Chapter 4

Where Do Drivers Look While Driving (and for How Long)?

Paul Green

Synopsis

It does not take a rocket scientist, or even a human factors expert, to realize that driving is a task that depends upon visual input. Although there are debates as to what percentage of the input is visual (i.e., the driving-is-90-percent-visual fallacy; see Sivak, 1996), one cannot drive without looking at the road. Hence, understanding what people look at, when, and for how long provides insight into how people drive. Disruptions of the road scanning process can increase the probability of a crash, the central topic of this book.

4.1 How Is Glance Behavior Described?

A. What are the terms used to describe glance behavior?

ISO/SAE STANDARDS

Recently, there has been agreement on standardized terminology for glance behavior in automotive contexts (International Organization for Standardization, 1999; Society of Automotive Engineers, 1999a). A fixation, the basic element of looking behavior (Figure 4.1), occurs when the gaze is directed towards a particular location and remains there for some period of time, typically around 0.20 to 0.35 seconds. During that time period, there may be some drift in the point fixated (also known as the point of regard or target), but that drift is typically less than a fraction of a degree. Fixations are separated by saccades, abrupt movements from one location to another. The Society of Automotive Engineers terminology distinguishes between saccades, movements within regions, and transitions, movements between regions, terms commonly used synonymously.

For many practical applications, the primary characteristics of interest are glance measures. A glance consists of all consecutive fixations on a target plus any preceding transitions. In Figure 4.1, notice that a glance can include multiple fixations. In the literature, sometimes the term fixation is used when the term glance is meant. Further confusion occurs because of the inconsistent treatment

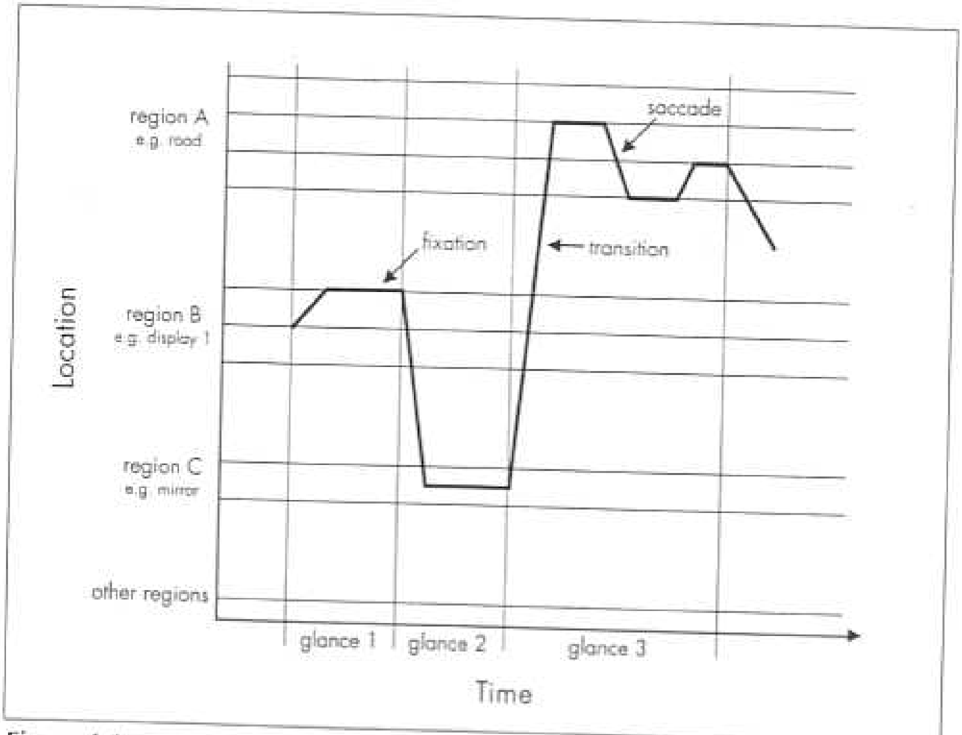

Figure 4.1

of the leading and trailing transitions. Sometimes neither is included in the fixation times, sometimes one is, and sometimes both are. The leading transition has been included in the glance definition here as a matter of convention. How fixations and glances are defined varies from document to document (including some of the documents cited in this chapter), though, more often than not, the terms are not defined.

If the transition diagram shown in Figure 4.1 was interpreted literally, one would expect a vision sequence to be a series of clear images intermixed with blurred images as the eye moved from location to location. Due to a phenomenon known as saccadic suppression (Matin, 1986), people obtain very little new information from the scene during saccades and transitions, as the visual system appears to continue reading out information from the last fixation. However, from the measurement perspective, the range of saccade and transition times is fairly limited, and they are short relative to fixation times. Thus, if the goal is to estimate glance duration, including the leading or trailing saccade or transition has only a small effect on the estimate of transition time.

For automotive safety, the primary characteristic of interest is eyes-off-the-road time. This time is the sum of all of the time associated with all glances not directed towards the road (in Figure 4.1, glances 1 and 2), plus transition time from off the road to the road (the first transition of glance 3 in Figure 4.1). Except for scanning mirrors and instrumentation, driving safety is compromised if one is not looking at the road.

B. What are some general characteristics of driver glance behavior?

Understanding the process by which drivers move their eyes should help readers comprehend the research described in the remainder of this chapter. When people begin to look at an object, they first rotate their eyeballs towards the object (at up to 275 degrees per second), and if the object is more than about 15 degrees from their current line of sight, their head then moves (at 100 degrees per second) about 50 milliseconds later. As a practical matter, this suggests that any readily detected object within 15 degrees of a fixated object can be fixated relatively quickly since no head movement is needed.

Figure 4.2 shows data from Robinson, Erickson, Thurston and Clark (1972) recorded from drivers at an intersection and while changing lanes on a highway. (See also Hallett, 1986; Land and Horwood, 1996.) The eye-head angle, the difference between where the head is pointed and the eyes are aimed, rarely exceeds 35 degrees. After their gaze falls on the object of interest, people often continue to rotate their heads to align it with the object in question. During the final phases of head rotation, the eyeball may rotate in the opposite direction of the head to maintain fixation. Thus, what people can see is physically limited by the angular velocity of the eye and head, the response time of the neck muscles, and the maximum acceptable angle between the eye and head. Some of these characteristics may be influenced by age. Of particular concern is how eye-head dynamics influence the scanning behavior of elderly drivers. Unfortunately, data concerning this topic do not appear in the automotive literature.

Drivers look at objects for a number of reasons, but regardless of the purpose, the distributions of both eye fixation and glance durations do not follow the typical bell shaped curve (the normal distribution), but rather are log normal (the logarithms of the durations are normally distributed). This is important because the statistical parameters that can be used to describe the "average," (mean, median, mode) are identical for a normal distribution but not for a log-normal distribution. For example, Rockwell (1988) (see also Taoka, 1990) reports data from several studies concerning the use of radios (Figure 4.3), mirrors (Figure 4.4), and other vehicle components. Notice that for the radio, the mean glance duration was 1.44 seconds, and while there were virtually no glances of 0.5 seconds or less, there were a moderate number of glances over 2.38 seconds. (See also Robinson, Erickson, Thurston and Clark, 1972 for data on glance distributions.)

