Review of Eye Fixation Recording Methods and Equipment

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16. Abstract

This report describes various methods for recording eye fixations including direct vision systems, indirect vision systems, EOG, limbus tracking, pupil tracking, corneal reflection, laser doppler, and direct contact. Products made by Applied Science Laboratories, BioPac, ISCAN, NAC, and Takei for this purpose are covered in detail. Information on other vendors is also provided. For automotive applications, off-the-head (remote) eye fixation recording systems from Applied Science Laboratories (model 4000) and ISCAN (Headhunter) should be considered for in-vehicle studies. These systems are very costly (typically $40,000-$50,000 or more). Experience has shown that weight and calibration problems are common with older on-the-head systems (e.g., NAC model V).

Where cost limitations exist, it may be possible to develop a custom on-the-head system that utilizes both EOG hardware (for a wide operating range) from BioPac and limbus tracking equipment (for central field of view accuracy) from either Applied Science Laboratories (model 210) or Permobil Meditech (model Ober 2). To identify gaze direction relative to the world, a head tracker (purchased from Polhemus or Ascension Technology) would also be needed. That system should be designed to avoid manual data reduction.

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Table of Contents

Forward

The report was supported by funding from the University of Michigan IVHS Industrial Advisory Board, a consortium of companies and government organizations that have provided gift funds to support research. The purpose of this report is to review the literature on the collection and analysis of eye fixations, emphasizing automotive applications and data collection hardware. Funding limitations prevent it from being an exhaustive review of the topic. Limited information on head sensors is also provided.

Sponsors of this research include:

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Several gaps in this report may exist, especially concerning equipment found only in Japan. It is hoped that feedback from sponsors of the research can be used to fill those gaps and will lead to an updated version of this report.

I would like to thank Mr. Hideki Hada of Mitsubishi and Mr. Takao Ishiwaka of Nissan, as well as Marie Williams, Eileen Hoekstra, Ann Grimm, and Colleen Serafin of UMTRI for reviewing drafts of this report, and especially Mr. Bill Janson of Logicon Technical Services for his extensive comments. The author would also like to thank Jose Velez of Applied Science Laboratories and Rikki Razdan of ISCAN for their input.

What Are the Objectives of This Report?

The goal of this report is to review the literature on the collection and analysis of eye fixations, emphasizing automotive applications and data collection hardware. Specifically, the report considers the following questions:

1. How can the direction of gaze be measured?
2. What are the advantages and disadvantages of each method?
3. What products are available for measuring the direction of gaze (and, to a lesser extent, head position)?
4. How much do the various products cost and what problems do they have?

Sections that follow consider why recording eye fixations is important for studying driving, methods for recording the direction of gaze, existing products, head trackers, occlusion devices, and the analysis of eye fixation data. Recommendations are also given.

Why Are Eye Fixations Important?

Driving is a task that the typical person performs an average of one hour per day for his or her entire adult life. It is one of the leading killers of young adults, with total deaths being just under 50,000 per year in the U.S. (U.S. Department of Transportation, 1989) and 11,000 per year in Japan.

Yet, at a detailed level, driving is not well understood. The purpose of driving is to get from an origin to a destination safely and efficiently. Guided basically by what they see, drivers manipulate a steering wheel to keep a vehicle in a lane. In addition, drivers also operate the brake and accelerator to control speed in response to other vehicles and traffic signals. Some researchers have remarked that 90 percent of the input in driving is visual, though it is unclear how driving input could be measured to reach such a conclusion. Nonetheless, it is apparent that what the drivers can see is critical and when visual input is diminished, by distractions, age, or inattention, performance can degrade and accidents may result. Hence, understanding where, when, and why drivers look is important. Typically, there are three measures of importance: the mean duration of each fixation to particular features (road edges, other cars, instrumentation, etc.), the number of fixations to each feature per unit time, and total glance time, the product of the first two measures.

Other measures of the attentional demands of driving (and safe driving behavior) include lane variance, speed variance, steering wheel reversals, time-to-line crossing, and time-to-collision, to name a few. Lane and speed variance refer to the moment-to-moment variability associated with staying in one's lane and driving at a constant speed. Clearly those driving erratically are more likely to have accidents.

Steering wheel reversals are an output-related measure (Verwey, 1991). As drivers become more fatigued and pay less attention to driving, they make fewer small corrections in steering but more large corrections. This often results in no change in mean lane error and sometimes only a small increase in lane variance.

Time-to-line crossing (TLC) is defined as how long it will take for any tire on the vehicle to touch any lane edge marking as the vehicle continues on its current course at the current speed (Godthelp, Milgram, and Blaauw, 1984). TLC computations require information on current speed, lane position, and yaw angle. This information is generally not available. Time-to-collision is how long it will take the vehicle to hit an object if steering and foot control inputs remain fixed. Current thinking is that drivers maintain a several second "cocoon" of safety around their vehicles and risk increases when the safety margin is reduced.

While all of these measures are important to those interested in safety, eye fixation measures are most important to engineers who are designing new in-vehicle driver information systems. Clearly, electronic maps, warning displays, and other information sources being added to cars should not be time-consuming to read. If they are, drivers might spend too much time looking at the instrumentation (instead of the road) and not see objects with which they might collide.

There are three ways in which in-vehicle displays might cause problems. First, problems might occur because the priority given to in-vehicle displays might be greater than that given to the road. This is most likely to occur for messages associated with a critical malfunction, such as a brake failure. However, such warnings tend to be very brief, quickly noted, and extremely rare, and hence are unlikely to be a significant problem.

A second perspective is that problems could occur with in-vehicle displays that provide frequent messages. Navigation displays are most often thought of in this context. Recent work, however, shows that drivers take into account the relative importance of navigation displays and road scenes, and tend to look when it is safe to do so (when there are no anticipated hazards). (See Wierwille, Hulse, Fischer, and Dingus, 1988.)

The third situation of concern is a display that takes a long time to read or hear. Particularly when the system involves interaction, people will continue to pay attention to it. Some have talked about a problem of "cognitive capture." It is this situation in which the author believes accidents are most likely to occur. This problem is often manifested in conversations.

Thus, the most useful indicator of driver performance with new in-vehicle displays is driver eye fixations. Fixation data indicate both the extent to which the new equipment distracts drivers from looking at the road (a safety issue) and how long it takes to read the display (a usability issue). Eye fixations have been recorded in numerous studies (e.g., Blaauw, 1975; Cohen and Studach, 1977; Mourant and Rockwell, 1972; Noy, 1990; and Rackoff and Rockwell, 1975. (See Serafin, 1992 for a review.)

Methods for Recording the Direction of Gaze

Determining eye fixation durations and frequencies for various points of regard requires both periodically sensing and recording the direction of gaze, and processing the gaze data to compute fixation statistics. Sensing driver eye fixations involves the continuous monitoring of eye position. There are basically two types of eye-tracking systems: on-the-head systems and off-the-head, or remote, systems. If the system is mounted on the head, then either the head needs to be fixed by a bite bar or some other means, or the head position needs to be recorded to determine the actual direction of gaze. In laboratory studies of reading, the head is fixed. Obviously, for studies of driving, especially on the road, a fixed head position is out of the question.

Sensing strategies for determining direction of gaze include direct vision, mirror-based systems, electro-oculography (EOG), limbus tracking, pupil tracking, corneal reflection, laser doppler, and direct contact. A description of each of these methods follows. While some are not useful in an automotive context, all are described for the sake of completeness.

The primary source of information for this report has been the literature. The classic paper reviewing eye movement recording techniques is Young and Sheena (1975), a paper that supersedes several early papers on the topic written by Young. An excellent review appears in Carpenter (1977). More recent summaries appear in Hallett (1986) and Borah (1989). Readers interested in this topic should review all these documents thoroughly, especially the Young and Sheena paper, if they are interested in specific measurements of the performance of various recording methods (shown in tables).

Direct-Vision Systems

The direct-vision approach has been employed by many researchers, notably by Wierwille and his colleagues in several recent studies (Dingus, Antin, Hulse, and Wierwille, 1989). In these studies a fixed video camera is mounted on the hood of the car facing the driver. The image of the driver's face is recorded on videotape. Often, the hood camera output is fed into a video splitter and combined with the image of a forward scene camera and possibly input from other cameras. Those include a camera showing the interior (to record use of secondary controls) and a camera aimed at the steering wheel. By placing bands of white tape around the steering wheel rim every degree or so, steering wheel angle can be determined from the videotape.

In utilizing this method, some creativity is required to mount the camera securely to protect it from the wind and the elements. In Wierwille's work, a large camera was used. Mounting and blocked view problems are lessened with miniature or subminiature (thumb-sized) cameras that have a wide field of view lens. Good color cameras of this type (e.g., Panasonic WV-K5152) typically cost several thousand dollars each. In fact, should such be available, it would be better to place the camera inside the vehicle, either on the A-pillar (where it has a clear line of sight to the driver), on top of the instrument panel (where it may sometimes be blocked by the driver's hands), or concealed inside a climate control vent. The vent location has been used by European researchers, though the low placement makes it difficult to discern between looks to various road locations.

An interesting variation of this approach, currently being explored at UMTRI in a study of mirror use, is to place a camcorder with a gyrostabilized lens in a van and then unobtrusively monitor randomly selected vehicles in traffic. There are some problems with this method in getting a stable image. Further, where the driver looked can be determined only very generally (e.g., to the instrument panel, as opposed to a specific display).

While direct-vision systems are easy to implement, data analysis can be quite difficult since data reduction involves manual frame-by-frame coding by an experimenter. Allowing for about 1 second per video frame, the data reduction time is 30-40 times the duration of the recording. Split-screen recording of input eliminates the problem of synchronizing multiple VCRs (as was done in the past), and recording analog and digital inputs (say from operating secondary controls) can reduce other problems associated with synchronizing multiple data streams. However, as is discussed later, data analysis is still predominantly manual (and very boring).

Mirror-Based Systems

Some of the early studies of eye fixations used the mirror-based approach, and it is still used today. In Fitts' work on pilot eye fixations (Jones, Milton, and Fitts, 1949), a movie camera was mounted in the aft portion of the cockpit and aimed forward at a mirror between the pilot and copilot. Moving the camera to that position reduced interference with the forward visual field and made the camera controls more accessible. However, the longer sight distance and dependence upon an intermediate mirror makes the system more sensitive to vibration. When subminiature cameras are available, direct vision recording systems are preferred. However, in academic settings, researchers can afford to buy mirrors and camcorders, but not subminiature cameras. In those cases, indirect vision systems are an option.

Analysis of data from indirect vision systems follows the approach of direct-vision systems. The author does not know of any ongoing investigations of driver eye fixations using this approach.

Electro-Oculography (EOG)

Eye gaze direction can be identified by electro-oculography or EOG (Kris, 1958; Martin and Harris, 1987; Shackel, 1960). Of the references on this topic, Shackel (1960, 1967) are the most commonly cited. In brief, there is a front-to-back voltage difference across the eyeball; the cornea being more positive by about .40 to 1.0 mV. (See Figure 1.) As the eyeball rotates, the electrical dipole rotates with it. To sense eye position, three surface electrodes are placed around the eye socket, one above, one below, and one on the temple, though sometimes a fourth electrode is centrally placed on the forehead. (See Figure 2.) As the eyeball rotates, the voltage differentials measured change. The recorded potentials are fairly small, in the range of 15-200 microV with nominal sensitivities of the order of 4 microV per degree of eye movement. EOG systems can be fairly easy to construct. Data are usually recorded by a computer using standard analog-to-digital boards and stored for further analysis. EOG systems, however, tend to respond fairly slowly and are not extremely accurate. There are large baseline shifts and the baseline needs to be adjusted from time to time so that when gain is added, the sensor is not overdriven. Further, EOG systems require placement of the electrodes by a knowledgeable person.

