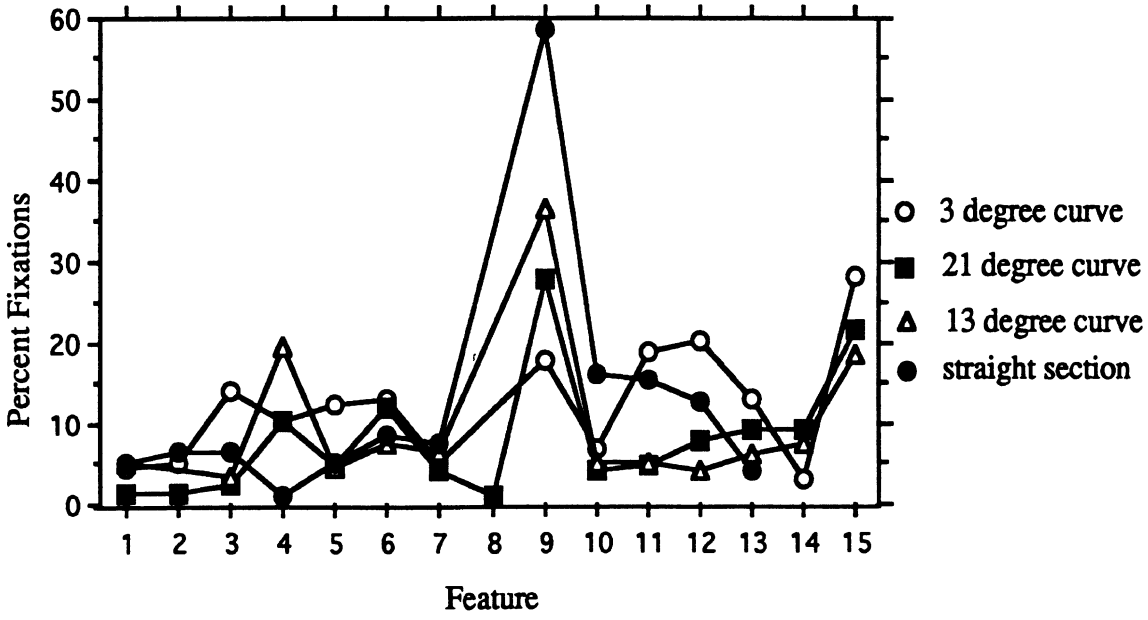
In the MANOVA, there were significant main effects due to gender ($F[2,167] = 4.23$, $p = 0.0161$) and feature ($F[28,334] = 9.44$, $p = 0.0001$). A significant two-way interaction, geometry by feature ($F[72,334] = 9.44$, $p = 0.0002$), was present. The geometry by feature interaction in Figure 10 shows that fixations to oncoming cars (feature 3) on the 3 degree curve (103 milliseconds) were shorter than fixations to oncoming cars on the other two curves (588 milliseconds) and the straight section (541 milliseconds). It should be noted that since subjects seemed to track oncoming cars rather than fixate on them, this movement was considered as one fixation. One explanation for this result may be that, on sharp curves, subjects use oncoming cars as a cue to the length of the curve. On a shorter curve, this is not necessary.



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

Figure 10. Fixation durations to the road and car features for the four road sections

Also, as indicated in Figure 11, there were more fixations to the far field (feature 9) on the straight section (59 percent) than on the three curves (3 degree--18 percent; 21 degree--28 percent; 13 degree--37 percent). Perhaps, drivers tend to fixate as far down the road as possible on a straight section, but look at other road features on curves.



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

Figure 11. Percent fixations to the road and car features for the four road sections

A significant age by gender interaction (F[2,167] = 4.12, p = 0.0179) was also present. As shown in Figure 12, younger women (217 milliseconds) had longer fixations than older women (152 milliseconds), while older and younger men (163 milliseconds) did not differ.

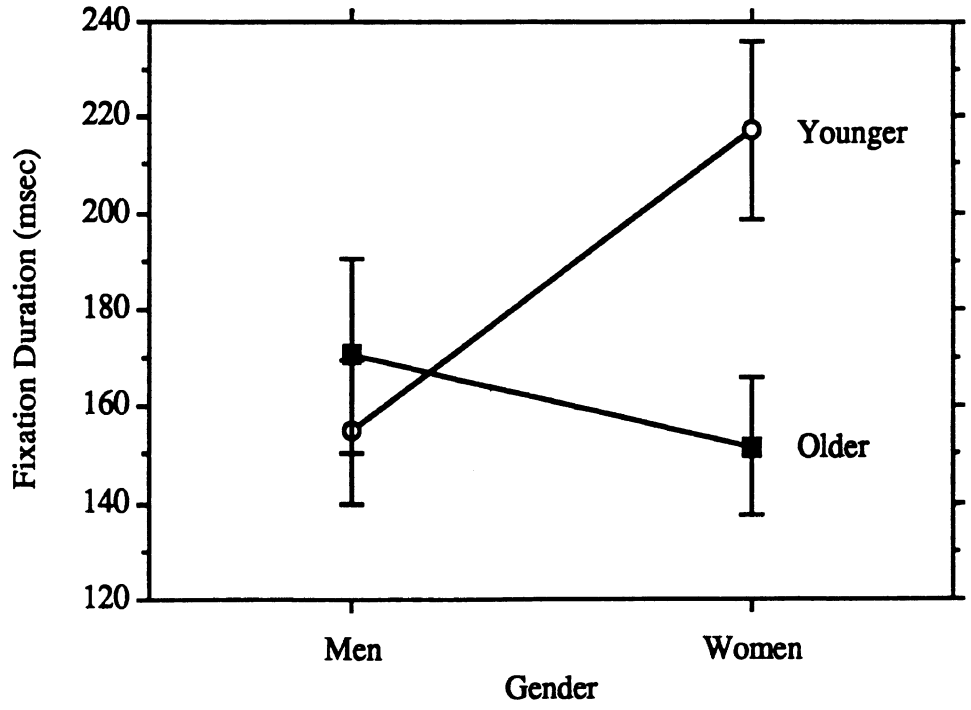


Figure 12. Fixation durations for men and women

Distributions of Fixation Durations

The distributions of fixation durations for the four road sections are shown in Figures 13 through 16. All of the distributions are lognormal with more fixations tending to be shorter and only a few longer.