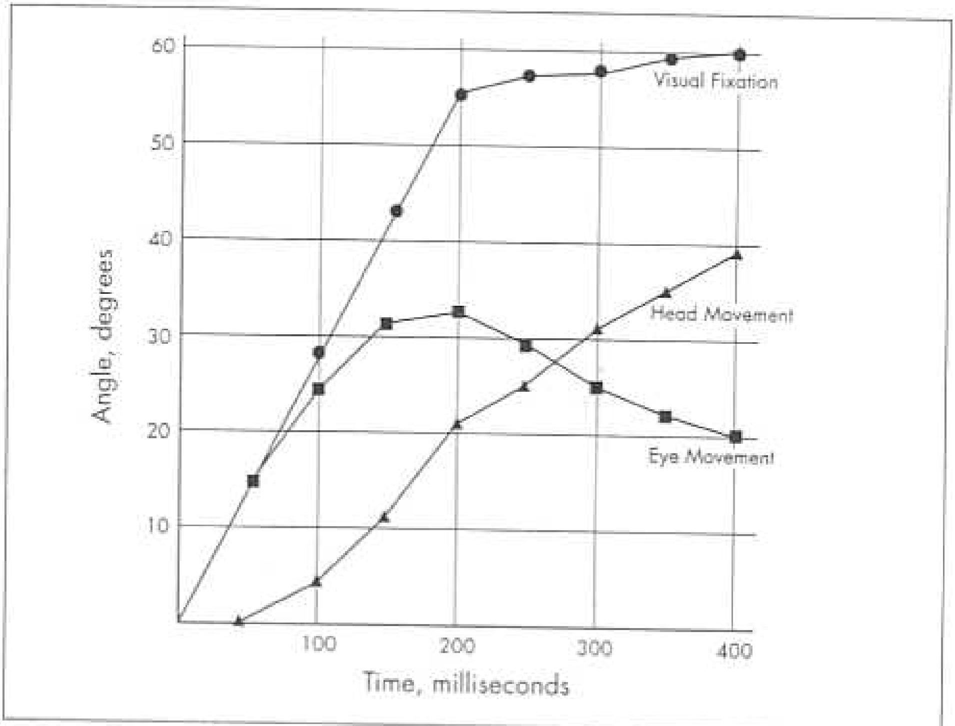

Figure 4.2

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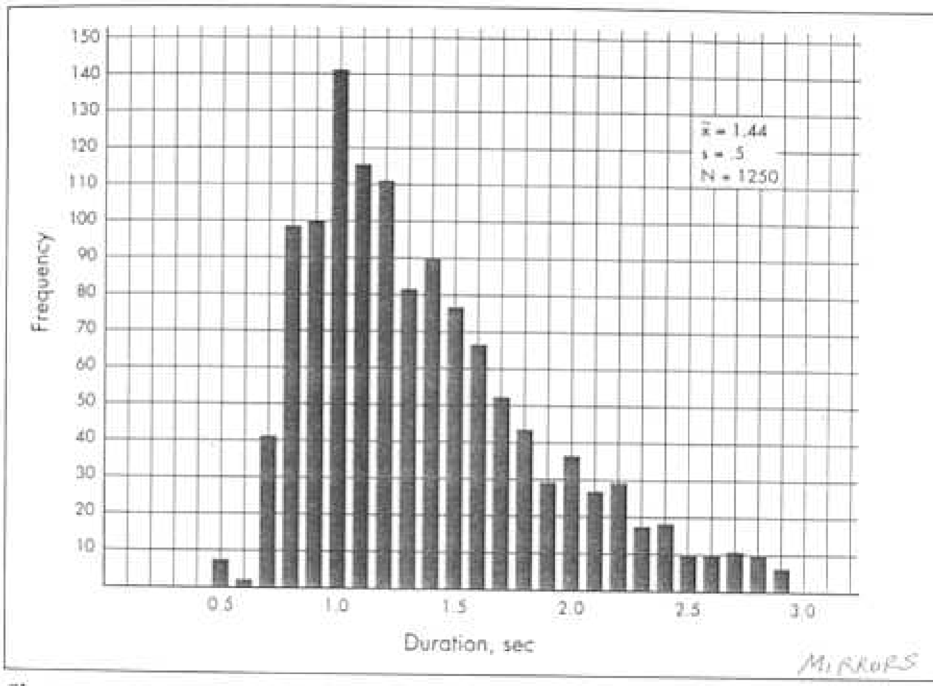

Figure 4.3

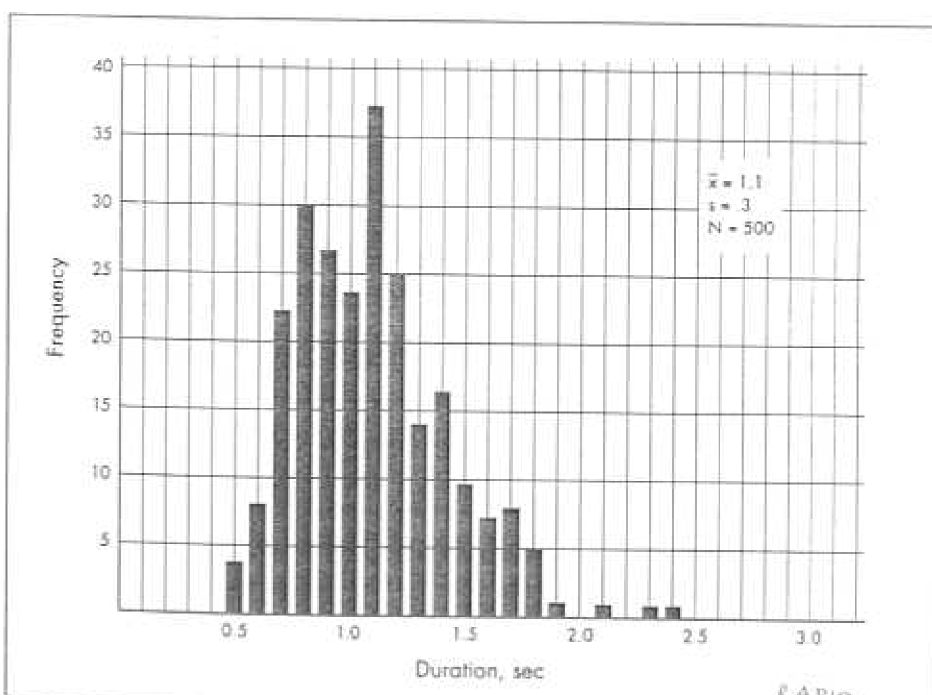

Figure 4.4

ROCKWELL (1988)
also see TAOKA (1990)

Interestingly, when the experimenter and method are the same, as was the case here, the data are fairly consistent across studies, with differences in the means of approximately 10 percent. Differences across studies and experimenters are unknown, though Rockwell suggests comparing mirror glances, a fairly well structured task, to establish relative baselines (a performance benchmark).

Rockwell (88)

Rockwell also observed that older (over 45) drivers tended to have longer glance durations than younger (under 35) drivers (by about 5 percent, on average), and men had longer glance durations than women (by 11 percent, on average). The small age difference may be due to small differences in the mean age of subjects in his experiments. However, the primary differences were in the number of glances required to complete a task. For example, older drivers required 20 percent more glances to complete radio tasks.

Δage

Because of the log-normal shape of the time distributions and moderate levels of variability for glance durations, relying on the mean as the sole descriptive statistic for glances can provide misleading implications for safety. In many situations, the major concern may be the few but very long glances away from the road or some critical aspect of the road. Thus, in assessing the risk of particular situations, practitioners need to consider several distribution statistics.

C. How is glance behavior measured?

Where drivers look can either be determined directly (from the recording of a camera aimed at a driver's face, the direct observation method), or by using special electronic devices often referred to as "gaze trackers" or "eye movement recorders" (Green, 1992; Williams and Hoekstra, 1994). Direct observation data are very boring and labor intensive to reduce, since the videotapes must be played back frame by frame. For standard video equipment (operating at 30 frames per second), times are accurate to the nearest 33 milliseconds. Differences between the actual and measured look locations can be on the order of 10 degrees visual angle for a typical analysis when the head is stable (Schieber, Harms, Berkhout and Spangler, 1997), so direct observation data can only provide a rough indicator as to where drivers are looking. As a guide, the visual angle between the road and a speedometer is about 15 degrees.

Electronic devices typically measure (1) the reflection of a beam of light off of the cornea, (2) the electrical signals of the muscles controlling the eye, or (3) the location of the boundary between the white and dark parts of the eye. None of these methods is ideal. These devices are fairly expensive but generally more accurate (within a few degrees) than direct observation. Each technology has its specific limitations (use in daylight, vertical accuracy, wearer discomfort, etc.) and mostly for reasons of equipment cost, direct observation is more commonly used. Practitioners are therefore cautioned to ask probing questions about (1) the accuracy (and precision) of the fixation location measures and (2) the accuracy of duration estimates. When independent verification of accuracy and precision is not provided, as is often the case, experimental results should be examined with some reservations. When provided, claimed accuracy may exceed that allowed by the technology.

Because of the challenges they pose, eye fixation studies are relatively rare, involving very small subject samples (often three or four drivers), and generally only a very small portion of the data collected is analyzed (sometimes only a one minute sample from each hour of driving). Further, glasses or contacts may interfere with measurements, a consideration of special relevance to older drivers, as almost all of them wear corrective eye wear. When compared with most human factors studies, the sample sizes of many eye fixation studies would be considered unacceptably small.

4.2 Why Are Eye Fixations of Interest?

A. Does visual demand actually relate to crashes?

Visual demand is the aggregate input from traffic, the road, and other sources the driver must process to operate a motor vehicle. While drivers can compensate for increased visual demand to some degree, human factors experts generally agree that increasing visual demand towards overload will increase crash risk. Clearly, there are more crashes in heavy traffic or on geometrically complex roads. For example, Shinar, McDowell and Rockwell (1977) reported that high accident curves elicited longer fixation durations (0.48 seconds) than no-accident curves (0.39 seconds).

Wierwille (1995) examined the visual demands of in-vehicle features. He utilized postcrash, police-reported narratives, e.g., "I was adjusting my radio, so I did not see the other car," along with glance measures and frequency of use data in the human factors literature to predict crash involvements (equation 4.1 and Table 4.1). An involvement is the participation of a single vehicle in one crash. If two vehicles collide, there would be one crash with two vehicles involved. The predictor is based on the aggregate eyes-off-the-road time with the glance duration raised to a power (because long off-road glances disproportionately add to risk).

$$\text{Number of involvements} = -0.554 + [0.335 \times (m)^{1.5} \times (n) \times (f)] \qquad \text{(eq. 4.1)}$$

Table 4.1
Factors Used to Predict Crash Involvements

Term (units)	Definition
m = mean glance time (seconds)	duration of each look to the component (speedometer, mirror, etc.)
n = mean number of glances	the number of times the driver looks at the component each time it is used
f = frequency of use (sequences per week)	number of times the component is used, where each time consists of a continuous sequence of glances

Adjusting for the relationship between involvements and fatalities, and between fatalities in North Carolina in 1989 (Wierwille's data) and the U.S. as a whole, Green (1999b) estimates that the number of fatalities in 1989 in the U.S. related to in-vehicle devices is:

$$-0.133 + [0.0477 \times (m)^{1.5} \times (n) \times (f)] \qquad \text{(eq. 4.2)}$$

So, if drivers used a device daily (seven times per week), and each use involved six glances of 1.5 seconds each, then approximately 3.5 fatalities per year would be expected from using the device in the U.S. (in 1989). However, this calculation assumes that all vehicles are fitted with the device. If only 30 percent of all vehicles had the device, the expected number of fatalities per year would be just over one.

This analysis looks silly to me

One of the practical strengths of this calculation is that it allows for preproduction estimates of the fatality consequences of various product designs. Thus, reducing the number and duration of glances associated with a product or feature, and the frequency of each task, has direct safety and, ultimately liability consequences.