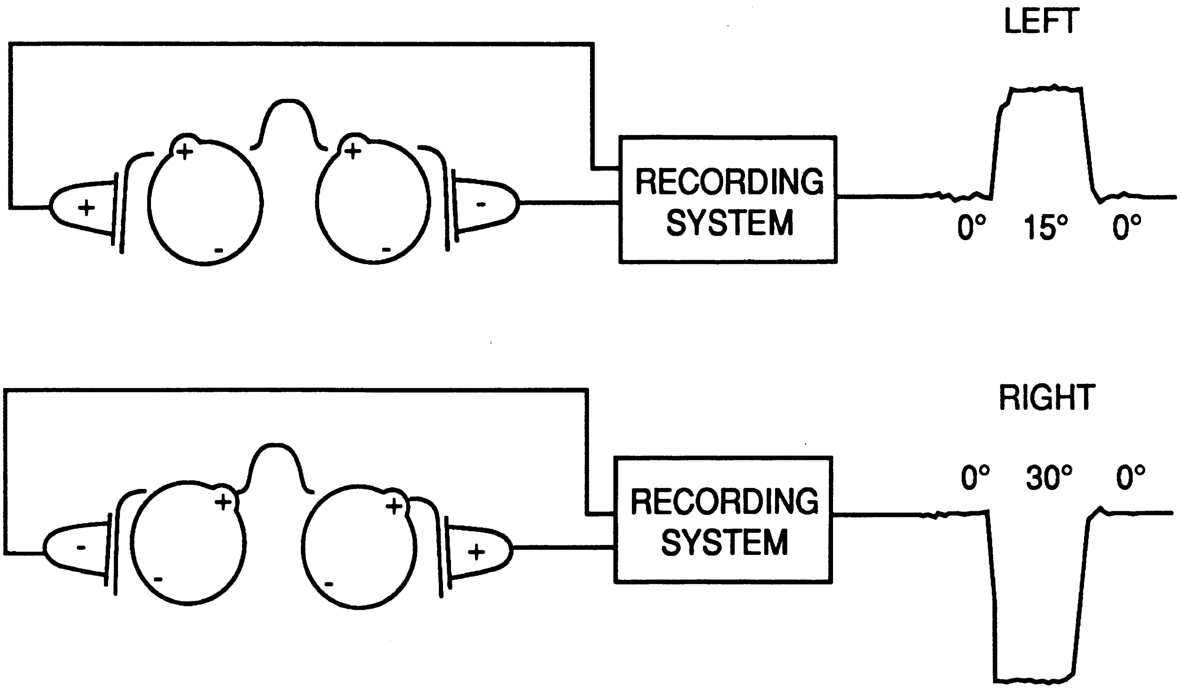

Figure 1. EOG Eye Tracking.
Adapted from Shackel, 1960, p. 22.

The author has been told by those using EOG that people are sometimes reluctant to wear EOG sensors because they are unsightly. Further, with EOG systems there are also perceived safety concerns relating to the electrodes. ("Am I going to go blind from an electrical shock?") While proper optoisolation methods reduce hazards to zero, optoisolation is not something that is understood by the typical adult.

In spite of these drawbacks, use of EOG recording schemes for automotive applications is in need of further examination, primarily because of its low cost and light weight. For studies of driving fatigue, or any study requiring monitoring drivers for more than 30 minutes, this is a big advantage.

Figure 2. Electrode Placement for EOG Measurements.
Source: Kris, 1958, p. 14.

Limbus Tracking

The limbus or boundary between the iris and the sclera (the white part of the eye), can be easily detected optically and tracked by either computer software or by a human observer. This approach has been described and used by several researchers (Brown and Mowforth, 1980; Carmody, Kundel, and Nodine, 1980).

A simple system might illuminate the eye with low-power infrared or visible light and use a linear photosensor array to measure reflectance at various locations. Often the number of elements in the array is very limited and the sensors are tuned to a wide area, though in some designs the sensors are slits at various angles to improve sensitivity. Hence, as shown in Figure 3, differences in luminance are used to determine limbus location. Because of the anatomy of the human eye, limbus trackers offer reasonable accuracy in determining horizontal eye position (around 1 degree). Vertical position is measured by examining the area of the sclera visible between the iris and the lower eyelid. However, that area varies widely between individuals and the eyelid often interferes with measuring vertical position with any degree of precision (about 2 degrees). The range on the horizontal axis is about +/-15 degrees and slightly less on the y axis.

A variation on this theme is described in Carpenter (1977) in which a spot driven by an oscilloscope is focused on the limbus. The signal difference between the scattered light and the original source is used to drive the scope deflection circuits. This approach requires dim illumination levels.

Limbus systems tend to be simple and inexpensive, and are predominantly used for studies of reading. Because the sensors are quite light (often clipped onto a bare eyeglass frame or eyeglasses a subject might wear), limbus-tracking systems can be worn for extended periods of time. In studies of driving fatigue, that can be important. However, their susceptibility to loss of signal from lid droop may interfere with conducting such experiments. When the sensor fields are circular (as shown in the figure) the relationship between the direction of gaze and the output signal is not linear. This is eliminated by using slit-shaped photoreceptors. Limbus trackers are easily interfaced to computers and many commercial products provide such interfaces, a key advantage.

Readers interested in a discussion of commercial products using this method should see Borah (1989).

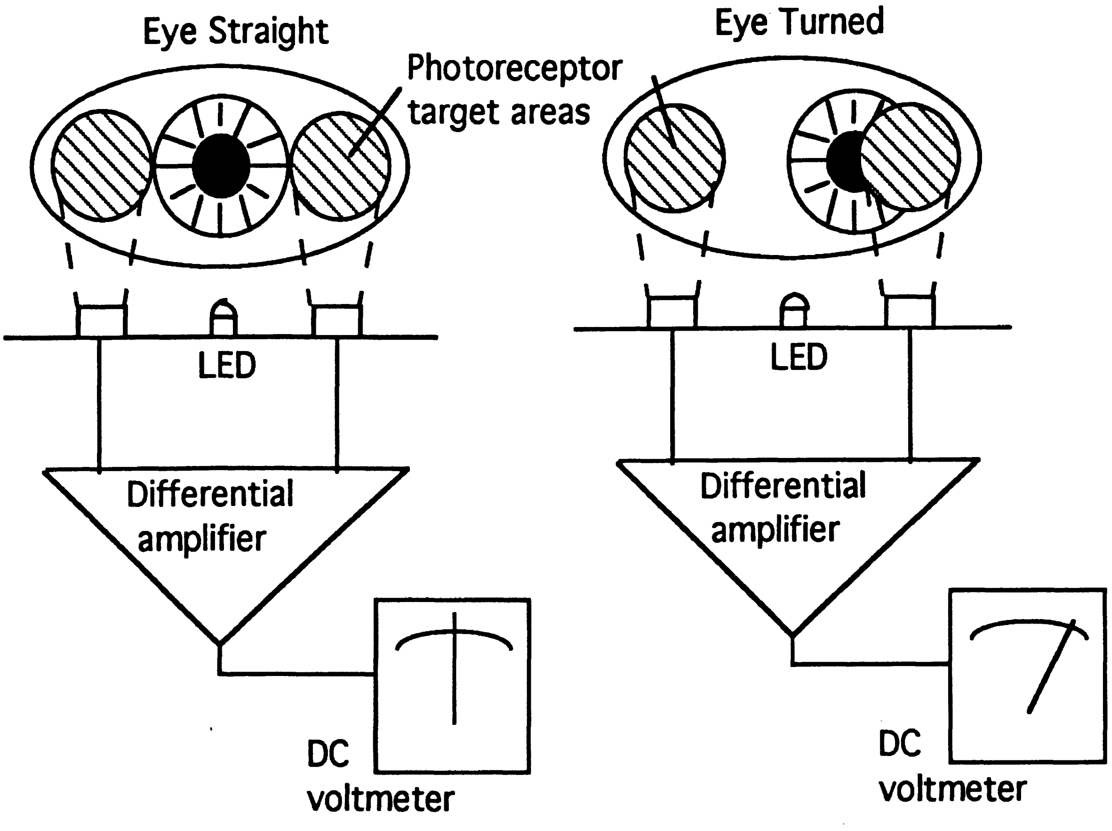

Figure 3. Limbus Tracking Mechanism.
Adapted from Goldberg (1980)

Pupil Tracking

There are two basic ways of imaging the pupil, referred to as bright pupil and dark pupil tracking. (See Borah, 1989 for a discussion.) The retina is highly reflective and any light falling on it is reflected back to its source. Should the illumination be close to the observer's line of sight, then the pupil will appear bright. This can be achieved by including a beam splitter in the optics. Figures 4 and 5 show the optics and image for bright pupil tracking systems. Should the illuminating source be well off the observer's line of sight, the pupil appears dark (as it does under normal diffuse lighting). The exact placement of the illuminator is not critical. In theory, dark pupil tracking is less sensitive to changes in ambient illumination that cause the pupil to constrict or dilate. Figure 6 and 7 show the dark pupil optics and image.

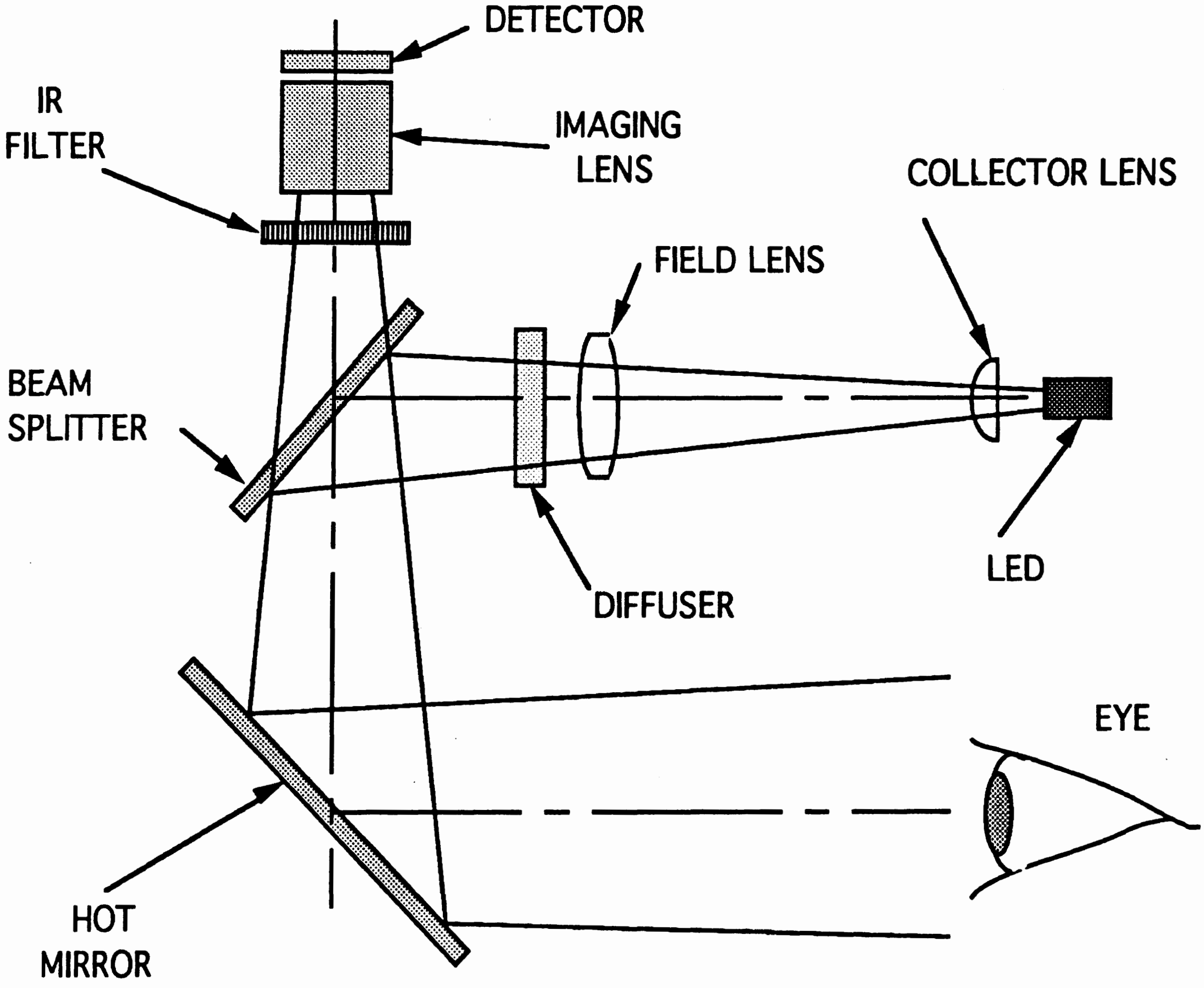

Figure 4. Bright Pupil Tracking Optics.
Source: Borah (1989), volume II, p. 35.