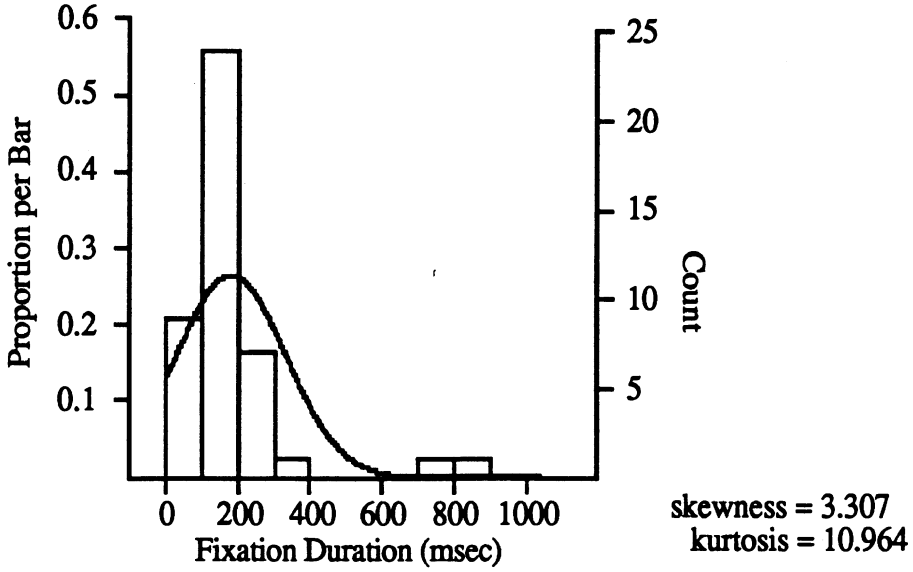


Figure 13. Distribution of fixation durations for the straight road section

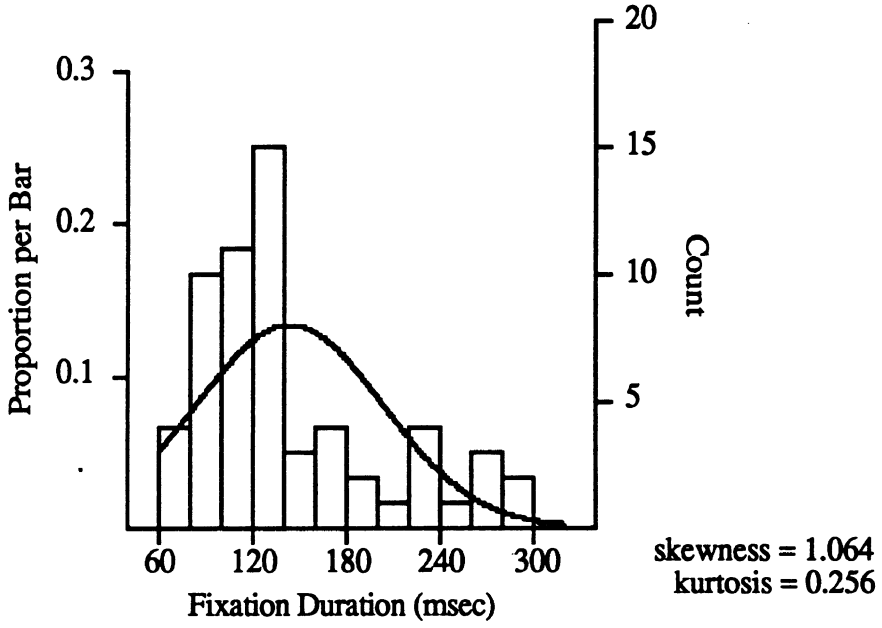


Figure 14. Distribution of fixation durations for the 3 degree curve

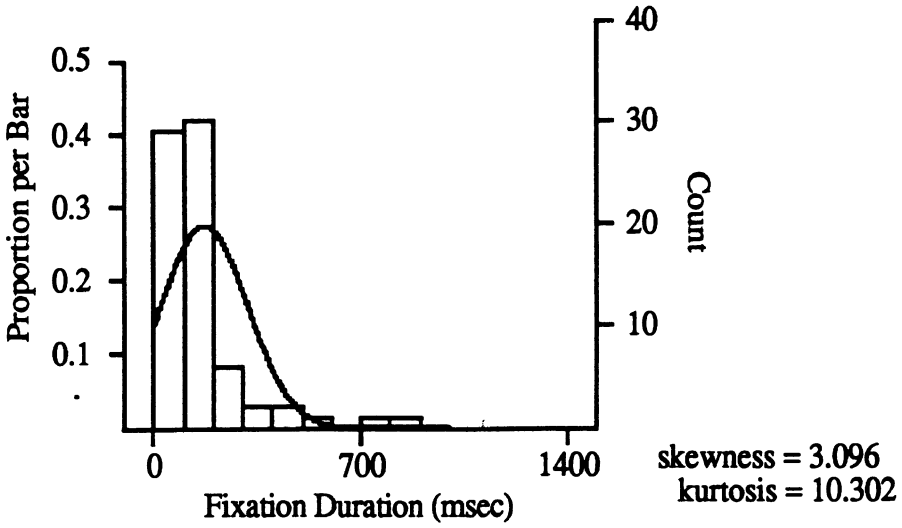


Figure 15. Distribution of fixation durations for the 13 degree curve

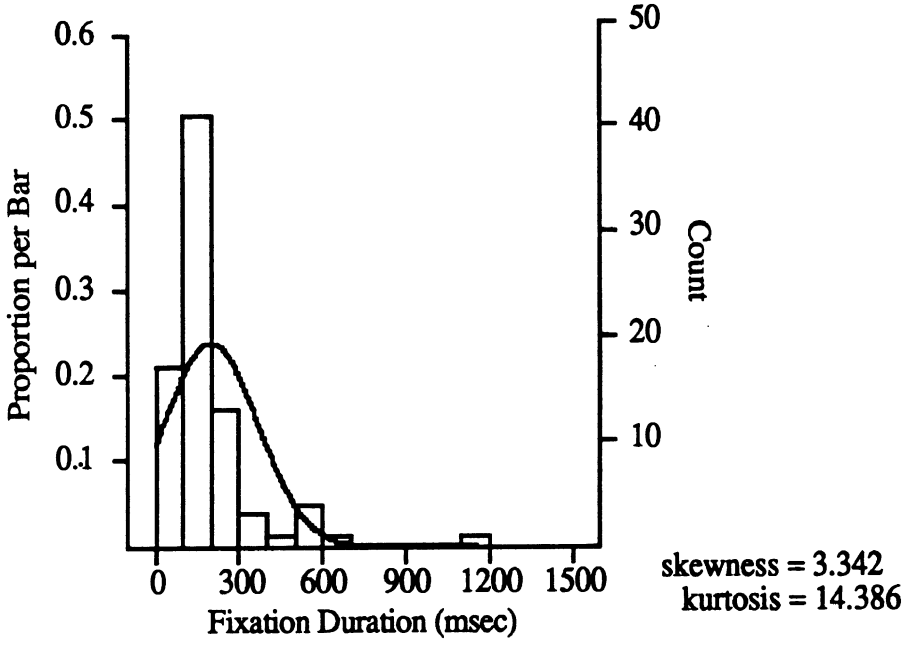


Figure 16. Distribution of fixation durations for the 21 degree curve

Fixation Probabilities

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 17 through 20. On the straight road section, the probability of fixating on the far field is the highest (40 percent). The scenery on the right and left sides of the road have an equal probability of being fixated (11 percent). The other road and car features have less than a 10 percent probability of fixation.