B. Does looking at an object guarantee the object is noticed?

One might assume that tracking a driver's eye fixations would provide an almost perfect indication of where the driver's attention is directed as voluntary eye movements are usually accompanied by an attentional shift. In fact, fixations to locations (e.g., eyes off of the road) and attention to those locations (e.g., mind off of the road) can be disassociated. This is sometimes referred to as "looked but did not see." Louma (1988) recorded where drivers looked on a real road and asked them questions about what they had seen as they drove. Table 4.2 shows the recall probabilities and, in parentheses, the fixation times (available in only some cases). Objects fixated were likely to be recalled. However, fixating on an object did not guarantee attention to that object (as indicated by the recall data), and further, some objects that were not fixated (viewed peripherally) were recalled. Objects were more likely to be recalled if they had a direct effect on driving, and as indicated by the data, those objects were sometimes fixated for a longer period of time. Since visual demand is related to crashes and demand is indicated by eye fixations, studying eye fixations should provide an understanding of precrash behavior and crash mitigation. However, those assessments should be coupled with analyses that identify the extent to which fixated-upon objects are or can be made relevant. In situations in which sign, marking, or traffic signal conspicuity is contested, eye fixation analyses, combined with relevance assessments, may be helpful in resolving an impasse.

Table 4.2
Recall Percentages (and Mean Fixation Time in Milliseconds) for Road Signs and Markings

Object	Fixated and recalled	Fixated but not recalled	Recalled but not fixated	Neither fixated nor recalled
speed limit sign	100 (644)	0	0	0
game crossing sign	60 (410)	0	7	33
no pedestrian crossing	47	7	33	13
pedestrian crossing ahead	8 (420)	54 (283)	0	38
pedestrian crossing sign	0	21 (127)	0	79
crosswalk lines	29 (532)	50 (395)	7	14

Source: modified from Louma (1988)

4.3 What Is Typical Looking Behavior?

Where do people normally look when they drive? As an example of research on this issue, Mourant, Rockwell and Rackoff (1969) had eight students drive both on the open road and in a car-following situation. For the first trial, drivers read all signs, as would an unfamiliar driver. For the second trial, they read only the signs necessary. For the third trial, they did not read the signs.

Figure 4.5 shows the spatial distribution of fixations from one driver (two road conditions × three trials) with each figure representing about 2.5 minutes of data. Notice the wide distribution of fixations, many of which were above the horizon and to the right of the road (looking for signs). Given the limits of accuracy of direct observation described earlier, many of the inferences made here require use of an electronic eye fixation recording system (as they did) and could not be made by a practitioner simply observing a driver.

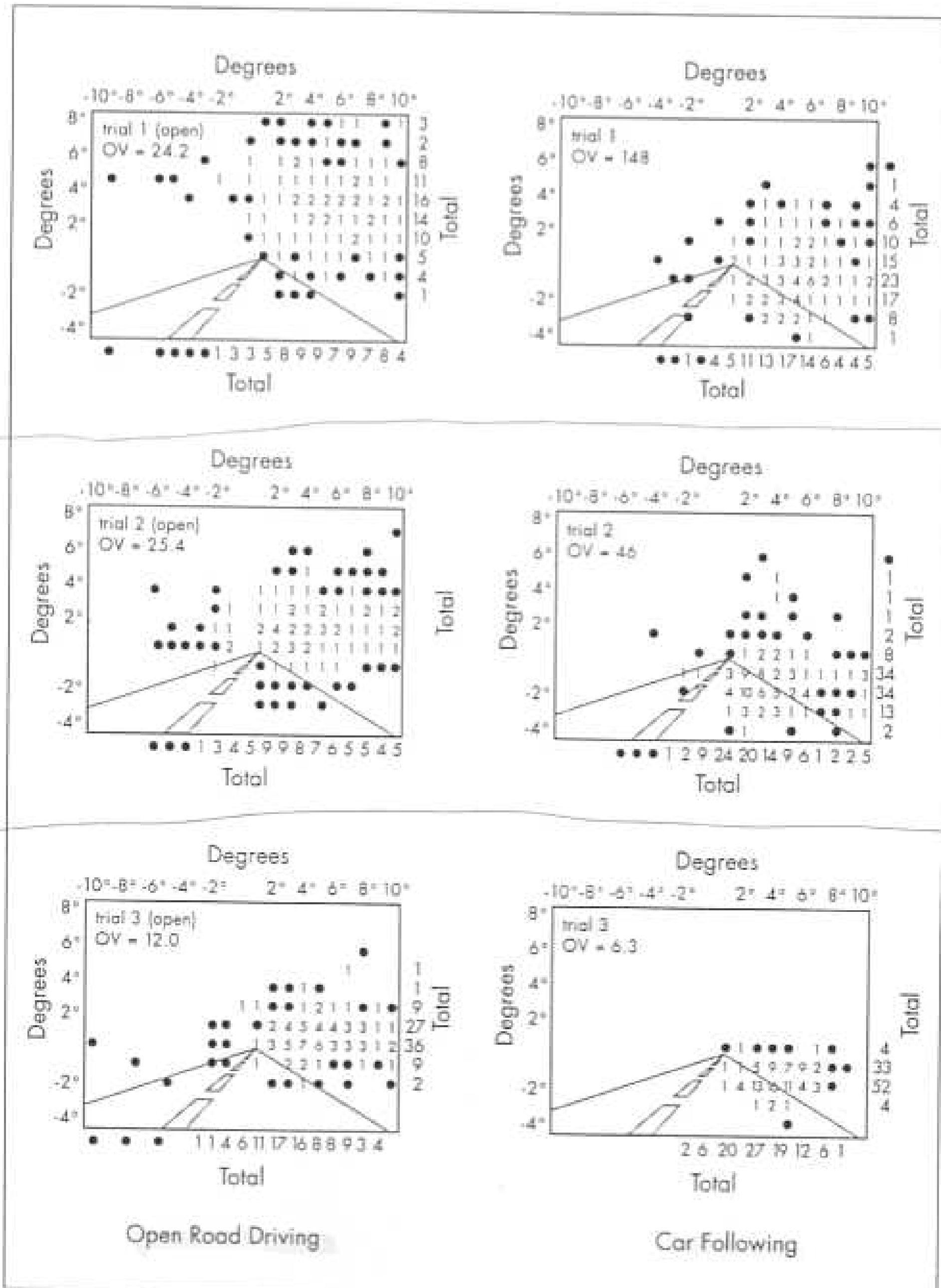

Figure 4.5

Data from one driver
Breadth of fixation shrinks for ...
Mourant, Rockwell + Rackoff (1969)

Table 4.3 shows the objects fixated upon for the just described data sets, basically straight roads. When following a vehicle, that vehicle becomes the primary source of visual information to the driver. Interestingly, one-fifth of all fixations examined in this study were to an undefined "out of view" location. Thus, drivers may spend a reasonable fraction of time looking at objects that do not promote safe driving.

Table 4.3
Sample Fixation Distribution Data (percent)

	Following			Open Road		
Category	Trial 1	2	3	1	2	3
looking ahead	31.2	32.8	30.7	50.4	54.2	58.3
lead car & other vehicles	38.8	40.4	44.3	—	—	—
vehicles	—	—	—	5.0	4.0	6.7
road & lane markers	2.2	4.3	1.8	2.2	2.3	2.0
road signs	4.9	4.3	2.5	7.5	6.2	5.4
bridges	5.8	5.0	5.4	8.0	8.1	7.1
out of view	17.1	13.2	15.3	26.9	25.2	20.5

Source: Mourant, Rockwell and Rackoff, 1969, p. 7.

For practitioners, these data provide context suggesting where drivers might normally look to first detect signs, objects in the road, and other safety-relevant items. They do not indicate, however, how likely a driver is to see a particular object. Readers seeking additional information on normal looking behavior should consult Serafin (1994).

4.4 How Is Glance Behavior Affected by the Road Environment?

A. Where do drivers look when driving curves?

Clearly driving on curves is more dangerous than driving on straight roads and one would expect some adjustment in fixation distributions due to curvature. Figure 4.6 shows the distribution of fixations to various locations on the road as a function of road geometry (straight, left curve, right curve) and the presence of a lead car for both day and night conditions (Olson, Battle and Aoki, 1989).

As was shown in the previous section, eye fixation distributions for curves are different from those for straight sections. Driving on curves has received considerable attention, in part because driving curves is more difficult than driving on straight sections, and because crashes are more likely on curves. As indicated by ratings of road "curviness," drivers are clearly aware of the key curve geometric characteristics, including both curve radius and deflection angle (a measure of curve length) (Riemersma, 1991). When driving on curves, drivers spend more time looking at the edge lines than they do for straight-ahead driving in order to obtain critical guidance cues. For example, Olson, Battle and Aoki (1989) report the fraction of time spent on the inside road edge increases from about 10 percent for a straight section to about 30 percent for left curves and about 40 percent for right curves of unspecified radii. (See Figure 4.6.) For larger curve radii, drivers tend to have larger preview distances (Jurgensohn, Neculau and Willumeit, 1991), often looking towards the vanishing point, and scatter their fixations over a wider area (Blaauw, 1975).