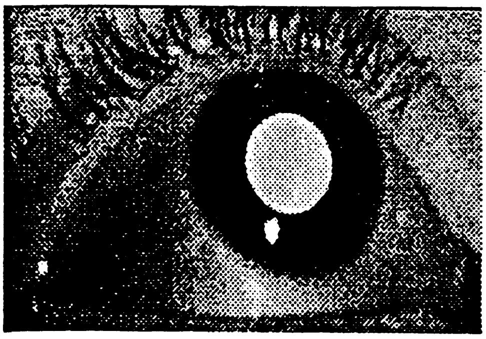

Figure 5. Bright Pupil and Corneal Reflection.
Source: LC Technologies, 1992, p. 1.

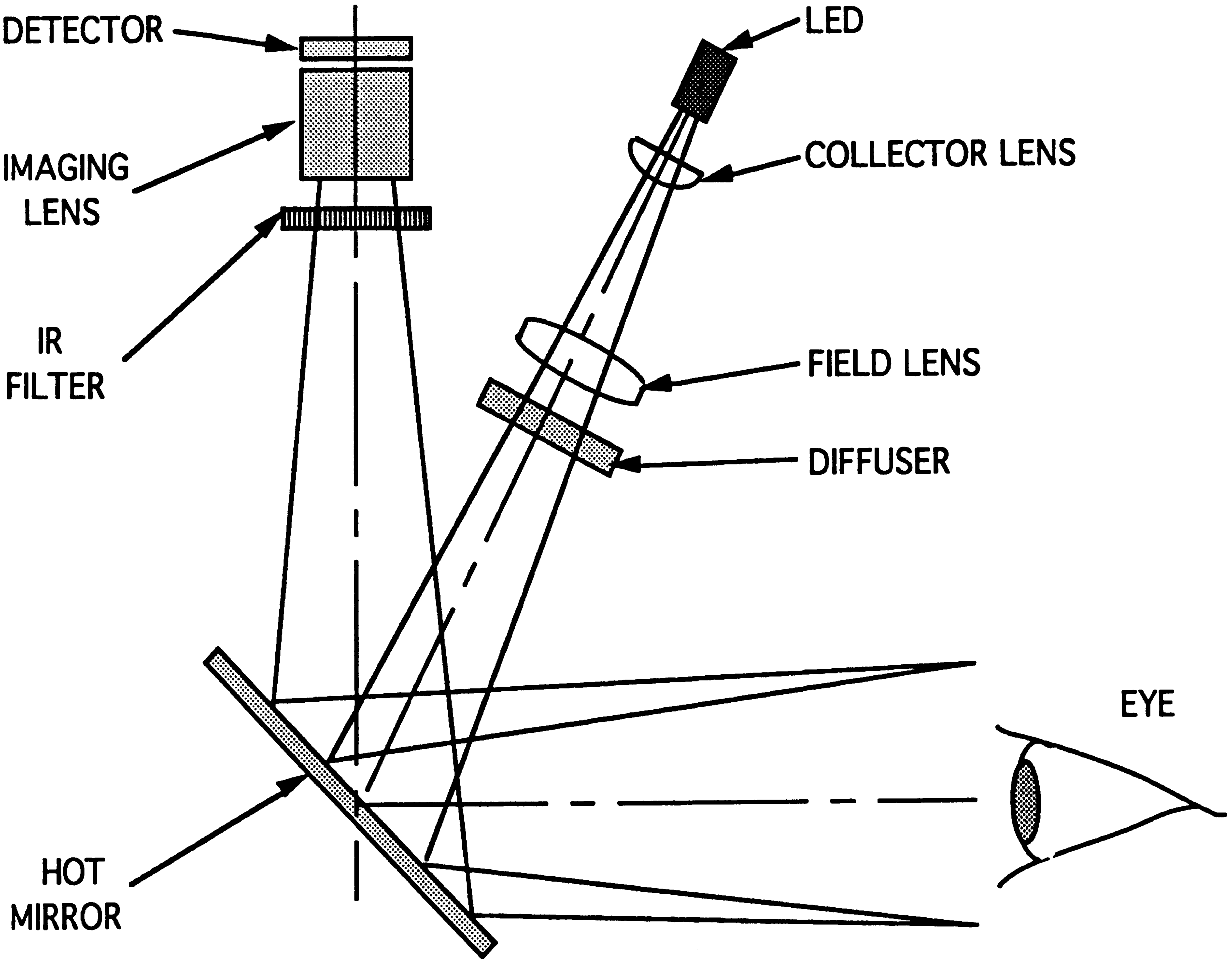

Figure 6. Dark Pupil Tracking Optics.
Source: Borah (1989), volume II, p. 36.

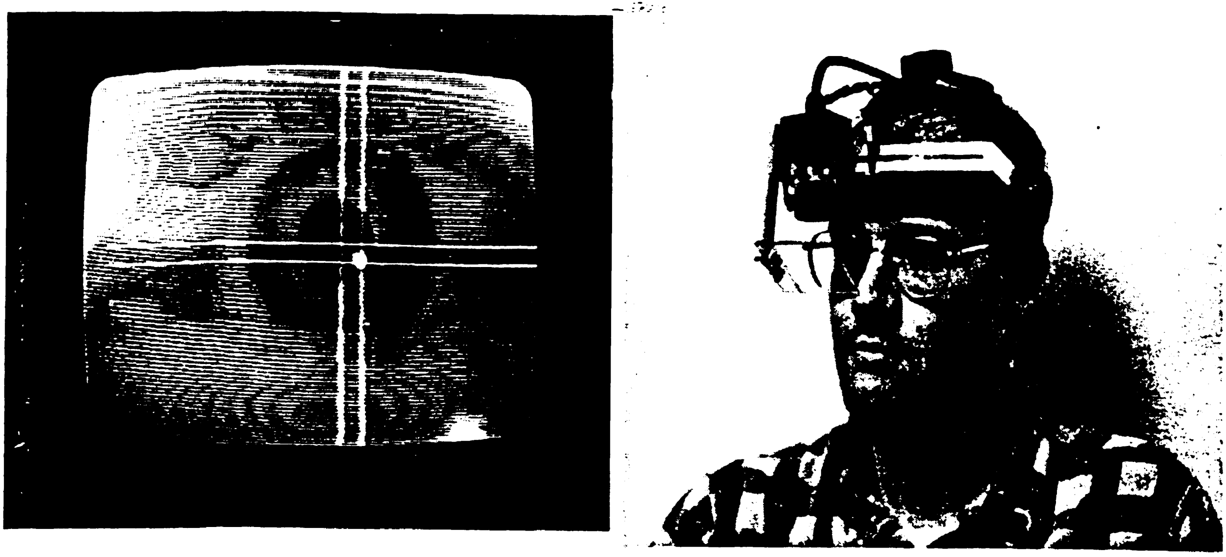

Figure 7. Dark Pupil Tracking Device.
Source: Razdan and Keilar, 1988

Borah indicates that bright pupil systems are preferred when the pupil diameter is above 3.5 mm and dark pupil preferred when it is below 2.5 mm. The 3.5 mm figure corresponds to luminance of about 100 cd/m^2 and the 2.5 figure to about 10,000 cd/m^2 (Boff and Lincoln, 1988, volume 1, p. 100.). To put these numbers in perspective, bright displays might have luminance as high as 100 cd/m^2, so for examining them bright pupils systems are preferred. Bright pupil systems also work well in offices where light levels are typically 25-100 fc (about 250-1000 lux). Kerst and Bos (1988) found that illumination levels of about 9700 lux were typical for sunny days, 4000 for overcast days, and 1 lux for nighttime. If the scene reflectance is 10%, illumination levels (in lux) will be about 30 times these values. This suggests using bright pupil systems for night conditions and dark pupil systems for daytime. The author believes that dark pupil systems are preferable overall, as well as for studies of driving.

Pupil tracking systems tend to be straightforward to use and invariably provide interfaces to computers. This simplifies data reduction.

A related and novel method for recording eye fixations is to use an ophthalmoscope to scan for retinal blood vessels (Carpenter, 1977). These retinal features are difficult to detect and track, and systems of this type are unlikely to be used in automotive contexts.

Corneal Reflections

Many of the better eye-fixation recording systems use reflections from the cornea to determine gaze direction. (See Eizenman, Frecker, and Hallett, 1984.) As shown in Figure 8, reflections from four boundaries can be sensed--the front and rear surfaces of the cornea, and the front and rear surfaces of the lens. Of these four, the front surface reflection is particularly bright, while the fourth Purkinje image (P4) can be particularly dim. Figure 9 shows the frontal view of the first two images. As the eyeball rotates, so does the corneal bulge, a hemispherical surface in front of the eyeball. As a consequence, the direction in which the light is reflected changes. This is sensed by a video camera. Measuring accuracy is improved if the corneal front surface reflection (first Purkinje image) is used in conjunction with others, typically P4 (Carpenter, 1977). Because of the optics, in double Purkinje systems P1 and P4 move by equal amounts when the eye is displaced, but move relative to each other when rotated. (See Cornsweet and Crane, 1973.)

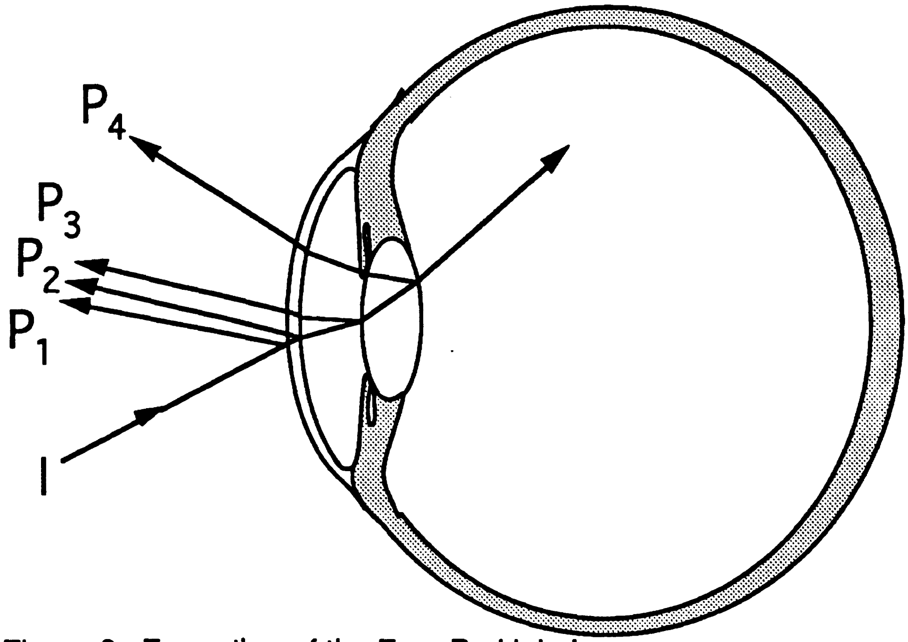

Figure 8. Formation of the Four Purkinje Images.

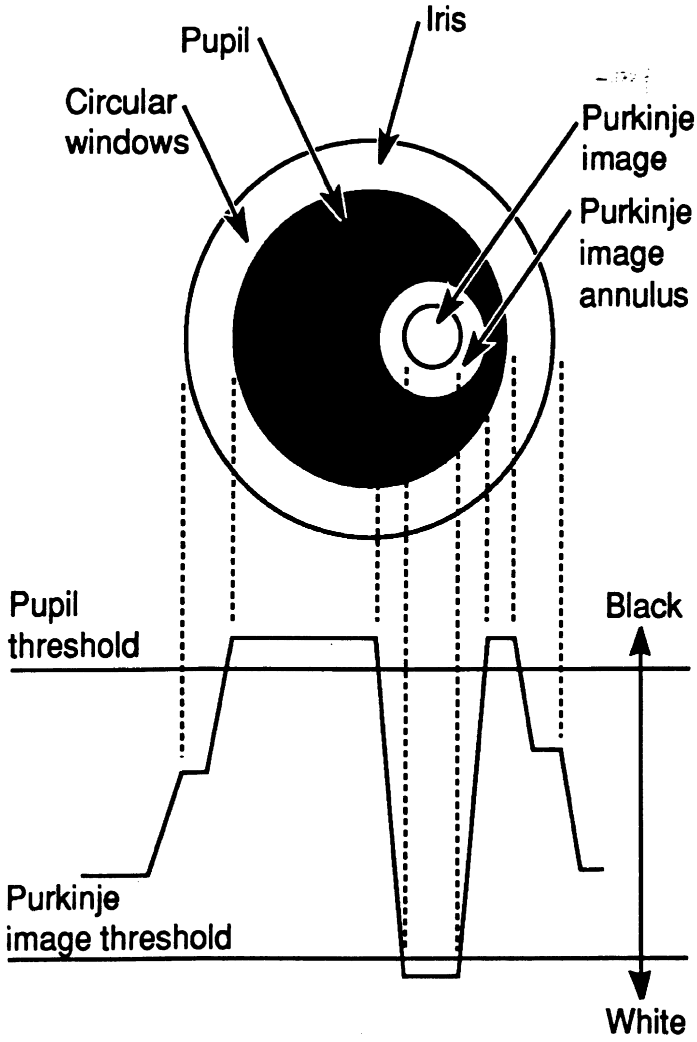

Figure 9. Double Purkinje Image.
Source: Myers, Sherman, and Stark, 1991, p. 17.