On the 3 degree curve, the probability of fixating on road features is more evenly distributed than on the straight section. For example, the probability of fixating on the right road edge straight ahead is 16 percent and the probability of fixating on the right lane is 12 percent.

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 on a curve) is higher (13 degree--28 percent fixations; 21 degree--23 percent fixations) than the probability of fixating on any other road and car feature. The probability of fixating on the right road edge straight ahead is 14 percent and 18 percent for the 13 degree and 21 degree curves, respectively. On the 13 degree curve, the probability of fixating on the left edge line is 15 percent and the center line only 6 percent, while on the 21 degree curve the probability of fixating on the left edge line (9 percent) and center line (10 percent) is more evenly distributed.

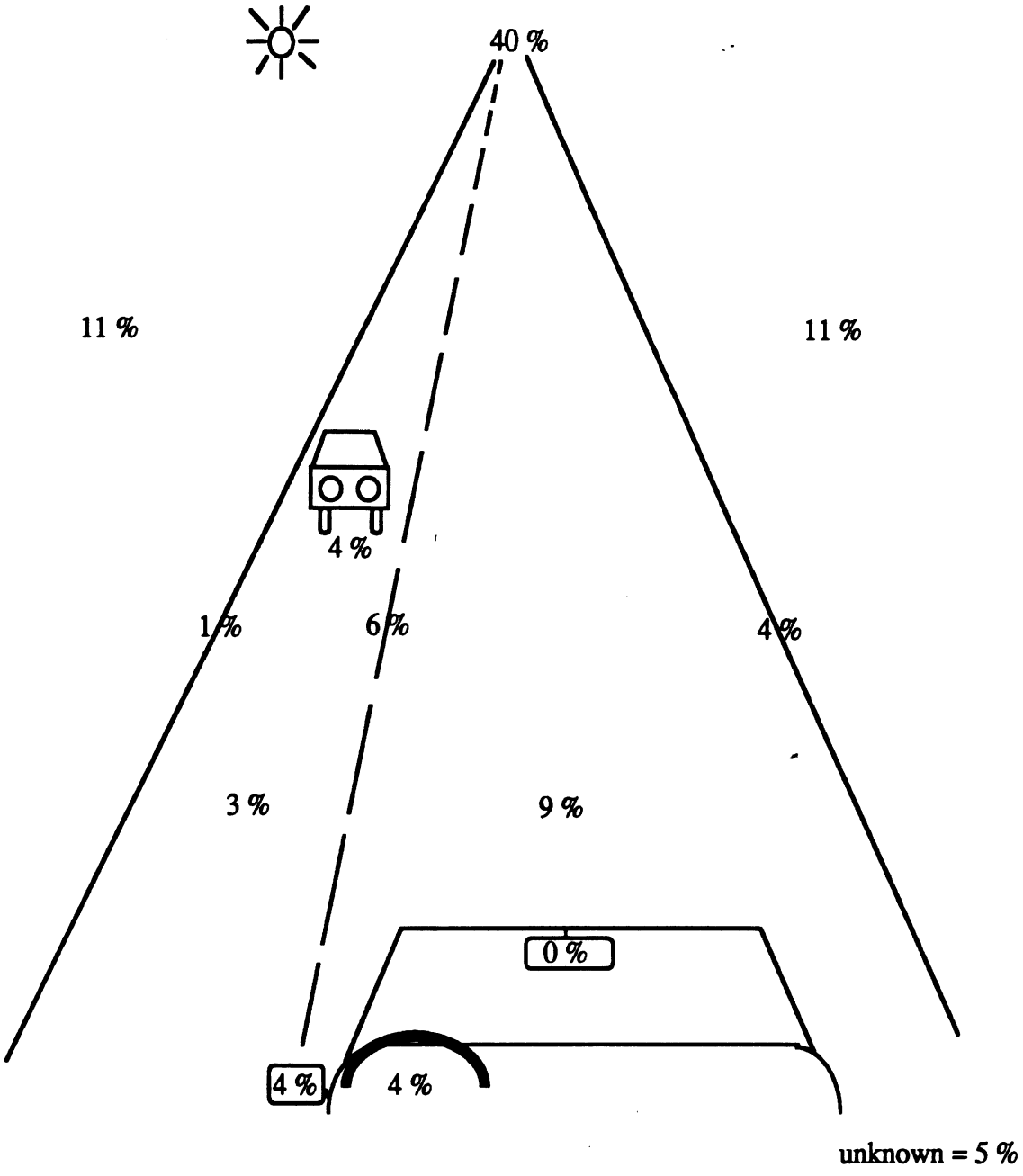


Figure 17. Probability of fixating on features on the straight road segment

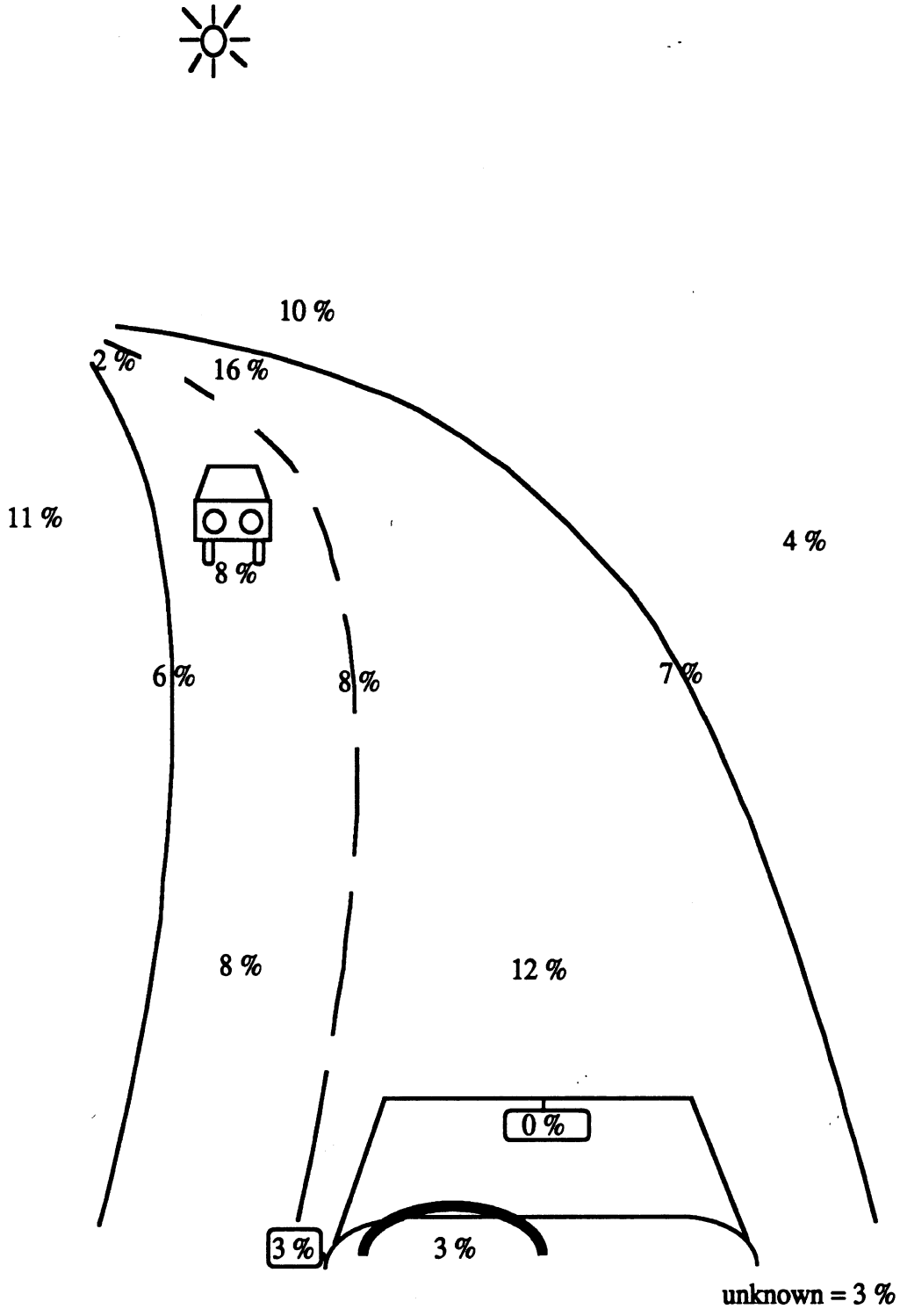


Figure 18. Probability of fixating on features on the 3 degree curve

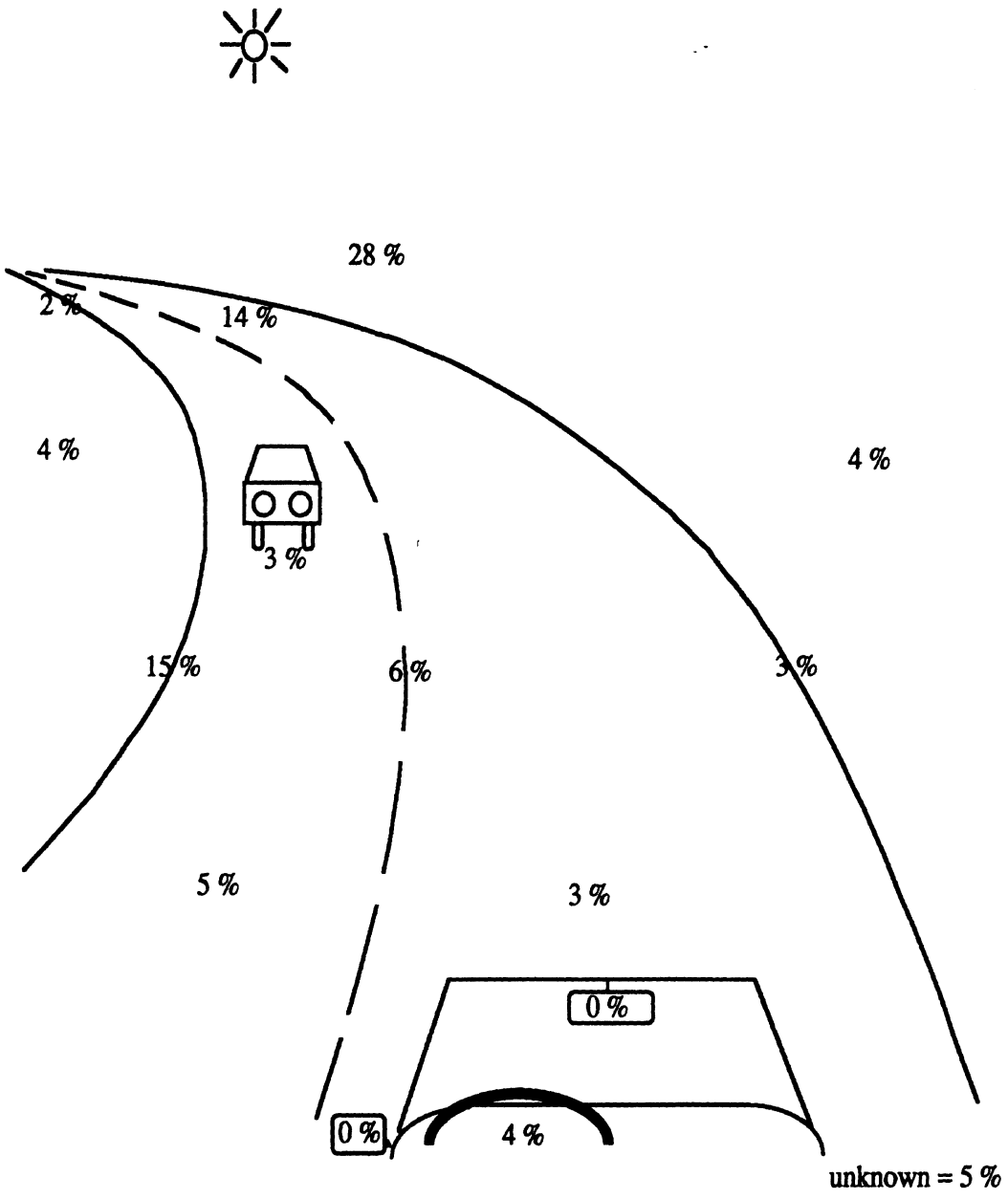


Figure 19. Probability of fixating on features on the 13 degree curve

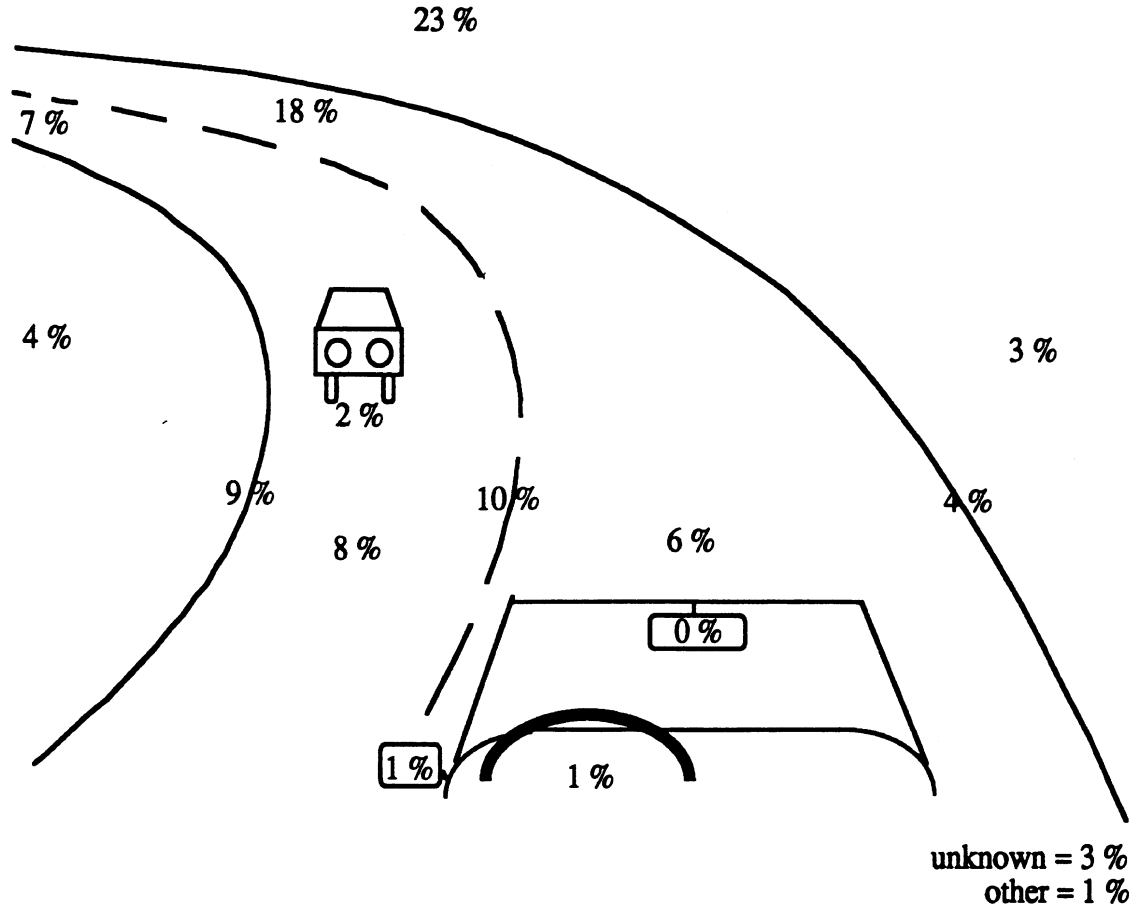


Figure 20. Probability of fixating on features on the 21 degree curve

Driving Data

Lane deviation and speed data are presented in Figures 21 and 22, respectively. For subjects 1 and 2, no lane deviation data was collected for the road segments and no speed data was collected for the 3 degree curve due to equipment problems. Lane deviation was measured from the left edge of the left front tire to the right edge of the center lane marker.

Lane deviation was greatest on the straight section and the 21 degree curve, and least on the 13 degree curve. In general, lane deviation ranged from approximately 1 to 2.5 feet. Given a car width of 6 feet and lane widths of 10 to 11 feet, this would leave 2 feet on the right and left sides of the car when it was in the center of the lane. Thus, drivers were well within their lane on all of the road sections.

From the speed data, drivers were slowest on the 21 degree curve and fastest on the straight section. Thus, as road curvature increased, speed decreased. For the most part, drivers drove at or below the posted speed limit of 50 miles per hour.