Eye movements for curves

When driving on a straight section of a road without a lead vehicle, about 25 percent of the time was looking at the center of the lane during the daytime versus

Day vs night

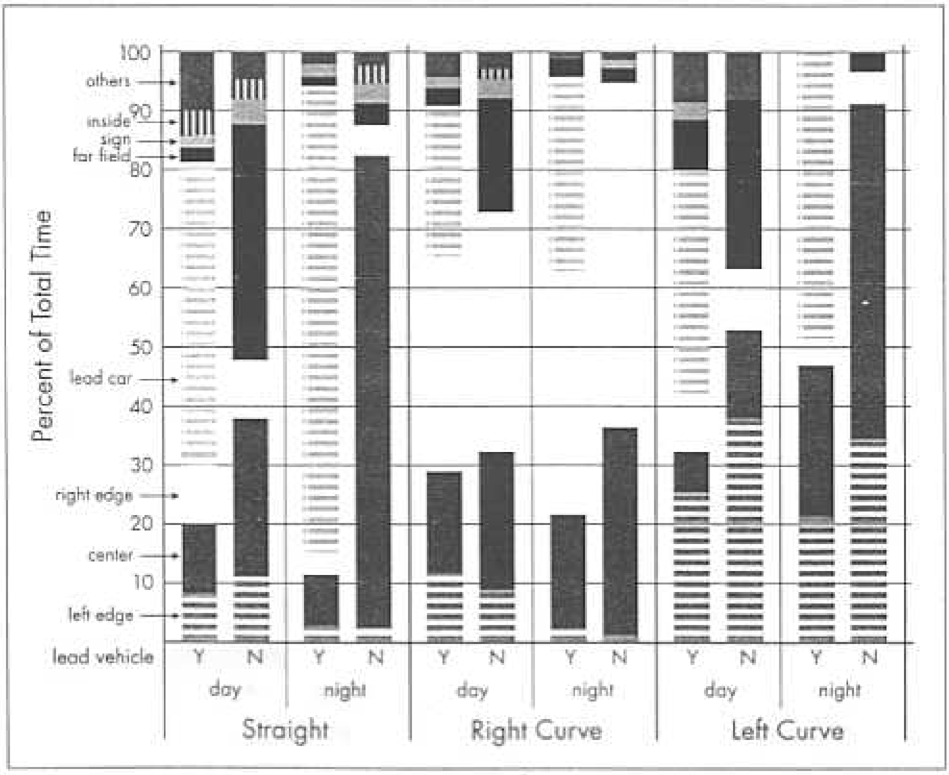

Figure 4.6 Olson, Battle & Aoki (1989)

80 percent at night. Introducing a lead vehicle raised the daytime value to 50 percent but left the night value unchanged. A different picture emerges when the percentage of fixations is the dependent measure (rather than the time as shown in Figure 4.6). For example, during the daytime without a lead vehicle, the percentage of fixations to the center of the road decreased by only a few percent. However, the nighttime value dropped to just over 50 percent of the fixations, as did the percentage of fixations to a lead vehicle. Thus, in examining glance behavior, the choice of the measure of interest (either the percentage of time or the percentage of fixations) will affect the value reported. This is because not all fixations are of equal duration, so various glance measures may not be interchangeable.

A more qualitative difference between straight and curved sections is a change in the pattern of fixations. Data from Bengler, Bernasch and Lowenau (1996) suggest that when driving curves, the predominant pattern is a large number of shifts left and right at some distance ahead of the vehicle. For straight sections, the predominant pattern is believed to involve more of a straightahead close-far variation, though such patterns are also present in curve fixation patterns. For example, Zwahlen (1993) indicates that the general pattern of fixations is to make a series of fixations, each one of which involves looking successively farther down the road followed by a fixation closer to the vehicle to restart the sequence. The ratio of fixation sequences that ends with a forward fixation versus a backward fixation is 3:1. Similarly, Jurgensohn, Neculau and Willumeit (1991) refer to a sawtooth pattern of fixation distances.

SAWTOOTH PATTERN

Where drivers look on curves also depends on the curve radius. For example, Fitzpatrick et al. (2000) had subjects drive a simulator depicting a single lane road and periodically request a 0.5 second glimpse of the road (normally blocked by a translucent face shield) by pressing a button. Based on the analysis of fixation of twelve selected subjects, where drivers looked varied with the curve radius (Figure 4.7). Notice that as the curve radius increased, the likelihood the driver would look inside the curve to obtain guidance information decreased. How likely drivers are to see signs and pedestrians in high demand situations will depend on where drivers normally look. These data suggest a tendency to look towards the inside of a curve, especially in a right curve. However, one must bear in mind that the sight distance along the inside of a curve is generally less than the sight distance along the outside of the curve. Detection occurs when a target is in view (which depends on sight distance) and when the driver looking at it (which in turn depends on where they look most often).

occlusion technique

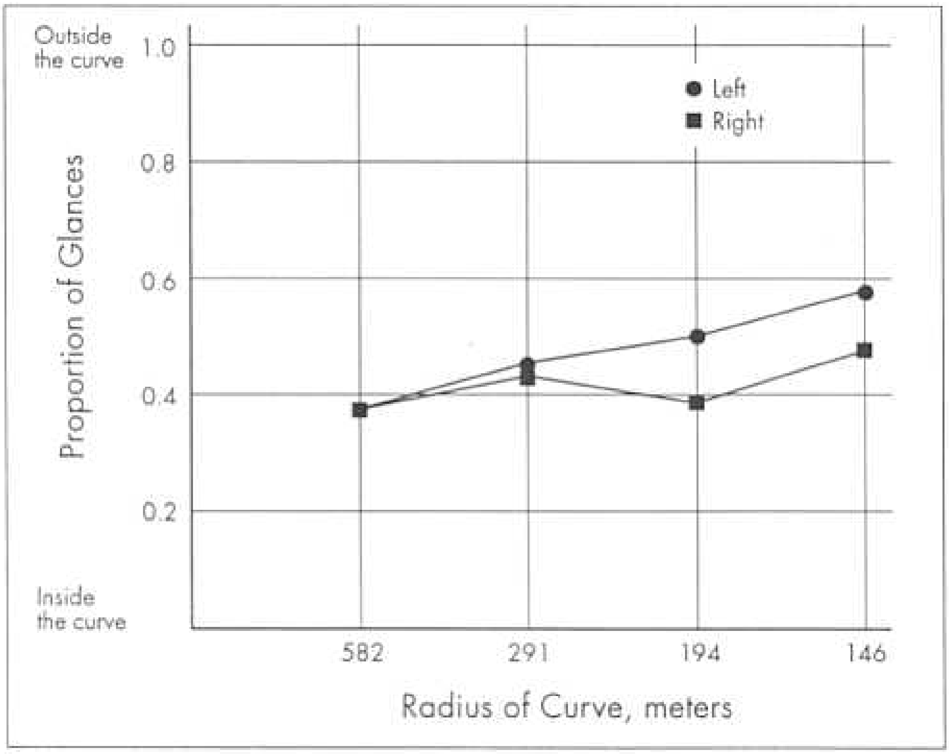

Figure 4.7 data from occlusion technique in simulator Fitzpatrick et al (2000)

Other evidence on where drivers look comes from Afonso, Brandelon, Huerre and Sa Da Cost (1993). Data were collected both on a test track and on the open road with two sets of ten drivers. Based on the data presented, the authors estimate that for experienced drivers the mean fixation distance (meters) = 0.19 × speed + 21 where speed is in kilometers per hour. For the same group, the mean fixation time (milliseconds) = 0.04 × curve radius + 240, where the radius is measured in meters. For novices, the sight distance is typically 10 to 20 meters less than experienced drivers, with the difference between the two groups increasing with speed. Mean fixation times for novices were about 10 milliseconds less than for experienced drivers, a tiny amount, though the difference increased with horizontal curve radius.

To identify the curvature cues used by drivers, Land and Horwood (1995) showed subjects a simulated curving road on a computer monitor. Three drivers were shown one or two 1-degree horizontal slices of the road scene positioned from 1 to 10 degrees below the horizon. (See Figure 4.8.)

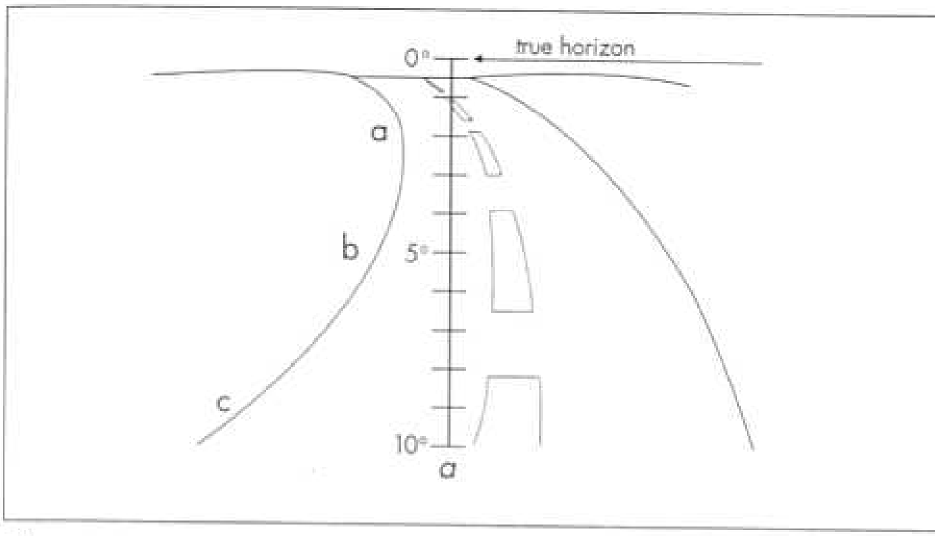

Figure 4.8

When a single horizontal slice of the road was shown near the horizon, steering inputs were smooth but lane position stability was poor. When the segment was near, lane position stability was good but steering inputs were jerky. When two strips of the road were shown, performance was best when the strips were widely separated, i.e., one was quite close to the vehicle and the other near the horizon. This suggests that it is not all of the road that is critical to steering, but specific portions. Thus, if a person was driving and the edge lines at a midrange distance were not visible, but those close to the vehicle and those near the horizon were visible, one would expect a minimal decrement in driving performance.