Often the headgear for these systems is quite heavy and these systems can be difficult to calibrate. Figure 10 shows a cutaway view of the NAC model V and illustrates how the system works.

(A) The field lens ① sees the same view as the wearer (60° horizontal axis and 45° vertical axis). This image is recorded by the field MOS camera ② and then passed to the camera controller as the image signal.

(B) The near infra-red LED light from the eye mark spot lamp ③ then makes a direct virtual image on the cornea of the eyeball.

(C) This virtual image, is reflected by the IR mirror ④ and is transmitted to the X axis adjusting mirror ⑥ and Y axis adjusting mirror ⑦. It then passes through the focus lens ⑧ to reflection mirror ⑨, with final focus at the eye mark MOS camera ⑩ which is then transmitted to the camera controller as an image signal.

(D) Man moves his eyeballs using the eye muscles to bring an object viewed into focus. As shown in the diagram, there is a spherical cornea in front of the eyeball. Because of this spherical shape, the virtual image made by the LED lamp on the cornea will move slightly depending on the movement of the eyeball. The amount of change in position of the eye mark is magnified both optically and electronically.

(E) The camera controller mixes the field and eye mark images. It generates a '+' shape for the right eye and a '□' shape for the left eye to indicate eye marks on the TV monitor screen while superimposing the field image.

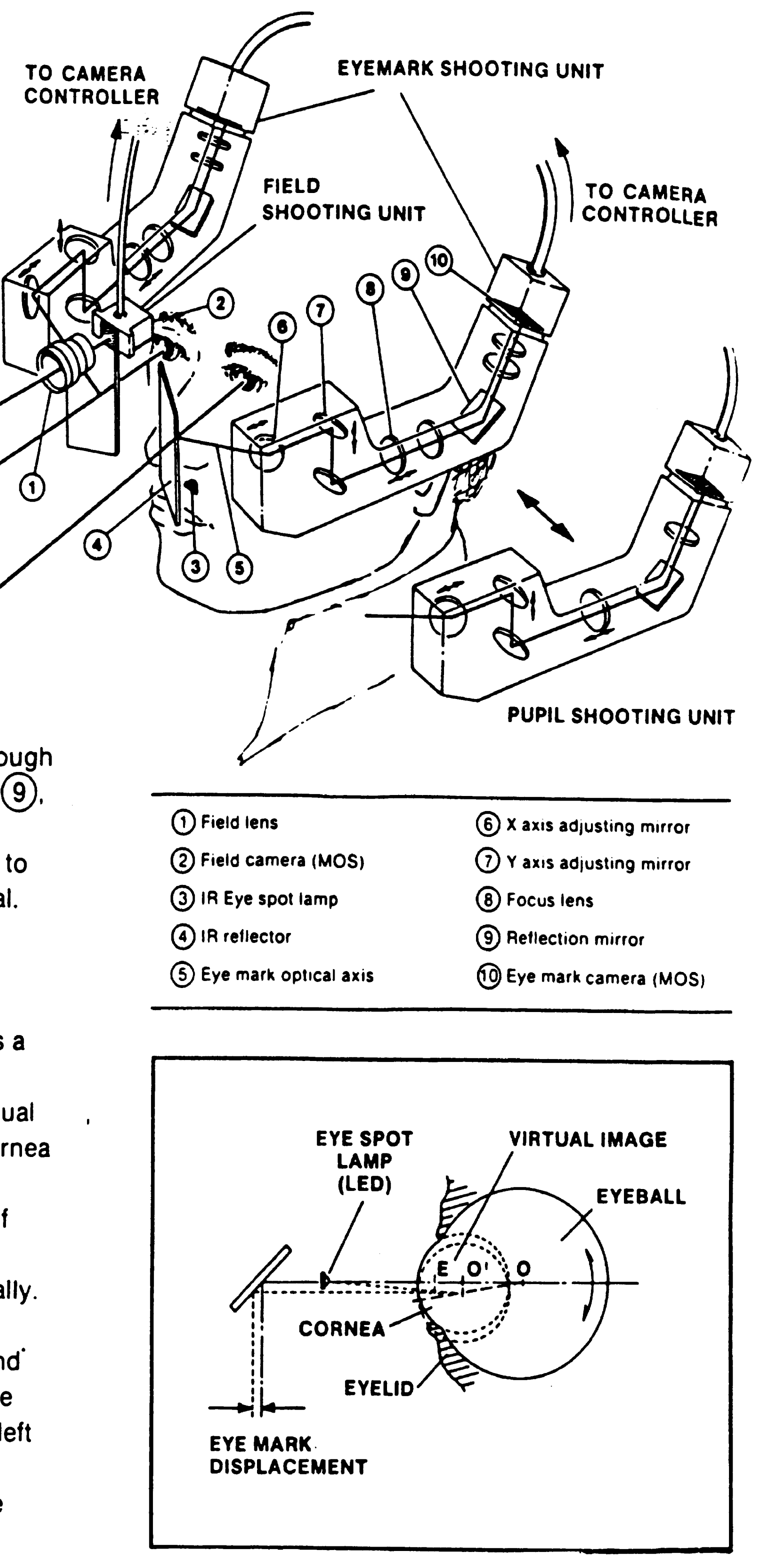

Figure 10. Operation of NAC model V.

Reflections from Attachments to the Eye

Accurate assessment of the direction of gaze can be achieved by attaching sensors to the eye. The most direct way is literally to attach a mechanical linkage to the eye ball. Carpenter (1977) refers to a system where a contact lens was mechanically connected to a bristle that left a trace of eye movements. A related approach is to place a small flat mirror on the contact lens and then measure the angle of reflection of an incident light beam as the eye rotates. The drawback of this approach is that the contact lens slips. To keep the lens from slipping, a slight negative pressure is applied to the rear surface by attaching a vacuum line to the device. Figure 11 shows an illustration of one such device. A variation of this approach is to place a small ball of mercury on the eye, using it as a reflective surface. Finally, there have been efforts to attach a magnetic coil to the eye and then sense the change in the magnetic field as the coil moves. The off-head field coils may be very large, too large to fit inside a car.

These devices must be placed on the eye with great care, and because of the fragile nature and potential damage both to the cornea and the ocular muscles, they have been used in only a limited set of laboratory conditions. Further, to prevent injury, this method is typically used only when the head is not free to move and the eye is anesthetized, and sometimes with the subject lying on his back. Hence this device is suitable only for laboratory research. Even then, it is suitable only for very few applications. Of the methods available, however, this is the most accurate. The author does not know of any automotive applications of this approach.

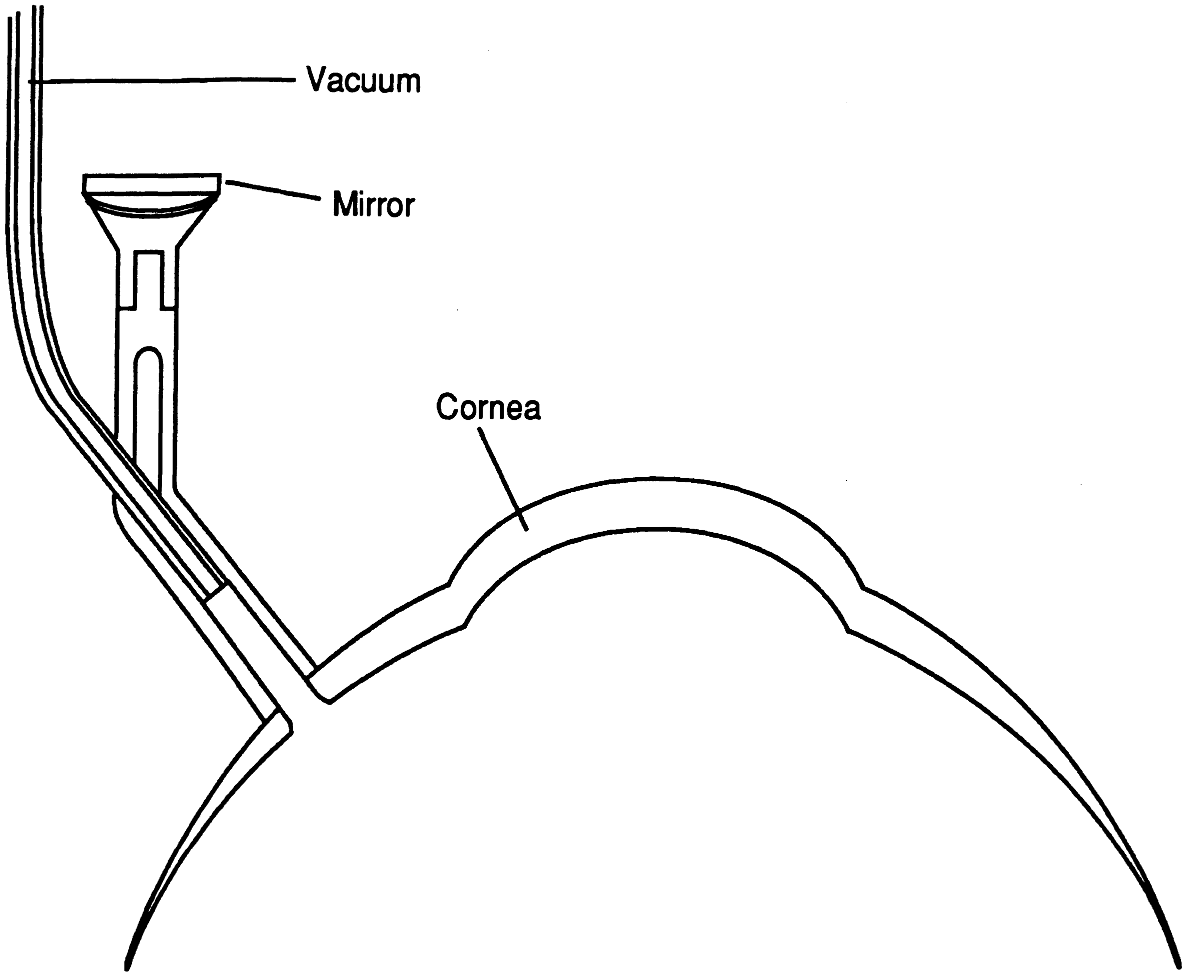

Figure 11. Contact Lens Device.
Source: Young and Sheena, 1975, p. 323.

Laser Doppler Velocimetry

In brief, the velocity of moving particles can be measured by the frequency shift of a laser scattered by those particles, here by particles in the cornea. Borah (1989) refers to prototype work done using this approach, but the author does not know of any commercial products based on it. In addition to technical problems in implementing the method, subjects are likely to object to having a laser, no matter how low the power, aimed at their eyes. Furthermore, the sensing scheme is more suitable for recording eye motion and not eye position.

Combinations of Measurement Techniques

Tracking a single landmark on the eye does not allow distinction between rotation of the eye in the socket and translation due to head movement. This is much less of an issue for on-the-head systems than off-the-head systems. Even for on-the-head systems, tracking multiple landmarks improves accuracy. The most commonly used combinations are the pupil and the first Purkinje image (often referred to the corneal reflex or CR) and the first and fourth Purkinje images (or dual Purkinje image). An illustration of the geometry for the first combination is shown in Figure 12. See Young and Sheena (1975) and Gale (1981) for further details.