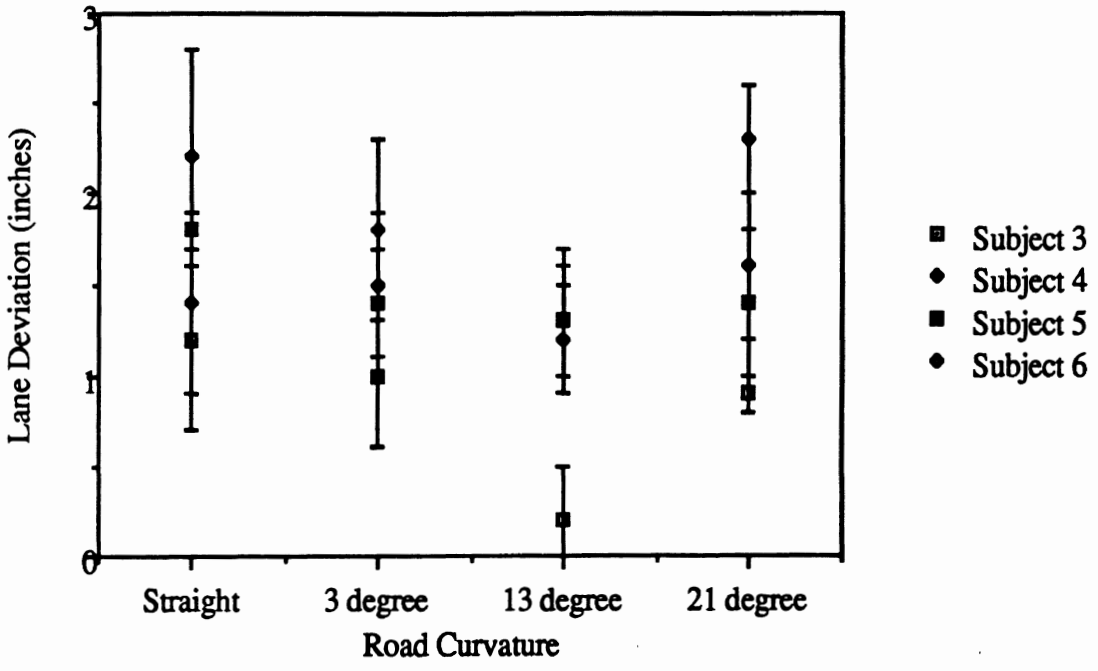


Figure 21. Lane deviation data for the four road segments

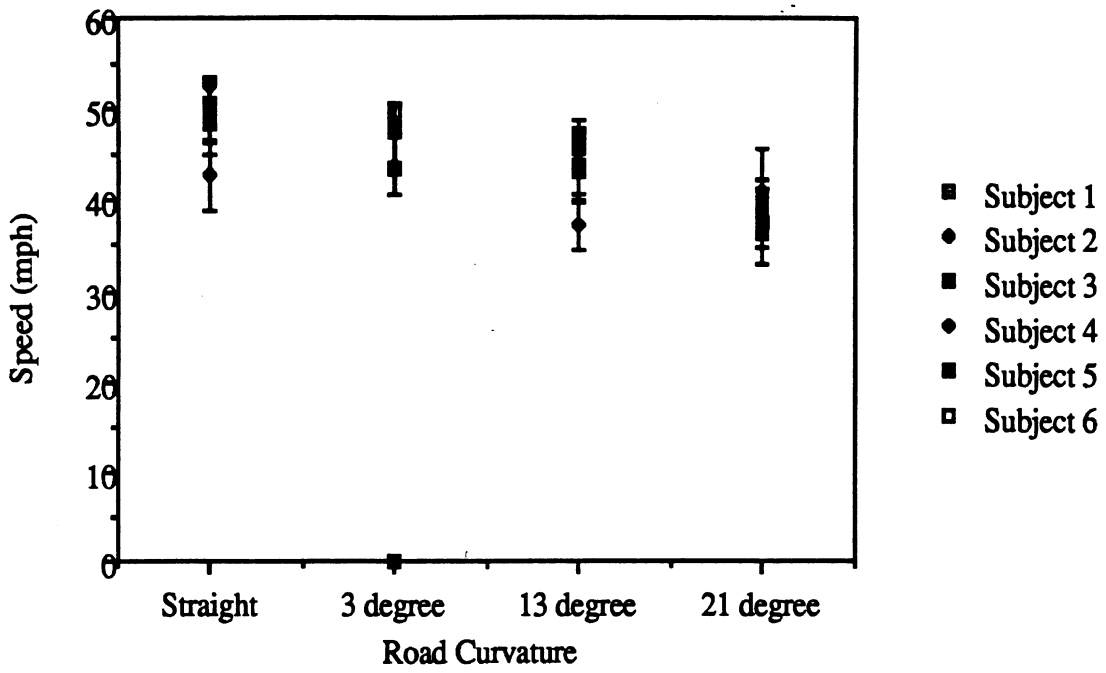


Figure 22. Speed data for the four road segments

CONCLUSIONS

The results of this study indicate that there are some differences in eye fixations depending on the curvature of the road. On straight road sections, drivers direct more of their fixations straight ahead, down the road (far field), whereas on curves, fixations are more evenly distributed toward other road features. On the straight section, the probability of fixating on the far field is 40 percent, whereas on curves it ranges from 10 percent (3 degree curve) to 28 percent (13 degree curve). Fixation durations are fairly consistent among different road curvatures, except for 3 degree curves where fixations to oncoming cars are brief when compared with fixations on sharper curves and a straight section. In terms of age effects, younger women had longer fixations than older women, but no age difference was found for men.

The results presented are preliminary; they are based on only eight drivers, two in each age and gender group. Ultimately, eye patterns of 32 drivers (eight in each age and gender group) will be examined, which could lead to substantially different results.

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APPENDIX

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

Reference	Method	Road/Time	Subjects	Indep. Variables	Dep. Variables	Form of Results	Conclusions/Comments
Blauuw (1975) -same as Blauuw and Riemersma (1975)	on-road	one-way lane crash barriers on each side 2 l. curves 1 straight sect. no road signs max vel=80kph each section is 276m long day	n=5 male 22-28 years lic. for 3 years 30,000 km	road-straight -l. curves R=83.6 m R=95 m 3 trials	eye movements	horizontal and vertical eye positions w.r.t. vanishing points horizontal and vertical distributions of eye positions w.r.t. 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 r. lane
Results:	**% Fixations (dur. time>100 msec)** R=83.6m:R=95m:straight l.edge-0.8:3.9:8.4 l.marker-0.5:1.4:3.1 l.lane-7.5:10.4:14.7 cntr marker-3.4:3.2:6.1 r.lane-14.2:17.8:12.8 r.marker-3.4:2.9:2.5 r.edge-11.6:10.6:6.9 sky-42.2:27.9:39.2 other-16.4:21.9:6.3			**Mean # Fixations** (dur. time>100 msec) R=83.6m-31.1 R=95m-28.8 straight-21.0 S1-36.3 S2-28.2 S3-14.6 S4-21.9 S5-33.6	**% Fixations Out of view** S1-11.3 S2-21.6 S3-20.3 S4-42.7 S5-20.1		
Cohen & Studach (1977) Exp. 1	on-road	rural d/n-not stated	n=9 avg age=23.5 >20k km driven gend-not stated	curve--right,left driver--exp, inexp	eye movements --duration --horiz. amp.	fix. dur. as function of road horiz. amp. as function of road	
Results:	**Fix. Durations** 0.41 sec-exp, l.curve 0.32 sec-exp, r.curve (sig) 0.46 sec-inexp, l.curve 0.52 sec-inexp, r.curve(nsig)			**Horiz. Amplitude** exp.-l. > r. curve inexp.- nsig.			
Exp. 2	on-road	rd-not stated d/n-not stated	n=6 avg age=24 exp & inexp gend-not state	road-r. crv approach (2 sections)	fix. duration fix. point on road -right, left, mid	# fix. as function of road fix. dur. as function of road	
Results:	**Fix. Durations** rd. sections-sig subjects-sig		**# Fixations** nearer curve-r, > l. side farther from curve-nsig.				

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 mi -3-90 deg turns -centerline but no edge lines day and night	n=6 males 20-34 years	road-straight -r. curves -l. curves amb. illum-day - night car following-yes	fixations-number -durations *on 8 visual field features*	% total time on features as function of road % total fix. on features as function of road mean time/fixation as function of road	far field>300 ft. ahead l.edge,center,r.edge are 100-300 ft. ahead