Not only do the portions of the road vary in their importance to steering overall, but their importance varies as a function of road geometry as well. Laya (1992) collected data from four curves, both in a simulator and on a real road, for beginners and experienced drivers. Laya reported the scan paths for experienced drivers varied when approaching, driving, and exiting a large radius curve, in three distinct phases as shown in Figure 4.9. Land and Horwood (1996) express similar views. The scan paths were more concentrated for right curves than left curves, especially for experienced drivers and at higher speeds. For real roads, while in the curve, there were two scan patterns, one near the middle of the road and a second alternating between near and far locations on the road. During the exit phase, glances were scattered over a wider range. It is important to emphasize that these phases depend on what the driver can see (e.g., the beginning of a curve), not the current location (in a straight section).

Laya (1992)

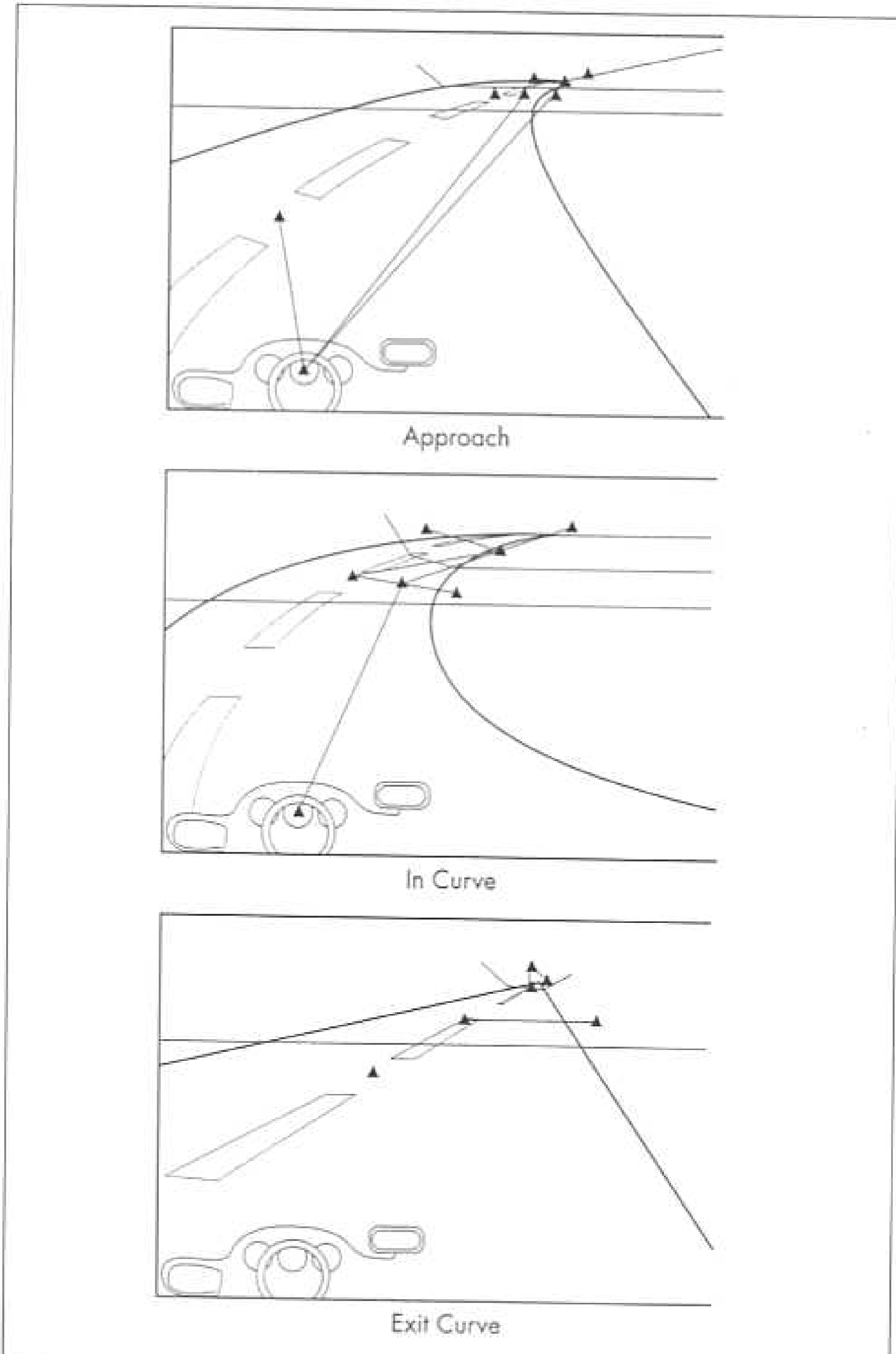

Figure 4.9

Loya (1992)
IATSS Journal

More to the point, Tsimhoni and Green (1999) conducted an experiment using the visual occlusion method described earlier (pushing a button to get a glimpse of a road), reporting the fraction of time the road could be seen as a function of position along a curve. They found that the visual demand began to increase about 100 meters before the curve, peak just after the beginning of the curve, and drop off throughout the curve. The demand of the exit did not mirror the demand of the entry. This suggests that if a regulatory or guide sign must be placed along a curve, it should occur at the end.

Although there is general agreement as to what elements of curves are important for safe driving, there may be some disagreement as to the values associated with fixations to various locations. Table 4.4 shows the percentage of fixations from Blaauw (1975) for two similar curves (approximately 90 meters radius) found at an interchange, along with data from Olson, et al. (1989) for a curve of unknown radius. Notice that within Blaauw's study (and based on data from only two curves) fixation percentages to particular zones generally differ by less than 3 percent, except for the percentage of fixations to the sky, where the difference is just over 14 percent.

Table 4.4
Fixation Percentages for Two Studies

Olson et al.'s Locations	Blaauw's Locations	left curve 1 Blaauw	left curve 2 Blaauw	left curve Olson
left edge	left edge + left marker	1.3	5.3	28
	left lane	7.5	10.4	
center	center marker	3.4	3.2	20
	right lane	14.2	17.8	
right edge	right edge + right marker	15.0	13.5	10
far field	sky	42.2	27.9	26
sign + inside + others	others	16.4	21.9	16

In contrast, the differences with Olson's data are often 15 percent for critical locations. However, since neither author provides a precise description of how the locations were defined, locations that share the same names could, in fact, be quite different.

Thus, there is considerable data on driving curves. The key finding is that the pattern of fixations varies with the portion of the curve sequence (approach and entry, in curve, exit), with demand being greatest at the entry. Exiting a curve does not mirror entering a curve. Thus, in evaluating hazards associated with curves, the approach and entry sections deserve particular attention.

B. How do traffic and other external demands affect where drivers look?

A significant amount of driving occurs in traffic and drivers often look at traffic when it is present. Nonetheless, the number of studies that involve driving in traffic has not been overwhelming. (See, for example, Sivak, Conn and Olson, 1986.) One potential driver response to significant external demands (for example, due to traffic or excessively high speeds) is perceptual narrowing or tunnel vision. In this response, drivers may compensate to avoid overload and re-

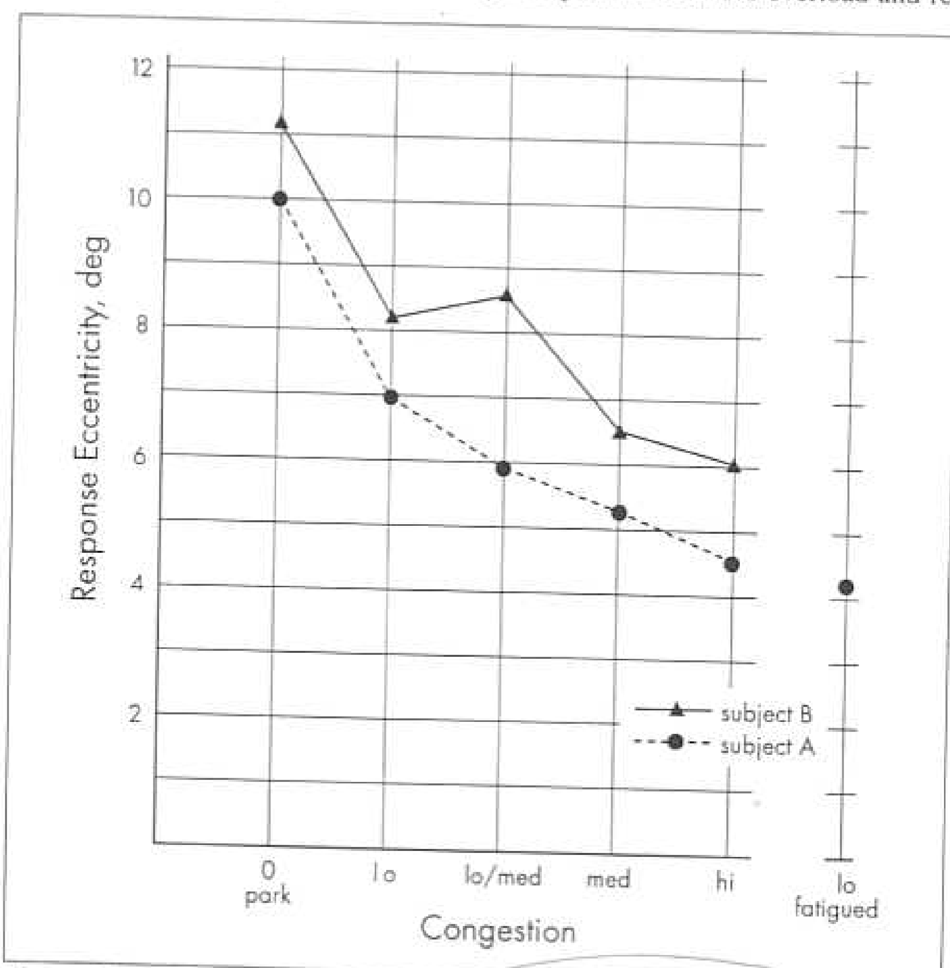

Figure 4.10

Miura (1992)

reduced UFOV (whole living) as a function of increased demand duce the field of view searched, concentrating on objects directly in front of them. In examining eye fixations for roads driven at two speeds, Kayser and Hess (1991) (see also Spijkers, 1992), found that the average number of fixations within a constant (50-meter) interval decreased as speed increased, but the mean duration of fixations increased, suggesting that perceptual narrowing does not occur. Kayser and Hess suggest that with increased demand, it is not that the periphery is ignored, just the less important targets (which tend to be on the periphery).