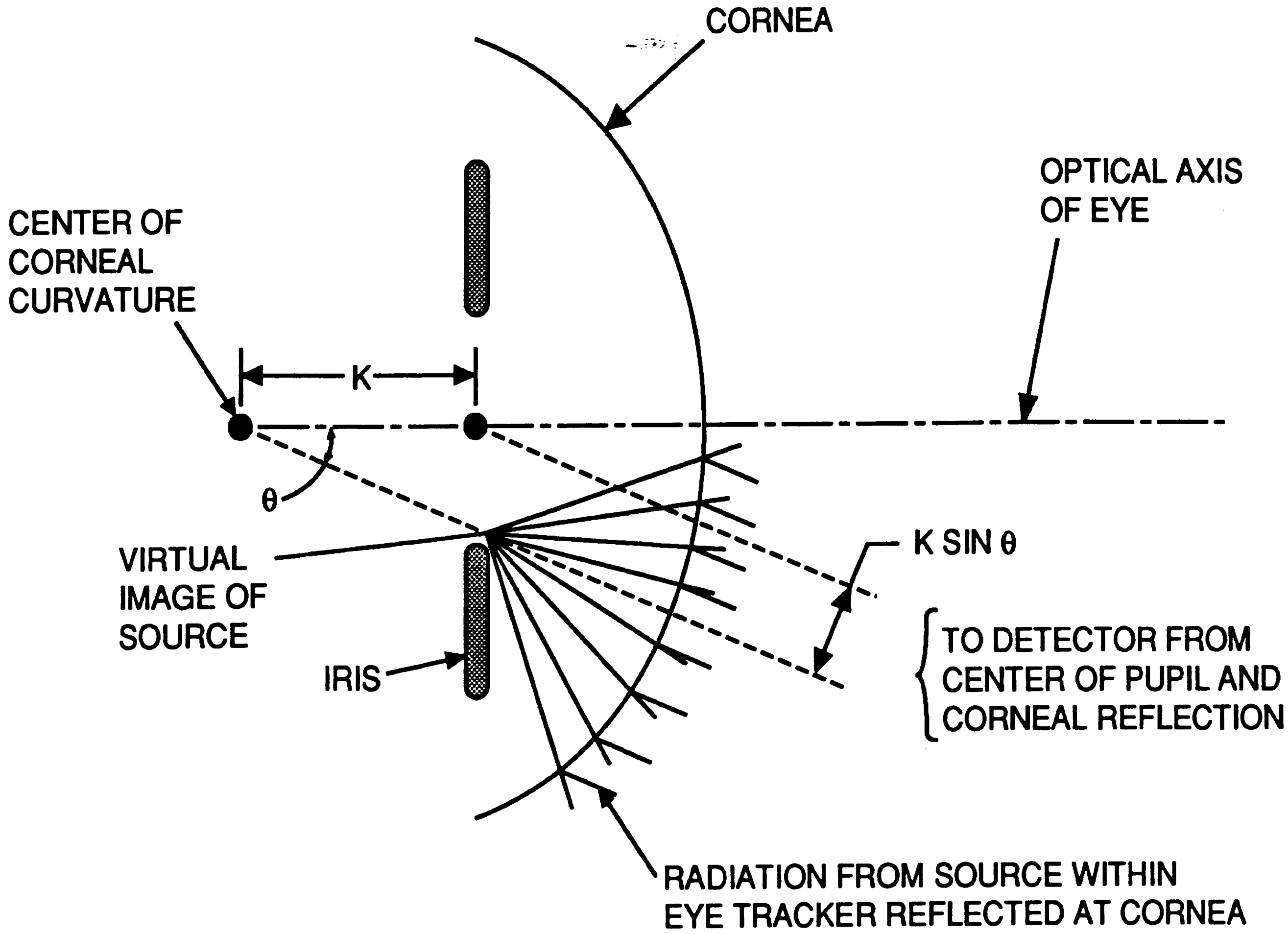

Figure 12. Pupil and First Purkinje Combination.
Source: Applied Science Laboratories, undated, p. 11.

Reduction of Eye Fixation Data

As noted in the section on direct vision sensing, eye fixation data are not only difficult to collect, but manual reduction and analysis is very laborious. (See Baloh, Kumley, and Honrubia, 1976; Mason, 1976; Pavlidis, 1980; McConkie, 1981; Hatamian and Anderson, 1983; McConkie, Scouten, Bryant, and Wilson, 1988; Sung and Anderson, 1991 for information on analysis procedures.) This is particularly true for the less expensive eye-fixation recordings.

A record of a series of eye fixations will show a rapid movement (saccade) to an object of interest (as fast as 1000 degrees/second), a drifting of the eye near the target (over part of a degree at a rate of 4 minutes of arc/second), and then after 200-800 ms, movement to another location. Also observed in the record will be vergeance motions (to keep both eyes on the same target, typically at 10 degrees/second).

For driving, interest is primarily limited to studying fixations to objects. There is no interest in describing smooth pursuit actions, or studying vergence (retinal disparity) or drift. However, because physiological nystagmus (tremor) is particularly affected by alcohol, there is interest in that motion as it relates to the development of intoxication detection devices. This behavior is one of many that police officers look for when performing roadside evaluations.

Typically, eye fixations are recorded both electronically and on video (at 30 or possibly 60 frames per second, but sometimes faster). It is common wisdom that it is undesirable to rely on the video record for the fixation data. Reduction of these data requires viewing each frame and classifying where the driver is looking, entering the location using a code. This may take a second or so, and is extremely boring to do. This leads to the 30:1 to 40:1 ratio given earlier. Said another way, a typical week might involve testing a driver for an hour and then spending the remainder of the week coding the data. This approach is not cost effective. Once the fixation locations are available for each frame, fixation durations must then be computed.

It is therefore critical that consideration be given to acquiring an eye-fixation recording system with a built-in data-logging capability, either serial or analog. While the added capital cost of equipment is significant, the payback in reduced labor costs occurs quite quickly.

Products for Sensing Direction of Gaze

A preliminary list of vendors of eye-fixation recording equipment follows. Products are listed alphabetically by vendor. Each of the products listed in this section may have potential automotive use.

Applied Science Laboratory
335 Bear Hill Road
Waltham, MA 02154
(617) 890-5100, fax (617) 890-7966

Applied Sciences Laboratory (ASL) is one of the best known vendors of eye-fixation recording systems in the U.S. and is believed to have the largest market share. Their sales staff is very receptive to requests for information. ASL's basic model, the 210, is a limbus and eyelid tracker mounted on a pair of spectacles or headband. Figure 13 shows the control unit. It provides for digital, analog, and video output. Figure 14 shows the headband assembly with sensors and a scene camera. The basic unit costs $7500, the headband another $375, and a scene camera (needed for human factors studies) another $3750. There are additional costs for a recording computer, interface card ($500), and software ($3800 for the data recording software, $2500 for the analysis software). The cost of a system to provide head-relative gaze location, video output of where the head is pointed, and analysis software is about $15,000. A head tracker is needed to provide absolute information on direction of gaze. ASL claims performance of the 210 is equivalent to a NAC model IV eye-fixation recorder and reports they have heard of the model 210 being used in a car. Horizontal position of the eyes is measured over a +/-15 degree range with a reported accuracy of about 1 degree. This range is somewhat limited for in-vehicle research. Vertical range is +/- 15 degrees with an accuracy of about 2 degrees.

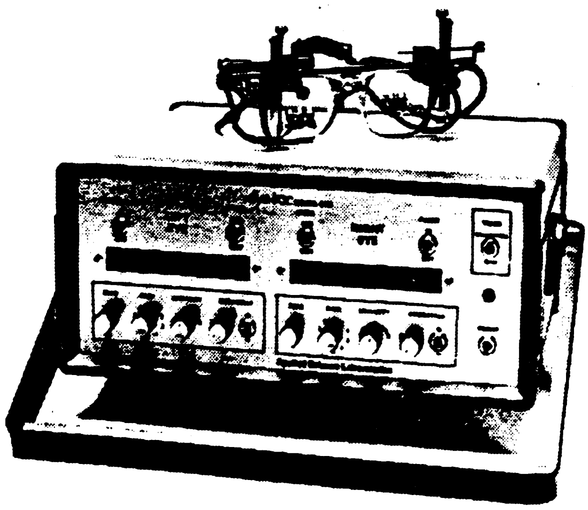

Figure 13. ASL model 210 Control Unit.
Source: Applied Sciences Laboratory, undated, p. 2-1.

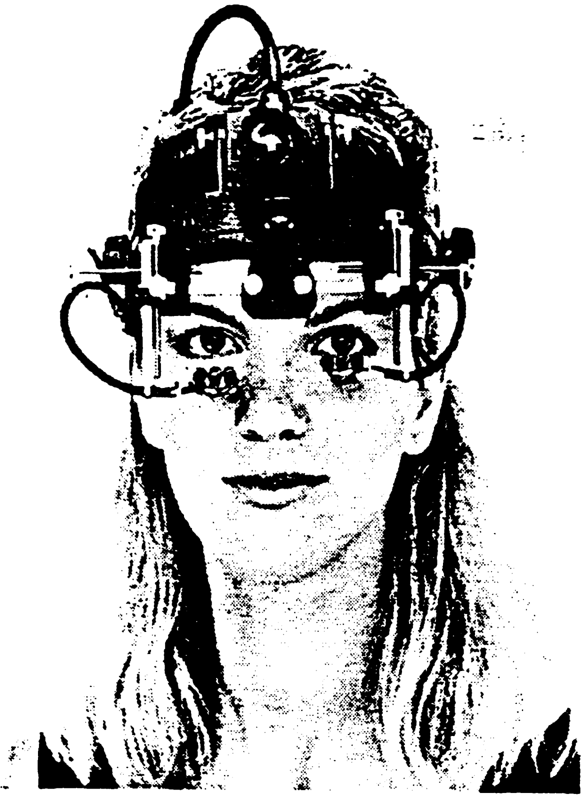

Figure 14. ASL Series 210 Headband Assembly.
Source: Applied Sciences Laboratories, undated, p. 2-2.

The 4000 series includes several top of the line systems made by ASL and it is this series that ASL notes has often been used in studies of driving. They strongly recommend it over the model 210 for this application. Figure 15 shows the 4000CU control unit, which is roughly 2 feet by 1.5 feet by 1.5 feet and weighs 80 pounds. The 4000SU (preferred for in-vehicle use) is smaller, occupying a single slot in a 19-inch rack and weighing 20 pounds. It provides analog, digital, and video output. Typically, the 4000 series sensor is mounted on a helmet, though a headband can be substituted. The system works with most types of eye glasses and contact lenses, with thick frames and hard contacts being the problem cases, making eye fixation data more difficult to obtain for mature drivers. With hard contacts, the movement of the lens with every blink interferes with the optics. Interference due to spectacle frames and hard contacts is a problem for all corneal reflection systems, not just the ASL 4000. For the off-the-head (remote) implementation, the head box is 1-2 cubic feet, quite adequate for most driving tasks.

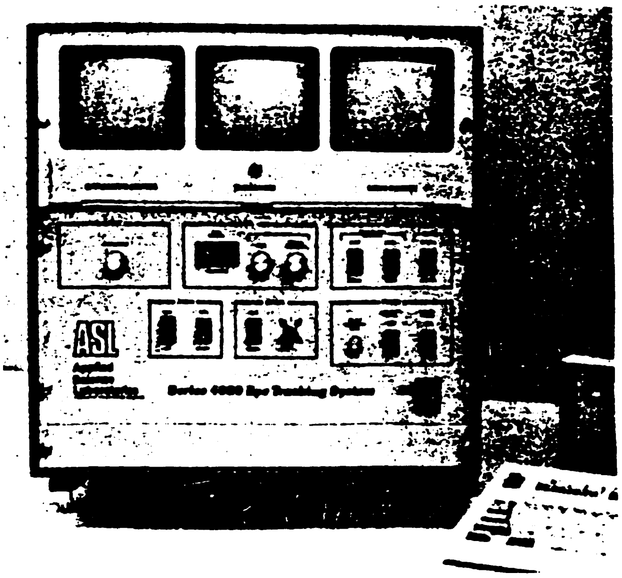

Figure 15. ASL Series 4000 Control Unit.
Source: Applied Sciences Laboratories, undated, p. 5-3.