Results:	% Time	% Total Fixations	Fixation Duration (sec)
	•straight-lead(d/n):no lead(d/n)	•straight-lead(d/n):no lead(d/n)	•straight-l d(d/n):no l d(d/n)
	l.edge-9/13:12/2	l.edge-14/6:15/8	l.edge-.4/.72:.55/.4
	center-13/8:28/81	center-18/13:24/53	center-.4/.75:.73/2.1
	r.edge-10/5:11/8	r.edge-14/15:16/16	r.edge-.45/.43:.44/.58
	lead car-54/81	lead car-37/52	lead car-.9/1.95
	far field-2/1:40/2	far field-2/1:25/2	far field-.29/.2:.93/.35
	signs-1/2:3/6	signs-2/3:6/9	signs-.29/.43:.3/.6
	inside-2/0:3/1	inside-2/0:3/1	inside-.53/0:.41/.75
	other-10/1:5/1	other-13/10:9/10	other-.56/.43:.41/.6
	•r.crv-ld(d/n):no ld(d/n):l.crv-ld:nld	•r.crv-ld(d/n):no ld(d/n):l.crv-ld:nld	•r.crv-ld(d/n):no ld(d/n):l.crv-ld:nld
	l.edge-11/2:8/1:27/20:38/35	l.edge-9/5:12/2:21/20:29/31	l.edge-.72/.35:.3/.25:.53/.8:.6/1.3
	center-18/18:23/27:8/23:13/56	center-20/28:31/49:11/27:20/48	center-.34/.59:.34/.85:.28/.41:.31/1.25
	r.edge-37/43:42/60:11/3:9/5	r.edge-24/30:30/41:11/12:13/11	r.edge-.71/1.12:.72/1.7:.6/.29:.3/.78
	lead car-28/35:x/x:38/48:x/x	lead car-29/31:x/x:33/40:x/x	lead car-.48/1.0:x/x:.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-.3/.66:.49/.49:.33/.2:.53/.63
	signs-2/0:3/2:1/1:2/1	signs-2/1:4/2:3/2:4/1	signs-.37/.29:.3/.34:.23/.34:.34/.3
	inside-0/0:1/0:0/0:1/0	inside-1/2:2/1:0/0:1/0	inside-.28/0:.28/0:.37/0:.29/0
	other-5/1:2/1:6/1:5/1	other-10/2:4/1:10/1:8/3	other-.35/.25:.35/.59:.5/.37:.46/.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 driving exp. 13k avg annual mileage old n=8 60-70 years 46-60 years driving exp. 14k avg annual mileage	amb. illum-day -night driving condition -open road -car following -light traffic age-young v. 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	conc. index-% in view time in 3 deg x 3 deg 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 sig. influenced by IVs unit for time is seconds fixation time -consecutive fixations separated by at least one visual degree

Results:

Fixation Time (old:young)
(mean,st.dev)
day,l.traf-1.52:1.61,1.44:1.60
day,carfol-2.41:3.97,2.15:3.53
night,l.traf-1.89:1.97,1.86:1.80
night,carfol-1.99:5.12,1.82:2.57

Travel Distance (deg) (old:young)
(mean,st.dev)
day,l.traf-4.32:4.31,2.64:2.61
day,carfol-3.63:2.32,1.69:1.02
night,l.traf-3.94:3.26,2.16:1.38
night,carfol-3.72:3.41,2.52:1.39

Std. Dev. Look Time Away from Scene Ahead (old:young)
day,l.traf-0.62:1.34
day,carfol-0.93:0.69
night,l.traf-1.46:0.74
night,carfol-0.74:1.54

Activity Index (old:young)
day,l.traf-2.29:2.22
day,carfol-1.21:1.01
night,l.traf-2.15:1.54
night,carfol-2.43:1.02

Conc. Index (old:young)
day,l.traf-74.7:70.5
day,carfol-75.9:85.8
night,l.traf-65.6:69.8
night,carfol-73.0:77.5

Mean Time/Area (old:young)
day,l.traf-1.90:1.99
day,carfol-2.14:1.52
night,l.traf-2.61:2.09
night,carfol-3.08:2.50

% Time to Scene Ahead (old:young)
day,l.traf-77.8:71.6
day,carfol-78.4:84.5
night,l.traf-72.8:66.0
night,carfol-79.2:81.8

Mean Time per In-View Look Away from Scene Ahead (old:young)
day,l.traf-0.57:1.02
day,carfol-1.00:0.91
night,l.traf-1.15:1.15
night,carfol-0.74:1.29

Speedo-day,l.traf (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,l.traf (old:young)
% time-1.3:3.27
mean time/look-1.27:1.03
looks/min-0.57:1.92

Rear Mirror-day,l.traf (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,st.dev)
day,l.traf-3.17:3.11,2.88:2.58
day,carfol-5.31:10.12,5.19:3.42
night,l.traf-4.58:3.29,4.24:2.46
night,carfol-4.71:10.27,4.21:4.75