In contrast, Miura (1992) had subjects press a button when a small, randomly located target appeared on the windshield. Data were collected when the vehicle was stationary and while driving for four levels of traffic density. Figure 4.10 shows the data for the two subjects tested, with points farther to the right on the horizontal axis representing more challenging driving conditions. The vertical axis, the response eccentricity, an indicator of the size of the visual field, is apparently defined as the angle between a fixation point and a target that could be detected reliably. As demand increased, the visual field size decreased, supporting a perceptual narrowing explanation.

Thus, how looking behavior changes as a function of workload is a matter of debate. Most interesting, however, is the lack of data for congested situations, those in which crashes are most likely. This may, in fact, be due to the difficulty of conducting experiments in situations where the risk is high. For related material, see the section on the useful field of view in Chapter 2.

C. How have eye fixation data been used to assess the merits of road and vehicle markings, and signs?

Road edge markings, road signs (Bhise and Rockwell, 1973), and reflective treatments on trucks have all been designed so they can be readily seen by drivers, especially at night. As an example of work on this topic, Green and Olson (1979) examined the eye fixations of three drivers while driving an oval test track at night. Dummy targets (panels with various reflective markings) were place around the test track. The subjects identified the target orientation. Unknown to the subjects, the reflective treatment on a trailer parked on the side of the track was periodically changed. As expected, increases in the amount of reflective treatment on the trailer increased the percentage of time fixating on it, both for side and end views of the trailer.

As was noted earlier, the results of fixation studies are reinforced by the fact that drivers recalled seeing objects of interest. Together, these methods are very useful in assessing the effectiveness of markings. In many situations, the evidence desired might not be statistical data, but videotapes, for example, of drivers fixating on objects they alleged they could not see.

There have been a number of studies that have examined driver eye fixations to signs. For example, Zwahlen (1987) had forty subjects drive a two-lane rural road. For half of the subjects, speed advisory signs were provided in addition to curve warning signs for two curves of interest. Adding the speed advisory signs did not affect either the driving performance or eye fixations (two fixations of 0.5 to 0.6 seconds in both cases), suggesting the speed advisory signs provided no more benefit than curve warning signs alone. In this case, the absence of a change in fixation behavior strengthened the conclusions.

Zwahlen (1995)

In a related experiment (Zwahlen, 1995), thirty-two subjects drove on a rural two-lane road at night. Zwahlen again found that most curve warning signs were fixated twice, separated by a fixation to the road. The mean duration of the first look was 0.52 seconds and 0.50 seconds for the second look, differences that are quite small. A typical look to the road lasted 0.43. These data were used to develop a method to compute the minimum required legibility distance.

4.5 How Does Glance Behavior Change with Driver Characteristics?

A. How does glance behavior change with driving experience?

In human factors studies, individual differences are often the largest source of variability, so understanding them is important. Mourant and Rockwell (1972) collected eye fixations from six novice and four experienced drivers. Although there were no large differences among novice drivers in their scanning patterns as they became more experienced, there were large differences between novices and experienced drivers. Experienced drivers tended to look farther ahead, scan a wider area, and sample their mirrors more often. Mourant and Rockwell believe that novice drivers are overloaded and scan accordingly.

In contrast, Crundall and Underwood (1998), in an experiment involving thirty-two drivers, found no differences in the horizontal variability of the fixation locations between novices and experienced drivers, except for expressways, where the variability was greater for experienced drivers. Vertical variability was consistently greater for novices. Interestingly, the search strategies of novices were similar for all types of roads. The novice drivers in the Crundall and Underwood study were more experienced than those in Mourant and Rockwell (a mean of 0.2 years experience versus fifteen minutes in some cases) which may explain why there were the differences between studies.

Laya (1992) found that driving experience leads to shorter glance durations (means of 262 milliseconds for experienced drivers, and 296 milliseconds for novices). Similarly, Crundall and Underwood (1998) reported that experienced drivers had shorter fixation durations for suburban roads (324 versus 335 ms) and divided highways (349 versus 395 ms), but not for rural roads (381 versus 364 ms). Although statistically significant differences are claimed, these differences are at the limits of recording accuracy at 30 Hz (33 millisecond per video frame).

Thus, with driving expertise, drivers not only become more proficient in steering and maintaining a steady speed, but after years of practice, they alter where they look and for how long. Coupled with differences in willingness to engage in risky behavior, differences in search patterns serve as an explanation for why young drivers have crash rates in excess of middle-aged drivers.

B. What is the effect of fatigue on glance behavior?

Kaluger and Smith (1970) had each of three subjects drive on an expressway for a nine-hour session (with brief stops), and after twenty-four hours without sleep, for an additional session. Subjects were extremely drowsy in some sessions and some fixation data were lost due to drooping eyelids.

When drivers were fatigued, their mean fixation location was closer to their own vehicle by up to two degrees visual angle, and for some unknown reason, the average gaze location shifted two degrees to the right. In one of the fatigue conditions, the variability of the gaze location was reduced, suggesting perceptual narrowing. None of these changes were affected by the speed driven.

Galley and Andres (1996) reported the effects of fatigue when combined with minimal alcohol congestion (which they claimed should induce tiredness). Some fifteen drivers drove on an expressway for six hours, once with alcohol and once without. They did not find that alcohol or fatigue decreased saccadic (transition) velocity or increased blink rate, as had been found in the laboratory.

Thus, taken as a whole, it is uncertain if gaze patterns change as a function of fatigue. In attempting to explain the cause of fatigue related crashes, factors other than changes in scanning behavior should be considered first.

C. How do alcohol and other drugs affect eye movements?

Tharp equation

The drug of greatest concern in driving is alcohol. As is well known, increasing the concentration of alcohol in the blood increases gaze nystagmus (rapid horizontal oscillation of the eyes). According to the Tharp equation, the angle (in degrees) of the onset of nystagmus, the angle from looking straight ahead at which it is first detected = 51 – (105 × (BAC %)) (Goding and Dobie, 1986). Many police departments measure the onset of nystagmus in field sobriety tests, a procedure clearly supported by the literature.

A more general summary of the effects of a variety of drugs on eye movements (Table 4.5) appears in Stapleton, Gutherie and Linnoila (1986). (See also Table 4.6.) Notice that the emphasis of the summary is on the effects one might assess in a laboratory, not on the road (for example, of gaze patterns or distances). Stapleton, Gutherie and Linnoila also report that alcohol increases fixation durations (in contrast to Galley and Andres, 1996) and the number of correcting saccades, as well as decreases the chance of detecting critical, peripheral events and the smooth tracking of vehicles. Clearly, the effect of a particular drug on eye movements, and consequently on driving safety, is drug specific. Further, the number of drugs for which the effect on driving or driver's eye movements has been considered is extremely limited. This is of concern, given the need to provide warnings regarding drug administration and driving.

Table 4.5
Effects of a Variety of Drugs on Eye Movements

		alcohol	barbitu-rates	benzodi-azepines	metha-done	marijuana
saccade	max velocity	slowed	slowed	slowed	no change	no change
	latency	increase	increase	no change	no change	no change
	accuracy	no change	no change	undershoot	undershoot	no change
smooth pursuit	max velocity	slowed	slowed	slowed	no change	no change
	gain	decrease	decrease	decrease	no change	no change
nystagmus		produces & modifies	produces & modifies	modifies	unknown	no change
vergence		impaired	impaired	unknown	unknown	impaired

Table 4.6
Definition of Terms as Used to Describe Eye Movements in Table 4.5

Term	Definition
saccade	normal transition from one location to another, for example from the road to a mirror
smooth pursuit	movements that occur when the eyes are following a moving target such as a pedestrian
nystagus	normal tremor in the eye when looking at a location, mostly from side to side
undershoot	a movement that falls short of a target
gain	level of magnification, in this instance, how much eye movements increase as target movements increase

4.6 What Is the Effect of Vehicle Characteristics on Glance Behavior?

A. How do eye glance patterns vary as a function of the vehicle driven?

Kito, Haraguchi, Funatsu, Sato and Kondo (1989) collected eye fixation data in Japan in a car and a twelve-meter trailer truck. Both vehicles were right-hand drive (another distinction often ignored). Data were collected from five professional truck drivers, each of whom made ten turns in each vehicle at one intersection.