The basic system unit (4000SU) with data collection software can be purchased for $27,000. Allowing another $4000 for a scene camera, monitor and computer, a minimum working system to provide head relative gaze data is about $31,000. A head tracker adds $3875 to the price. More complete packages run from $55,000 to $103,000, plus there are many options that can add to the cost. The system requires a 386 computer. (Because the options are so numerous, readers interested in this product should review the vendor's product literature for the latest details.) Options include a head tracker, various tracking mirror systems, and so forth. Optics can be either on-the-head or mounted remotely. Series 4000 eye trackers examine both pupil and corneal reflection signals. The system is switchable between dark and bright pupil sensing. A unique feature of this series is the software that comes with the product for collecting and analyzing eye fixations.

EOG-Based Systems

Generally scientists do not purchase EOG systems as a package. Rather they acquire electrodes, signal conditioners, amplifiers, A to D boards, and computers from a variety of vendors, and build their own packages. Packages can be obtained from distributors of medical and biomedical instrumentation. As an example, BioPac Systems, Inc. (275 S. Orange Ave., Suite E, Goleta, CA 93117, phone: 805-967-6615, fax: 805-967-6043) produces suitable products. They sell two data acquisition systems for Macintosh computers--the MP20WA, an 8-bit system and MP100WS, a 16-bit system. These systems connect to Macintoshes and are optoisolated, a safety advantage. Sampling rates are 30-60 Hz, certainly fast enough for automotive applications.They are priced at $1995, and $2995, respectively. These prices do not include electrodes.

In addition, components can be purchased instead of systems. For example, an EOG100A Electro-Oculogram amplifier costs $495 for the MP100WS system and $395 for the MP20WS system. Electrodes cost $20-$30 each, cables a few dollars each, and interface software is about another $100. Should analysis software be desired, it is another $500. Thus, the price for an EOG package is about $3000 - $4000, fairly inexpensive relative to the other options. For those with computer data collection systems with A-to-D input, the cost may be considerably less as only the EOG amplifier, cables, and electrodes need to be purchased, a $600 investment.

An alternative source is Nihon Kohden, a major manufacturer of medical equipment in Japan. Their address is 131 Nishiochiai Shinjuku-ku Tokyo Japan 161. Further information on their products can be obtained by calling them at (03)-3953-1181. The author's understanding is that approval of the U.S. Food and Drug Administration is required before the equipment can be sold in the U.S.

ISCAN, Inc.
125 Cambridgepark Drive
Box 2076
Cambridge, MA 02238
(617) 868-5353, fax: (617) 868-9231

While this company is small, it has a reputation for being responsive to customer requests. ISCAN makes several models. (See Razdan and Kielar, 1988, for background information.) The RK 426 ($13,000) tracks both a dark pupil and corneal reflections (first Purkinje). The exact nature of the tracking algorithm used by ISCAN is proprietary. Its accuracy in better than 1 degree over a +/- 20 to 25 degree range. To form a usable system for automotive applications, several other components are needed--an RK-520 autocalibrator ($6800), remote optics ($7000), and a head tracker ($13,000) for a hardware total of $39,800. The head tracker (RK-464) is a modified Polhemus unit and allows the system to work inside a one foot cube. There are added charges for software ($1000-$3000). This combination can be purchased as a unit (Headhunter). Figure 16 shows a typical laboratory installation.

Figure 16. Typical Headhunter Installation.
Source: ISCAN, undated

As an alternative, the system can be ordered with an RK-436 pupil/dual corneal reflection tracking unit. It has a larger range than the RK-426 (+/-40 to 50 degrees) and is more expensive ($18,500).

For use in studying driver eye fixations, see Tsou, Rogers-Adams, and Godyear, 1991.

NAC Visual Systems
2-7, Nishi-Azabu 1-Chome
Minato-ku
Tokyo, Japan
03-3404-2321, fax: 03-3479-8842

U.S. distributor
Instrument Marketing Corporation
820 S. Mariposa St.
Burbank, CA 91506
(213) 849-6251

NAC has made eye-fixation recording systems for many years. They sell a number of other video and film-based recording products in addition to eye-fixation recording cameras. For many years their eye-fixations recorders have been widely used. The latest product, the model EMR-600, is not currently supported in the United States, though it is in Japan. It is a corneal reflection-based device and has a 40 degree sensitivity range. The field of view is 60 degrees horizontal by 45 degrees vertical, larger than most models. (In private discussions with other scientists, some have said this is a bit small.) Price sheets show the cost to be about $32,000 for the basic unit. Several thousand dollars may be necessary for desired accessories, especially a head tracker. Prices for software are not available. In the past, software for NAC hardware has been configured for NEC computers in Japan and reportedly will not run on standard DOS machines. Thus, the product is aimed primarily at the Japanese market.

Figure 17 shows the complete model V unit, and Figure 18 shows the replacement unit (EMR 600). Based on experience in recent UMTRI studies, the model V was found to be a bit too heavy for extended wear (beyond 15 minutes). The body weighs 1.6 pounds (720 g). The weight can be reduced by removing one of the pupil shooting systems, but that makes the head piece unbalanced.

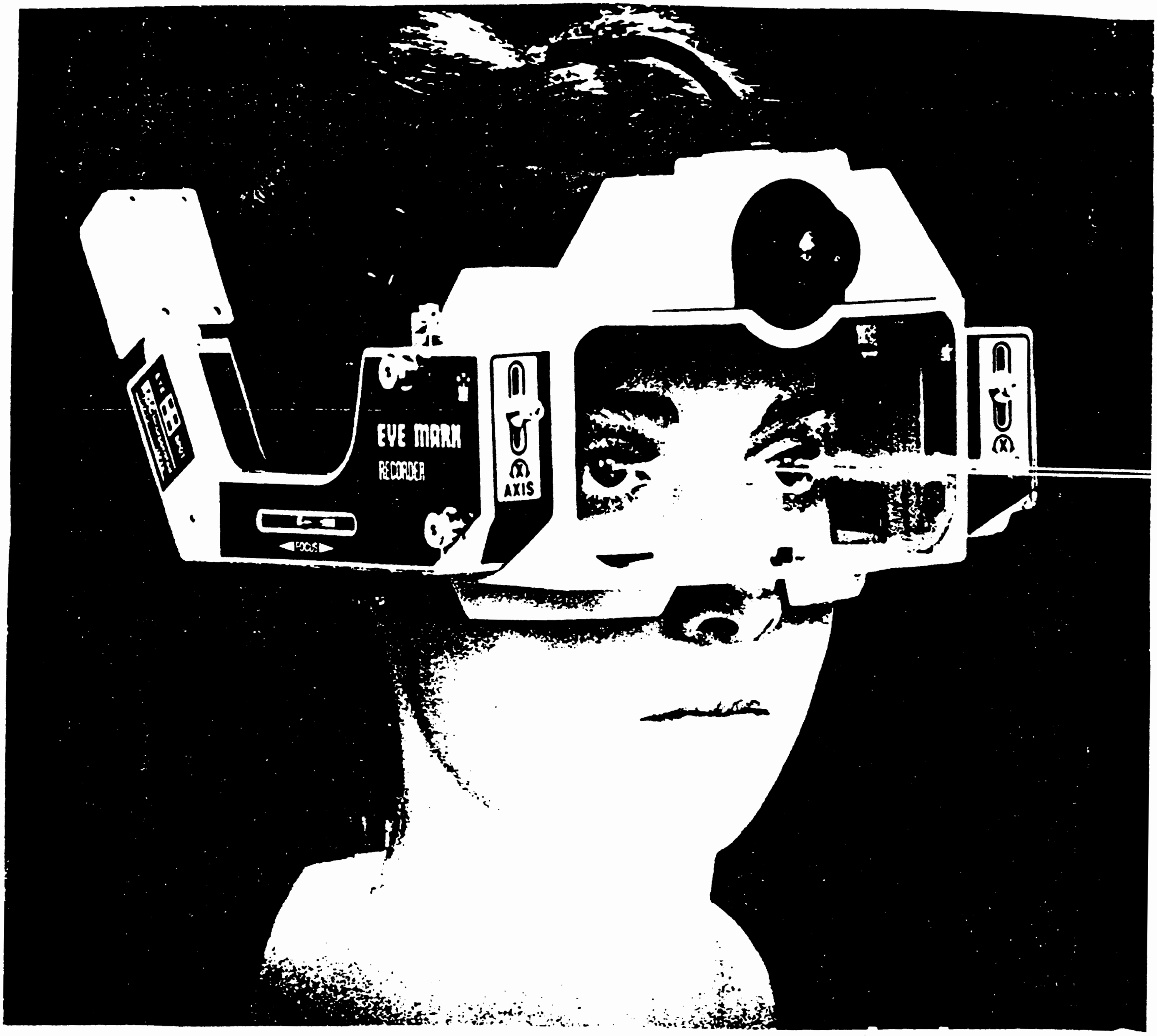

Figure 17. NAC model V Eye-fixation Recorder.

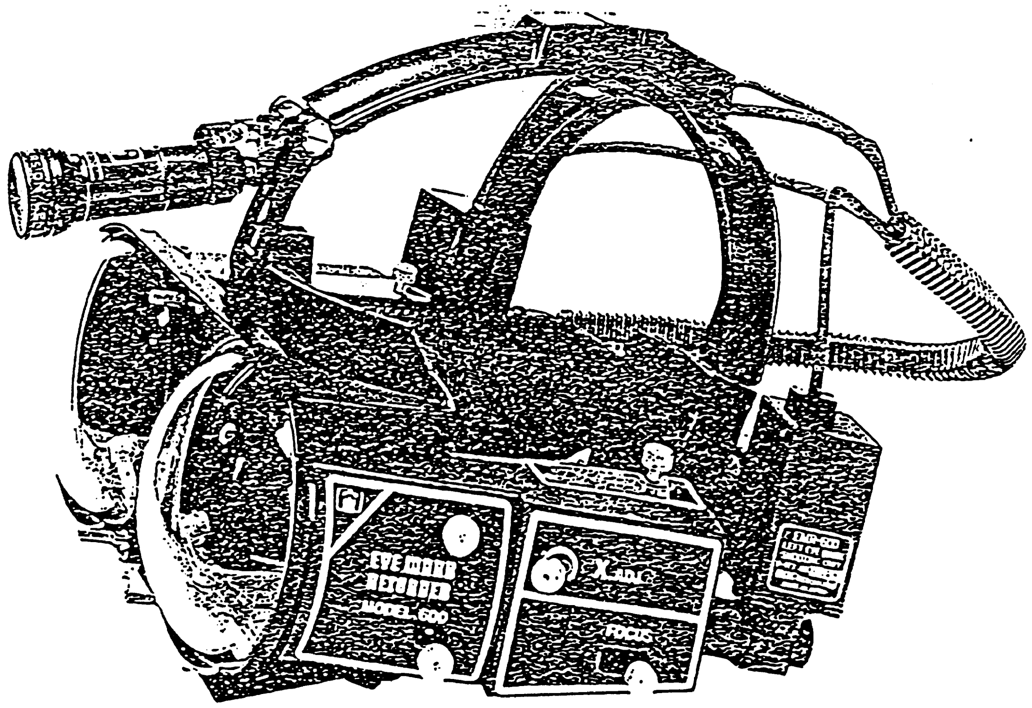

Figure 18. NAC model EMR-600 Eye-Fixation Recorder

Permobile Meditech
Box 120 861 00
Timra, Sweden
phone 46-60-572770 direct #60-572606
fax: 46-60-575250

U.S. distributor:
International Technology Group
36 Bradford Road
Natick, MA 01760
phone: (508) 651-0140, fax: (508) 653-0759

or
Permobile Meditech
6B Gill Street
Wolburn, MA 01801
phone: (617) 932-9009, fax: (617) 932-0428

This company makes the Ober-2. This product is not well known outside of Europe. The system was developed by Dr. Jan Ober, of the Institute of Biocybernetics and Biomedical Engineering of the Polish Academy of Sciences, and others. It was originally developed for studying reading. The basic unit (which includes the goggles, a full length card for IBM-compatible computers, a connection box to protect the electronics, and software) costs $17,200. The lastest version of the system is designed for 486 computers with a VGA card though a 386 will work.

There are several versions of the head unit including the goggles device (the standard configuration) and a unit that can clip on to a pair of spectacles. A CCD camera can be fitted to the goggles. The advantage of the goggles (which originally resembled a pair of swimming goggles) is that the unit is very stable on the head. The sensing unit has four infrared transmitter-receiver channels (vertical and horizontal for each eye) and can sense the direction of gaze at up to 1000 samples per second, far more than is needed for automotive studies. Typically sampling rates of 60 Hz or 120 Hz are used. The device works by sensing the reflectance distribution from the entire eye, which shifts as the eye rotates. It is not a limbus tracker. Because the location of the corneal bulge is apparent even when the eyes are closed, the eyes need not be open to sense their position. Figure 18 shows the device.