% Time In-View Away from Scene Ahead (old:young)
day,l.traf-11.1:18.1 night,l.traf-20.5:24.7
day,carfol-12.7:8.9 night,carfol-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 driving exp. old n=13 60-70 years 46-60 years driving exp. both avg 13-14 thous. km/yr	age-old -young driving condition -open road -car following amb. illumination -day -night	eye movements -vol. occlusion -mean travel distance velocity		aged drivers made longer eye travels than young drivers for day car following cond. aged drivers had larger st. dev of eye travels than young for all driving tasks except day open driving cond. aged drivers had longer eye open time than young drivers for all driving tasks aged drivers had larger st. dev than young for night tasks
Results:	**Mean Eye Travel Distance (degrees)** (day(young:old),night(y:o)) open-4.3:4.3,3.3:3.9 car fol-2.3:3.6,3.4:3.7 **St. Dev. 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(y:o)) open-0.7:1.6,1.4:2.5 car fol-0.7:2.0,1.6:3.5 **St. Dev. 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 frwy w/o illum 4-lane urban frwy w/illum rural 2-lane road day and night	n=4 male in college	road-4-lane divided rural frwy w/o illum -4-lane urban frwy w/ illum -rural 2-lane road amb. illum-day -night	eye movements -mean horiz. and vert. location -mean travel distance -CI=concentr. index time spent in most populous 3x3 deg. grid square -% time to objects -mean time per look		eye movement pattern shifted down and to left from day to night by about 1 visual degree eye movements more spatially disperse at night than day on unlighted frwy road right-r. edge line and r. road surface in front of driver road left-l. edge line and l. road surface in front of driver
Results:	**% Time (day:night)** (frwy w/o illum,frwy w/ illum,rural rd) road r.-0.3:7.7,9.6:15.4,17.2:5.9 road l.-1.1:37.8,16.1:20.2,10.3:4.6 scenery r.-2.4:0.3,2.8:3.7,7.2:1.2 scenery l.-3.2:8.3,11.8:0,0.8:1.7 strght ahd-92.6:42.7,57.5:60.7,64:83 sky-0.4:3.3,2.1:0,0.2:3.6 oncming hdlghts-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 ft wide -no edge lines -straight -0.3 miles -S curve -0.3 miles r.turn-37 deg l.turn-34 deg 4-lane div.hwy -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 IVs -% time in transit as a function of all IVs	considerable variability in drivers' eye movements from 1 replication to next individual drivers exhibit dif visual patterns on same highway c=close <75 ft in front of vehicle f=far 75-250 ft in front of vehicle road= >250 ft in front of vehicle
Results:	**% Time (subj1:subj2)** •rural str-day/night 1.c.l.edge-0:0/0:0 2.c.cntr line-0:0/0:.25 3.c.r.edge-0:0/2:0 4.f.l.edge-.65:0/0:0 5.f.cntr line-9.05:1.3/0.4:2.38 6.f.r.edge-12.9:17.35/61.6:37.5 7.road-71.05:60.75/5.7:53 other-6.35:20.5/29.4:6.9 •rural S curve-day/night c.l.edge-0:0/0:0 c.cntr line-0:0/0:.0 c.r.edge-0:4.55/.9:.8 f.l.edge-10:0/.15:2.55 f.cntr line-3.2:0/.25:8.5 f.r.edge-11.95:3.6/35.2:16.15 road-29.8:9.85/24.65:45.75 other-42.9:8.2/36.6:26.25			**% Time in transit(s1:s2)** •rural str-day/night (2-3)-0:0/0:0 (2-5)-0:0/0:.25 (2-6)-0:0/0:0 (3-4)-0:0/0:0 (3-5)-0:0/0:0 (3-6)-0:0/2.5:0 (4-5)-0.2:0/0:0 (4-6)-0:0/0:0 (4-7)-0:0/0:0 (5-6)0.2:0.25/0:0.25 (5-7)-2.4:0.5/0:.7 (6-7)-3.65:3.55/0:2.65 out<=>in-10.05:12.5/13.5:7.55 •rural S curve-day/night (2-3)-0:0/0:0 (2-5)-0:0/0:0 (2-6)-0:0/0:0 (3-4)-0:0/0:0 (3-5)-0:0/0:0 (3-6)-0:.15/.65:.15 (4-5)-.65:0/.15:.15 (4-6)-.15:0/0:0 (4-7)-.25:0/0:.45 (5-7)-.25:0/.4:2.7 (5-6)-.4:0/.25:.25 (6-7)-1.45:0/2.2:2.0 out<=>in-10.05:4.95/11.55:11.15		**% Time in transit(s1:s2)** •4-lane hway-day/night (2-3)-0:0/0:.95 (2-5)-0:0/0:.3 (2-6)-0:0/0:.1 (3-4)-0:0/0:.1 (3-5)-0:0/0:.7 (3-6)-0:0/0:.4 (4-5)-0.2:0/.08:0 (4-6)-0:0/0:0 (4-7)-0:.85/.08:0 (5-6)0:.1/.5:1.1 (5-7)-0:0.1/.6:.2 (6-7)-.65:.25/.3:.95 out<=>in-9.1:5.3/9.9:10.85 **% Time in Transit(40:60)** •4-lane hway-day/night (2-3)-0:0/.4:0 (2-5)-0:0/.6:0 (2-6)-0:0/1.1:0 (3-4)-0:0/0:0 (3-5)-0:0/.4:0 (3-6)-0:0/1.3:0 (4-5)-0:0/0:0 (4-6)-0:0/0:0 (5-7)-0:0/0:0 (4-7)-0:1.8/0:0 (6-7)-0:0/0:1.7 (5-6)0:0/.2:0 out<=>in-0:8.1/10.3:6.8	**% Time (subj1:subj2)** •4-lane hway-day/night c.l.edge-0:0/0:0 c.cntr line-0:0/0:5.3 c.r.edge-0:0/0:12.7 f.l.edge-0:2.7/.15:.15 f.cntr line-0:.35/4.8:13.9 f.r.edge-1.2:0.35/10.15:18.2 road-79.3:23.5/20.2:34 other-19.45:73.05/65:15.75 **% Time (40mph:60mph)** •4-lane hway-day/night c.l.edge-0:0/0:0 c.cntr line0:0/8:.0 c.r.edge-0:0/4.5:0 f.l.edge-0:5/0:0 f.cntr line-0:0/6.7:0 f.r.edge-0:0/60.8:21.7 road-0:63.1/0:41.6 other-100:31.9/20:36.7

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 accid. -11 no accid. -.05-.13 km long -5-19 degrees d/n -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 -fix. duration -travel dist. betw. successive fix. -fix. location concentrat. index times -fix. on objects in visual field -blinking -mirror looking	ANOVA	results provide empirical support for theoret. arg. of Gordon ('66) and Fry ('68) straight rd-concent. on focus of expansion curve rd-concent. on rd ahead and rd edge curve negotiation starts well in advance of the curve
Results:	**Fixation Durations** •sig-high acc v no acc curves 0.48 sec v 0.39 sec •sig-curves & appr. v str 0.41 sec v 0.60 sec •right:left (sec) approach,high acc-.17:.49 approach,low acc-.17:.23 curve,high acc-.40:.28 curve,low acc-.19:.27 **Fixation Locations** •r. v l. curve (sig) 3.6 deg to r. v 0.3 deg to l. •approach zone 1.7 deg to r., 1.2 deg above focus of expansion (foe) •straight 1.6 deg to r., 0.7 deg abv foe			**% of Time** •approach zone 23%-road 23%-scenery •curve zone (sig) 27%-scenery 23%-road •right v left curve (sig) road-55% v 38% opp.road,scen-5% v 24% **Blink % of Time** •str. v approach & curve (sig) 4.1% v 1.8 % **Travel Dist Btw Fixations** •approach & curve v str (sig) 3.1 deg v 2.6 deg **Concentration Index (sig)** .62 v .27 (str v crv & apprch)	**% Time on Speedo (sig)** 6.7%-straight 3%-curve **% Time- Rr V. Mirror (sig)** 3.7%-straight 2%-curve	concentration index -fixation time in 3 degree sq. area of highest fixation density divided by total fixation time

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 were of interest day and night	n=2 (day) n=1(night) nothing else stated	road-straight -r. curves -l. curves curve zone -approach -curve -leave radius of curve amb. illum-day - night	eye movements -fix. duration -# fixations	x-y eye fixation density maps spatial and temporal scan. summary measures as funct. of curve and amb. illum x-y CG for fix. for curve zone % total time on features as function of conditions % total fix. on features as function of conditions	curve approach and negot. is demanding night-short foveal preview distance and short prev. times roadway geometry influences fixation x-y centers of gravity and dispersions
Results:	**Fixations/100 ft** curve-3.56 straight-2.21 **Fixation Locations** r. curve-r. edge line l. curve-center line, l. edge line **Fixation Durations (sec)** night-0.46 day-0.39			•x-y center of gravity-eye scanning behav. influenced by curve 300-400 ft before curve begins •fixation patterns-night more concentrated on road ahead than during day			