The general pattern of glances was first a transition to the left or right (depending upon the turn direction), a short fixation, a transition in the opposite direction, another fixation, and so on, with gazes in the direction of the turn being most frequent. In part, this is because when driving on the left (as in Japan), a right turn involves crossing traffic. When driving on the right (as in the U.S.), one would expect glances to predominate in the direction opposite of the turn where crossing traffic occurs.

There were also significant differences due to vehicle type, with the number of "gaze movements" of large extent being greater for the truck, possibly because it required more time to complete the turn, so a greater clear distance was required (Figure 4.11). Furthermore, glances in the truck were clustered around 60 degrees from straight ahead, the location of the left rearview mirror. For large trucks, blind spots are a particular concern.

Differences due to vehicle type were also reported by Nagayama, Morita, Miura, Watanabem and Murakami (1979). They had three young men drive either a 650 cc motorcycle or a small passenger car on an arterial road. On average, the distribution of gaze fixation when driving the motorcycle was about six degrees below that for the car when driving. Further, about 30 percent of the motorcyclists' eye fixations were to the road, while that rarely occurred for the car. This difference in the look down angle was due to the different driving position of the motorcycle (the head is tilted downward slightly) and because the motorcyclist needs to be concerned about road bumps and potholes to avoid spilling, whereas a car is usually unaffected by bumps.

In the second experiment, eye fixations of three subjects were examined while driving two motorcycles (50, 400 cc) and an automobile. For the automobile, drivers tended to look farther ahead as the speed driven increased. In the larger motorcycle, drivers tended to look closer as speed increased, whereas for the light motorcycle, they looked closest when driving at 45 kilometers per hour as contrasted with higher and lower speeds. The statistical significance of these differences was not reported. Further, fixation durations tended to be longer for cars (150 milliseconds) than for both types of motorcycles (100 to 110 milliseconds). Given that the data were recorded at 18 frames/second (56 milliseconds/frame), the meaningfulness of these duration differences is uncertain. Thus, although the data set is rich, the lack of statistics makes their interpretation difficult. For additional data, readers should see Mortimer and Jorgeson (1975).

To summarize, the emphasis of driver eye fixation research has been on drivers of passenger cars. However, at the current time, over 50 percent of the vehicles sold in the U.S. are light trucks, minivans, sport utility vehicles, and heavy trucks, not passenger cars. In other parts of the world, motorcycles, motorbikes, and trucks predominate, and there is little understanding of how eye fixations for those types of vehicle differ from one another and from passenger cars. What drivers can see depends upon their eye height above the road, the field of view offered by the windshield glazing, and the location and size of mirrors. One reason for the popularity of light trucks, minivans, and sport utility vehicles is that the driver eye position is higher than for cars, enabling drivers to see farther down the road and over other vehicles. However, data for these classes of ve-

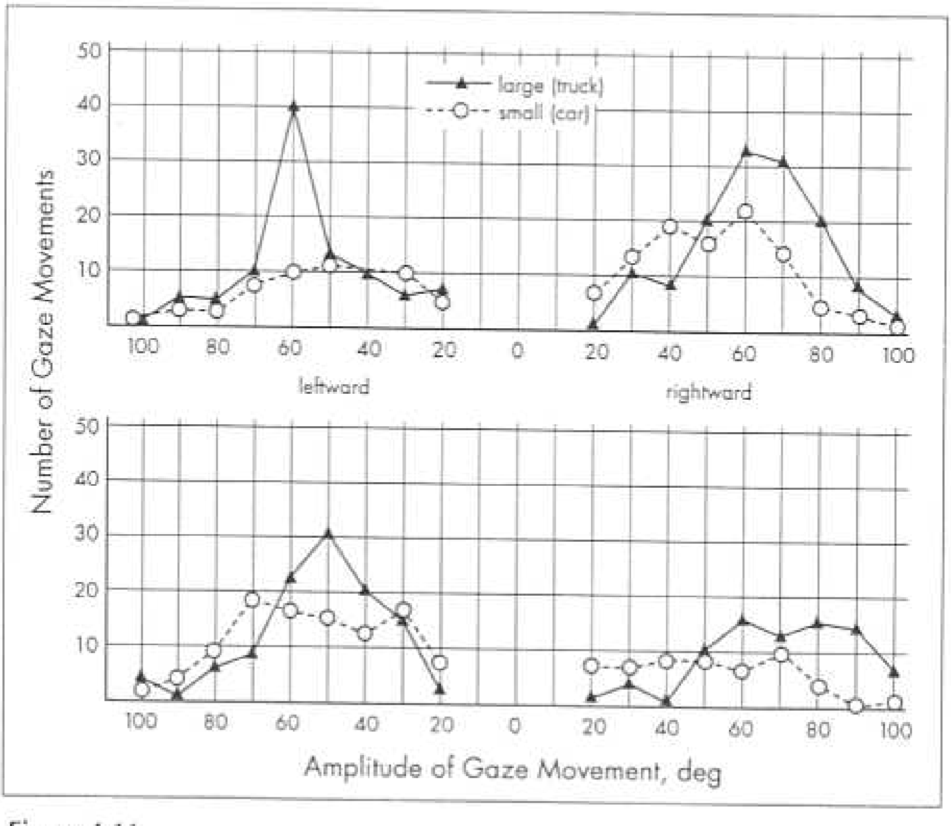

Figure 4.11

hicles are lacking. One would suspect that fixation patterns would change accordingly. This point must be kept in mind when applying older data collected in passenger cars to modern situations.

B. How does scene illumination alter glance characteristics?

night vs day

Mortimer and Jorgeson (1974) explored the relationship between eye fixation distributions and vehicle beam patterns for two drivers, a small sample. Baseline fixation data were also collected for both day and night driving. They found that the mean fixation duration (dwell time) was greater at night than during the day, but only on curves (Table 4.7). At night, fixations increased in frequency but decreased in duration the closer the target was to the vehicle. On straight sections of road, drivers looked less in the left lane at night than during the day. Opposing vehicles received 14 percent of the fixations during the day and 21 percent at night. (capture by opposing headlights)

In addition to differences in fixation distributions between headlamp illuminated night scenes and uniformly illuminated day scenes, there were also differences found between the various beam patterns examined. Just as in the adage that people look for the lost coin under the streetlight, because there is light there, so too do eye fixations remain mostly in the areas that are illuminated by the headlamps. Thus, when determining what drivers might be able to see at night prior to a crash (either based on the literature or test data), it is important to keep in mind the beam patterns of the vehicles being compared.

Table 4.7
Mean Fixation Duration (seconds) as a Function of Light Level

Road geometry	Day	Night
left curve	0.43	1.05
straight	1.93	1.18
right curve	0.47	1.35

Source: Mortimer and Jorgeson (1974), p. 10.

4.7 How Might In-Vehicle Devices Affect Driving?

The driver's task in the future may be quite different from what it is at present. Some systems, such as adaptive cruise control and lane maintenance, have the potential of disengaging drivers from real-time control. Others, such as navigation and other driver information systems, have the potential of overloading the driver and increasing the probability of a crash. Studies of driver eye fixations could provide insights into how these systems might affect driving.

A. What is typical looking behavior for in-vehicle devices?
Extensive data that relate to the use of in-vehicle features appears in Wierwille, Antin, Dingus and Hulse (1988). (See also Kishi, Sugiura and Kimura, 1992 and the section on in-vehicle devices in Chapter 10 of this book.) Figure 4.12 shows the mean glance times and the number of glances for a variety of in-vehicle tasks such as operating a vent, adjusting the fan and power mirror, etc. The navigation system-related times included determining the distance to the destination, changing the zoom level of the map, identifying the next cross street, etc. The very simple navigation system examined required consistently more glances and longer glances than conventional in-vehicle systems. Tijerina, Parmer and Goodman (1998) have reported much larger differences for tasks such as destination entry, use of cell phones, etc.

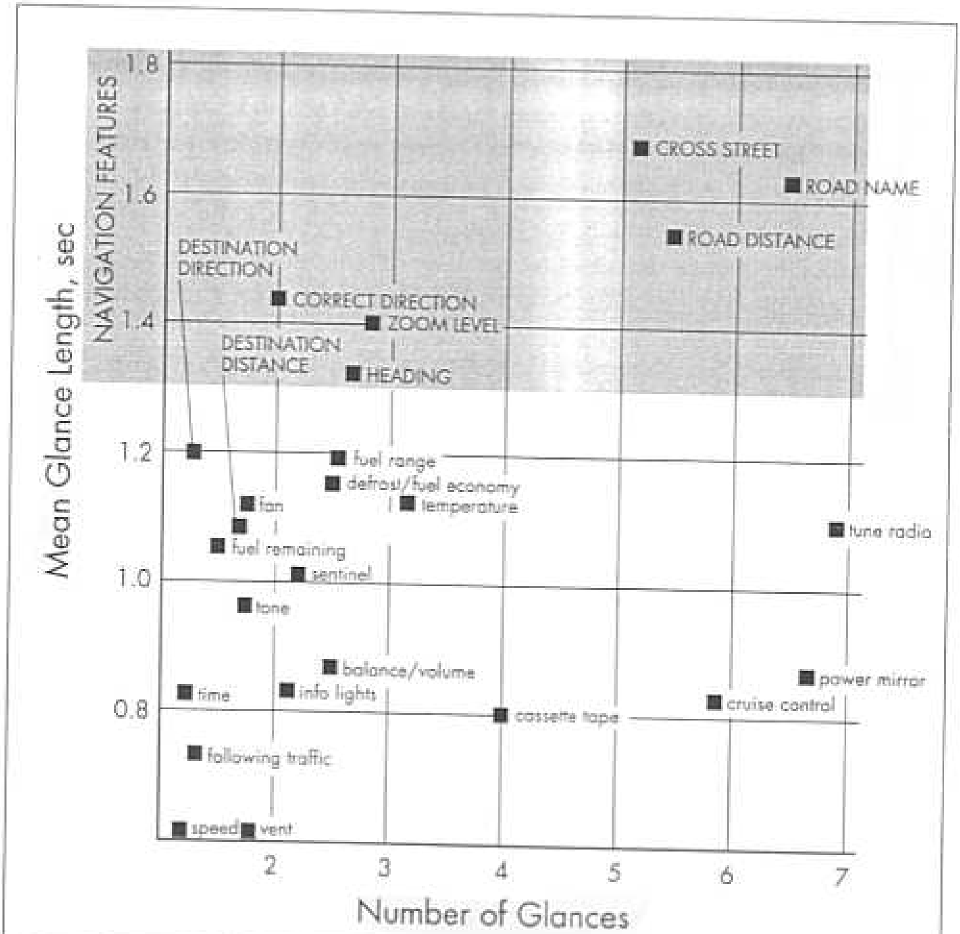

Figure 4.12

Wierwille et al (1988)