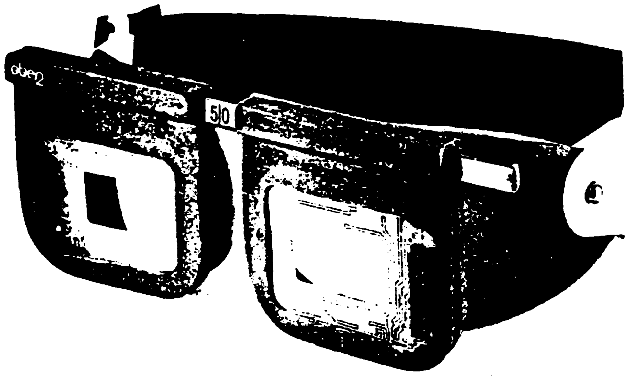

Figure 19. Ober 2 Eye Tracker

The field of view is about +/- 35 degrees horizontal by +/- 20 degrees vertical, though accurate information on the direction of gaze occurs over the full vertical field of view but only about +/-25 degrees horizontal. While the theoretical accuracy of the system is quite high (0.01 degrees), since the angle of gaze is coded as a 12-bit number for each axis, practical accuracy is about 0.5 to 1 degrees horizontally and 1 to 2 degrees vertically.

A reported major advantage of this system is the ease of calibration. The only hardware setting is the interocular spacing of the goggles. All other calibrations are in software.

There are several options that can be acquired. One of the more interesting is a board (Video Eye Position Superimposer or VEPS) that allows for superimposing the eye spot on a video scene. The card is compatible with PAL, SECAM, and NTSC video recorders and cameras.

Another option is remotely controllable shutters for the goggles. This allows the goggles to be used for occlusion studies (described later in this report).

As with several eye-fixation recording systems, software is provided. It appears that this software is well suited for studying reading. The software is written in Turbo Pascal 6.0. Its usefulness to driving research is unknown.

Finally, a system for monitoring head movements was planned at one time and may be available in the future.

Takei
6-18 1 cho-me Hatanodai
Shinagawa-ku
Tokyo 142
Japan
03-787-1054, fax: 03-787-8643

A product of which the author knows very little is the Takei Talk-Eye, a limbus eye tracker. (See Yamada and Fukuda, 1987; 1990; Yamada, Fukuda, and Hirota, undated for details.) Takei does not have a U.S. branch office and they have not exported this system. Their advertising is in Japanese, but materials in English will be available in the next month or so. The system was developed in collaboration with NHK. The Talk-Eye is unique because the head piece can be connected to a backpack radio transmitter that sends the data to a remote recorder. (See Figure 20.) The head piece appears to be modified safety goggles and the unit weighs 200 g, which is very light. Accordingly, the unit should remain stable on the head.

Analysis software is available for this device that runs on a Japanese NEC PC-9800 series computer and it is written in English. The price of a system is ¥4,552,000 (approximately $35,000), which is a bit expensive for a limbus tracker. The range of the unit is limited +/- 20 degrees horizontal by +/-20 degrees vertical. The accuracy is unknown.

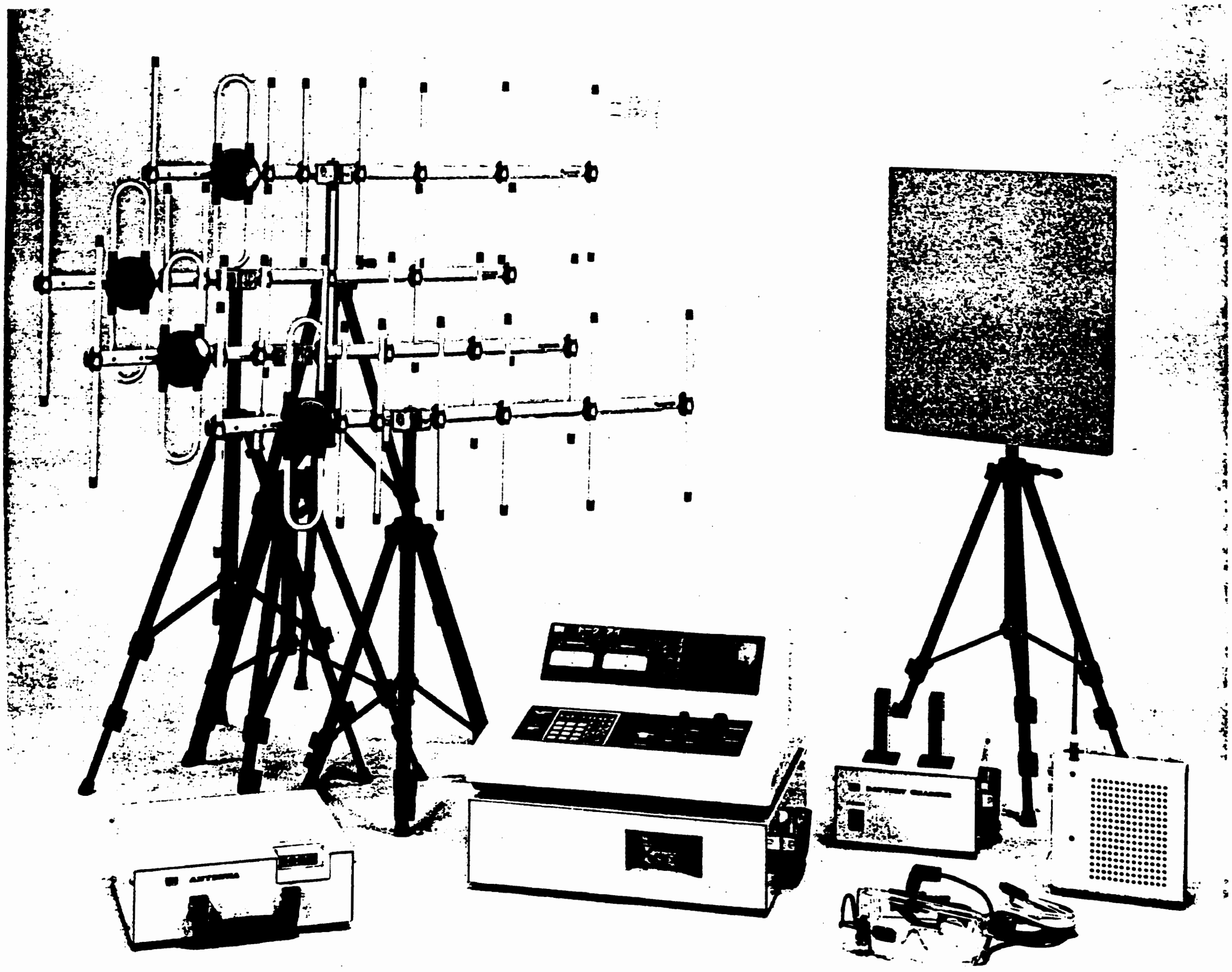

Figure 20. Takei Talk-Eye System.
Source: Takei, undated.

Other Vendors of Gaze Sensors

This section lists secondary vendors. This includes companies for which the author has incomplete information, vendors that do not make products suitable for automotive use, and companies that have withdrawn from the market (but may re-enter).

Dr. Eizenman
Institute of Biomedical Engineering
University of Toronto
215 Huron Street
Toronto, Ontario M5S 1A1
Canada

The author has been told that this organization has designed a helmet-mounted system (ELMAR) for aircraft applications. It uses both dark pupil tracking and can select among several corneal reflection measures. The system is believed to have a wider range than most corneal systems (+/- 40 degrees horizontal, +/- 20 degrees vertical). It is thought the system sells for $50,000 and can be purchased by organizations not involved in airframe simulation. These details have not been confirmed with the vendor.

Instructional/Communications Technology, Inc.
10 Stepar Place
Huntington Station, NY 11746
(800) 344-1778 or (516) 549-3000

This company makes products for studying reading. The existing product is a viewer that fits over an Apple II computer monitor and tracks the limbus. The device samples at 50 Hz and reportedly has an accuracy of two letters. The cost is $1800 for the hardware, $180 for the software, a very inexpensive combination. An MS-DOS version of the system is under development.

LC Technologies
4415 Glenn Rose Street
Fairfax, VA 22032
(800) 733-5284 or (703) 425-7509, fax: (703) 323-4782

LC Technologies makes an off-the-head system, the Eyegaze System, which is intended for recording where people look when using CRTs. (See Cleveland and Cleveland, 1992. See also Benel, Ottens, and Horst, 1991 for an example application.) The specific application was to allow disabled individuals to control devices by looking at various places on a display. Subsequently, a second product has been developed for human factors applications. The hardware consists of an IR illuminator and an IR camera that mounts below the CRT. Accordingly, their system is a bright pupil tracker. LC Technologies believes that sunlight will create problems for the system because their IR illuminator and sensor are set for low levels. Accordingly, the product may not work well in many automotive contexts (daytime).

Their basic product lists for $27,500 and includes all software and hardware, along with a 486 computer to record the data. The gaze cone is listed as 80 degrees, though the lower 15 degrees is clipped due to the lower eyelid. The accuracy is better than 1 degree. Without modification, this product may have limited application in an automotive context because the eyebox is roughly a cube with 2-inch sides. It is believed that the addition of their head tracker now in the planning stages will increase the size of the eyebox to a 1- foot cube. The basic product configuration is shown in Figure 21.

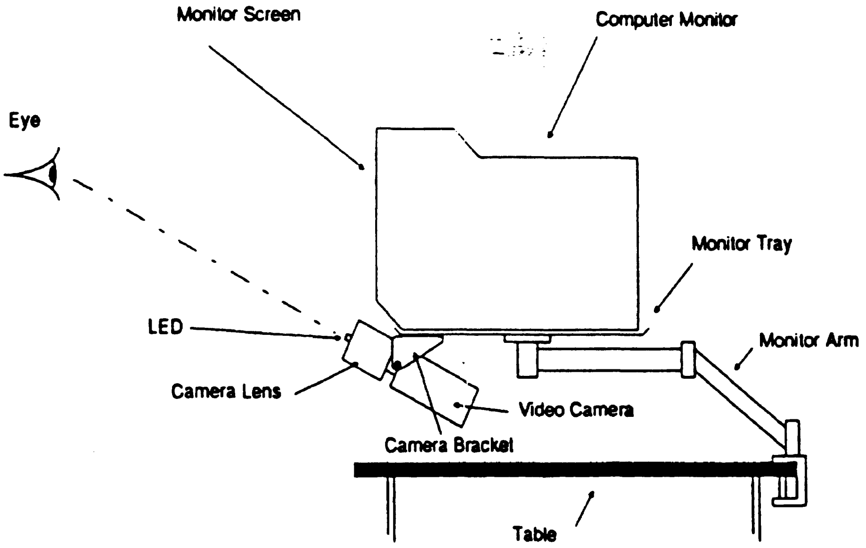

Figure 21. Eyegaze Development System.
Source: LC Technologies, 1992, p. 1.

MicroMeasurements, Inc.
Eye Monitor/Pupilometer Systems
1921 Hopkins Street
Berkeley, CA 94707
(510-524-0125)-disconnected

The phone number provided to the author is shown above, but with the previous area code (415). The author believes they still are in business. No other information is available regarding their products.

Sentient Systems Technology, Inc.
5001 Baum Boulevard
Pittsburgh, PA 5213
phone: (412) 682-0144
fax: (412) 381-5241

Sentient Systems used to make the EyeTyper, an eye gaze keyboard for the disabled. Knowledge from that product was used to develop five prototype helmet-mounted eye trackers for the Naval Air Test Center. Sentient Systems expects to re-enter the eye gaze recording business in the future.

Stoelting
Oakwood Centre
620 Wheat Lane
Woodale, IL 60191
(708) 860-9700

Their product was designed for laboratory use and requires stabilization of the head by a chin rest. It is not suitable for automotive use and is listed solely for the sake of completeness. Their eyetracker, model 12861, consists of a base unit (for the chin rest and camera mounts), an IR illuminator, a CCD eye camera, a scene camera, a signal processor, cables, and monitors. It does not include a computer but does allow for analysis of pupilometric data. The price of their base system (eye tracker, software, I/O board, and cables) is about $15,000. Several thousand dollars more is required for the computer.