B. How long can drivers look to the vehicle interior?

Another aspect of in-vehicle looking is how long driver are willing to look to the vehicle interior when there is no task to engage their attention. The value obtained may depend upon the decision criteria used by drivers such as (1) limiting the probability of a crash, (2) limiting the probability of a lane departure, or (3) achieving some subjective level of comfort/discomfort for the driving situation while looking away (Green, 1999b). Hada (1994) had twenty-two drivers look to windshield location, instrument cluster, or the center console locations where a display might appear for as long and as often as was deemed safe. The mean glance times were 1.09 seconds for driving on an expressway, 1.00 second for a rural road, and 0.84 second for a suburban street. Figure 4.13 shows the histogram of glance durations for all conditions. Consistent with the literature, the data follow a log-normal distribution. The 95th percentile is 2.2 seconds and the 99th percentile is 3.6 seconds. In contrast, the 10th percentile is less than 0.3 second. Thus, while long glance durations are possible at times, drivers feel safe when the durations are short, much shorter than typically required by the simple navigation tasks described previously.

Relate this to our ITSCAN2 data

These data and considerable other evidence (Green, 1999b) have served as the basis for SAE J2364 (Society of Automotive Engineers, 1999a), the recommended practice that specifies what drivers should be allowed to do while driv-

SAE 15-sec rule

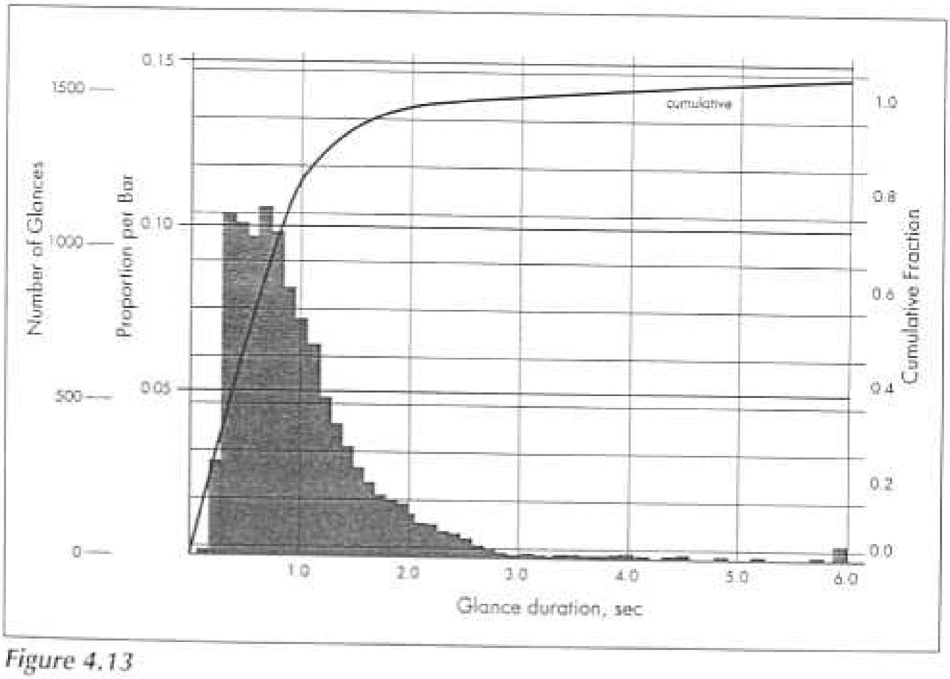

Figure 4.13

ing. In brief, no task, when tested statically, should take more than 15 seconds to complete (Society of Automotive Engineers, 1999b). This recommended practice, commonly known as the "15-second rule," does not imply that the driver can safely look away from the road for 15 seconds. For most tasks of 15 seconds' duration, the eyes-off-the-road time should be much less and will consist of a series of glances, not just one. Total task time was selected as the performance measure because it is easy to collect, correlated with eyes-off-the-road time, and calculable early in design (when design changes are easy to make). For tasks that are predominantly visual (e.g., reading maps), the glance duration data provided in this chapter should also be considered in establishing what is safe for drivers to do.

4.8 Conclusions

The intent of this chapter was to provide an understanding of driver eye fixations to promote safe driving, identify crash inducing contexts, and provide a basis for further study. In sum, this review makes fifteen key points.

1. The elemental unit of visual behavior is a fixation. A glance is a continuous sequence of one or more fixations to a target (sign, edge marking, gauge) along with the movements between fixations on that object. For automotive safety the primary measure of interest is the sum of the glance durations not directed towards the road, the eyes-off-the-road time. In some situations, eyes-off-the-road times can exceed 2.5 seconds.

2. Glancing at a target more than 15 degrees from the current point of regard usually involves (a) a rapid eye movement to the target, (b) a head movement 50 milliseconds later, and (c) counter rotation of the eye as the head is aligned with the target.

3. Fixation, glance, and search task durations are log-normally distributed.

4. Eye fixation data are difficult to collect, reduce, and analyze, and for that reason, they are not frequently measured by researchers. The most common data collection procedure is to aim a camera at the driver's face and record what transpires, not to use specialized recording systems. The temporal resolution of most eye fixation recording systems is 33 milliseconds. The fixation zones to identify where drivers look are not consistently defined, making the comparison of studies problematic. Because of the effort required, fixation studies often involve small subject sample sizes (four or less) and brief data collection intervals (one minute samples).

5. When drivers are not looking at the road, crash risk is increased. The expected number of fatalities from an in-vehicle task can be predicted from a combination of the number of glances to the device per use, the mean glance duration, and the frequency of use of the device (per week).

6. Glance data provide a useful but not perfect indicator of which objects in the driving environment are garnering the drivers' attention. The longer a glance towards an object, the more likely it will be noticed. When drivers do not look at the most significant objects for driving safely, changes in the environment, vehicles, driver selection, or driver training should be considered.

7. Where drivers look depends upon the driving situation. When there is no traffic, about one half of the glances are straight ahead. When there is a lead vehicle to follow, about 40 percent of the glances are to that vehicle and 30 percent to other locations ahead. The effect of following distance has not been examined.

8. Fixation patterns vary with road geometry (e.g., curves versus straight sections) with drivers looking more to edge markings on curves. The edge fixated upon depends on curve radius and curve direction. The eye fixation patterns for curves consist of three distinct phases: approach, driving the curve, and exiting. When in the curve, drivers use the road edges near the horizon to determine the curve radius (and to adjust the vehicle heading) and the edges near the car to adjust the lateral position.

9. The general scan pattern is for the driver to begin scanning close to the vehicle, make approximately two additional fixations to successively greater distances, and then repeat the pattern looking close to the vehicle.

10. As the demands of driving increase (e.g., more traffic), slight changes may occur in where drivers look (perceptual narrowing). Drivers may spend less time on secondary targets as demand increases.

11. Experienced drivers have somewhat shorter fixation durations than novice drivers. However, older drivers have slightly longer mean fixation durations than younger drivers.

12. Though there is little evidence available, the effect of fatigue on glance parameters appears to be minimal.

13. The effect of drugs and alcohol on eye movements is substance specific. The angle at which nystagmus (tremor of the eye when looking to the side) first occurs is directly related to BAC.

14. Eye fixation patterns vary with the vehicle type. For motorcycles, drivers tend to concentrate their fixations much closer to the vehicle than they would in a passenger car. In a large truck, the mirrors tend to receive more fixations than they would in a passenger car.

15. Data from driver eye fixations suggest that drivers feel comfortable looking inside a vehicle for about one second on average, though sometimes longer durations are acceptable. For many contemporary in-vehicle systems, glance durations are on the order of 1.0 to 1.5 seconds. For complex driver information systems, glance durations can be longer. When presented with complex tasks,

drivers increase the number of glances to the vehicle interior (separated by glances to the road), but do little to alter glance duration.

4.9 A Final Thought

Practitioners may find the current state of knowledge of driver eye fixations to be incomplete. There is a solid body of knowledge concerning the general process of controlling driver eye fixations, and some detailed information on driving under specific conditions. There are also data that provide an understanding of how various characteristics of the driving task and environment (curves, day versus night, vehicle type, in-vehicle task, etc.) generally affect driver looking behavior. What is missing from the literature, and what practitioners need most, is normative glance data for drivers of all ages for a wide variety of road geometries, vehicle types, lighting conditions, and driver states. Without such information, making decisions about what is atypical, unreasonable, or unsafe is a challenge.

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