Commercial Head Trackers

Since researchers are interested in where drivers are looking in the world and not just relative to the head, information on head orientation is needed. Several of the eye trackers described previously have head-tracking options. In some cases, however, a head tracker must be obtained from another vendor.

The leading vendor of head trackers is Polhemus, Incorporated, a subsidiary of Kaiser Aerospace and Electronics Company (Box 560, Colchester, Vermont 05446, phone 802-655-3159, fax: 802-655-1439). Their head trackers are magnetically-based devices.

The base unit, the ISOTRAK, lists for $3195. For most automotive applications the base unit is sufficient. It consists of a systems-electronic unit with an RS-232 interface, sensor, and source. Static accuracy of the unit at the standard update rate (58/second) is 0.13 inches RMS for x, y, z and 0.85 degrees RMS with the sensor 4 to 15 inches from the source.

Their most recent product is the 3SPACE FASTRAK, which lists for $5750. The device has a greater operating range (up to 10 feet) and provides a static accuracy of 0.03 inches RMS for x, y, z and .15 degrees RMS for orientation. Their literature notes that "large metallic objects, such as desks or cabinets, located near the transmitter or receiver, may adversely affect the performance of the system." Tsuo, Rogers-Adams, and Goodyear (1992) describe the use of the product in a car. The accuracy is unknown.

One recent addition is Ascension Technology Corporation (Box 527, Burlington, Vermont 05402, phone: 802-655-7879, fax: 802-655-5904). Their product, "A Flock of Birds," provides for 6D tracking over a 6-foot range with an angular resolution of 0.5 degrees RMS, quite adequate for driving. In a manner similar to the Polhemus products their advertising literature notes the following: "Large metallic objects in operating volume may degrade performance." Again, in-car performance is unknown.

Finally, we understand Logitech is working on acoustically-based product and is currently shipping a development system. The device is intended to be used as a 3D mouse. Interested parties should call Shawn McKenna at 510-795-8500 for details.

Occlusion Devices

An alternative way to determine the information needs of drivers is to block the drivers' view, an approach pioneered by John Senders (Senders, Kristofferson, Levison, Dietrich, and Ward, 1967). In the original experiments, drivers wore a motorcycle helmet with a translucent face shield. By pressing a switch, the shield could be raised or lowered. When lowered, light passed through so their light adaptation level did not change, but no shapes were discernible. Several means of varying viewing and occlusion times all led to the same results. Hence, the viewing time required for each driving situation was used as a measure of the attentional demand of the road. It should be noted that none of the driving was in traffic.

A more current variation on this idea is PLATO (Portable Liquid-crystal Apparatus for Tachistoscopy via visual Occlusion), a product sold by Translucent Technologies (362 Palmerston Boulevard, Toronto, Ontario, Canada M6G 2N6, phone: 416-978-3662, fax: 416-978-6924). This product consists of a pair of goggles in which LCD shutters have been substituted for the normal lens. The switching time is approximately 10 ms. Milgram (1987) describes the device in detail, shown in Figure 22. The cost is $2000.

Figure 22. Occlusion Goggles.
Source: Translucent Technologies, Inc., 1992.

Recommendations

Selection Criteria

Harris, Abramov, and Hainline (1984) describe criteria for selecting eye-fixation recorders. To date, empirical studies comparing these methods are rare (Lehtela, 1981; Ong and Harman, 1979) and none have specifically addressed automotive applications. Data requirements are described in Seeberger and Wierwille (1976). Based on those ideas and the author's thoughts, the following are considerations for automotive applications:

What is the spatial accuracy of the device?

Accuracy, here defined as the RMS difference between the reported and actual location should be within a degree or so. In most cases researchers are generally interested in where the driver is looking (e.g., to an outside mirror, close in on the road on the left, far on the left, etc.), but not exactly where the subject is looking. To put that in perspective, two 3.5-inch gauges (say a tachometer and speedometer) with 1-inch separation have a center-to-center visual angle of 9 degrees on an instrument panel (28-inch viewing distance). Two lines of 1/4 inch high text (the desired minimum for an information displays) separated by 1/4 inch would have a center-to-center visual angle of 0.9 degrees. For road scenes, the angular difference between the center and edge of a 12 foot lane at 200 feet is 1.75 degrees. Hence, to determine the general direction of where the driver is looking (road vs. instrument panel vs. mirrors, etc.) requires an accuracy of several degrees. To determine precisely where the driver is looking, accuracy of around one degree or better is needed.

What is the temporal accuracy of the device?

As was noted above, driver eye fixations are typically in the range of 200 to 800 milliseconds, though fixations to displays and mirrors can be much longer. Figures 23 and 24 show fixation durations to the radio and left mirror from one set of experiments. Using an engineering rule of thumb of 10% effects being important, that leads to 20 ms differences at the low end and 80 at the high end. Except for special devices, sampling is usually at 30 frames per second, suggesting errors of 33 milliseconds, a value within the desired range.

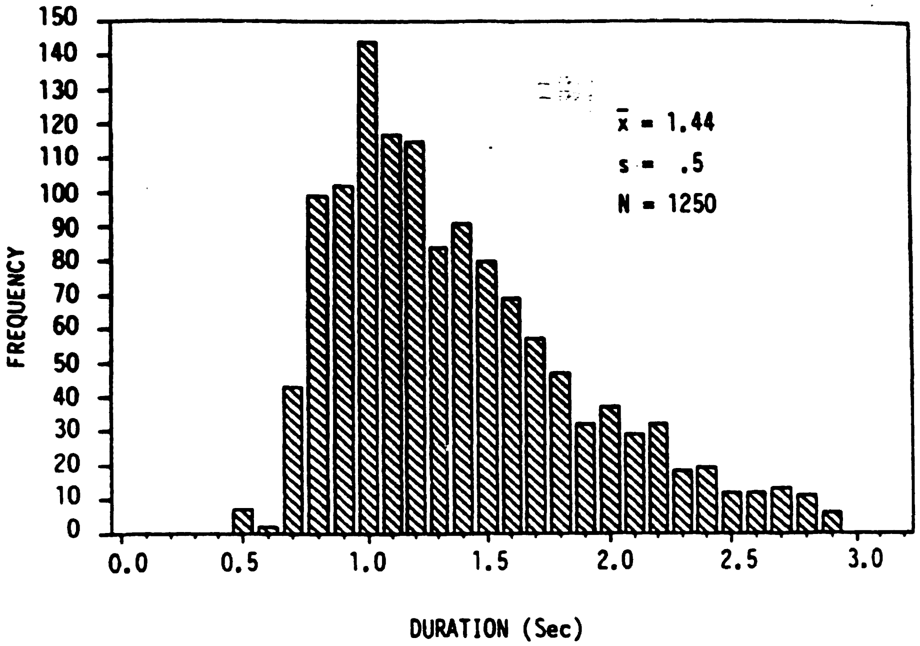

Figure 23. Distribution of Radio Glance Durations.
Source: Rockwell, 1988, p. 321.

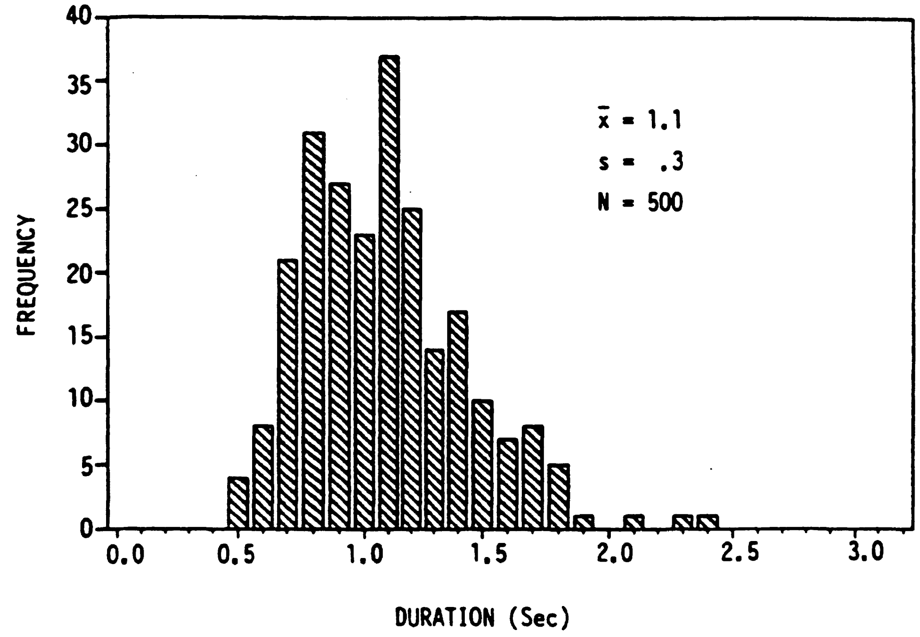

Figure 24. Distribution of Left Mirror Glance Durations.
Source: Rockwell, 1988, p. 321.

How much does the device cost?

Cost is clearly an issue in device selection. Currently, only defense contractors have the funding required to afford off-the-head devices. The author's general preference is for off-the-head systems because they are less likely to interfere with driving. Many of the devices limit peripheral vision, which in some situations can make driving more dangerous. Further, an on-the-head device may change scanning patterns, resulting in more head movement to see objects (instead of only changes in the eye gaze angle) or failure to look towards peripheral targets in other cases. Further, the weight of some on-the-head systems can make driving uncomfortable. However, examples of in-car use of off-the-head systems are rare (and there may not, in fact, be any). Off-the-head systems can cost close to $100,000. In considering the true cost of a system, the effort to install it in a test vehicle and make it work reliably must be considered. Most significant is the cost of collecting and reducing data. With off-the-head systems, objections to the "naturalness" of a study are less likely, so that studies do not have to be rerun. Also, most off-the-head system come with excellent software for reducing eye gaze data to fixation logs, reducing the total cost. The major impediments to acquiring these systems are limits in capital equipment budgets.

To put cost into a university perspective, equipment is typically 10% of the budget of an engineering research project. Hence, to pay for a midlevel system (say $50,000) would require a half million dollar project with no other significant equipment needs. Industrial sponsorship of automotive human factors research at that level for single projects is nonexistent, though a few DOT RFPs of that magnitude are now being issued. However, DOT contracts call for equipment to be returned after contracts have ended, which means that organizational capabilities to do research cannot be developed.

How much does the device weigh if it is an on-the-head device?

The author's limited experience with on-the-head systems is that they can be uncomfortable to wear. For young drivers, the NAC model V, a reasonably contemporary device, can be worn comfortably for about only 15 minutes or so before it must be removed. Time constraints for older drivers are unknown. This limit is both a result of neck muscle strain from supporting the weight of the device and pressure from the supports to hold the device fixed on the head. With practice and modification of the headgear, it may be possible to extend that period. As noted earlier, the 1.6 pounds (720 g) of the NAC model V is excessive. The author has the impression that extended wear of limbus tracker (a few hundred grams) is not a problem. Thus, the exact maximum desired weight of a head tracker is not known.

How much does the face plate reduce the incident light?

Several systems use a partially mirrored face plate to either reflect infrared light onto the eye or an image of the eye onto a camera lens. There is no accepted value, though some systems transmit about 85% of the incident light. This is most important for night-viewing studies and studies where the instrument panel displays are somewhat dim.

How long does it take to calibrate the device for each subject?

Experience has shown that there is considerable art to fitting an eye camera to a subject, and that it takes considerable practice to learn each system. Given the limited comfort duration for most systems, five minutes is a maximum, so that time remains to collect data.

Can the system be worn with glasses?

Most top of the line systems allow for the wearing of glasses, though glasses complicate the optics and calibration. Since that segment of the driving population that is elderly is significant and increasing, allowing subjects to wear glasses is important. Recent UMTRI experience with the NAC model V shows that for that device, getting good data while subjects wear contacts (either hard or soft) or eye glasses is difficult.

What is the field of view?

Many eye-fixation recorders restrict the lateral edges of the field of view (such as the NAC model V). As a consequence, drivers tend to make both head movements and eye movements when wearing the device, but only eye movements when the device is not present. For the NAC model V, the field of view can be expanded by removing one of the pupil shooting units. The field-of-view requirements will vary with the driving task (e.g., expressway driving vs. rural roads). For example, Ishiwaka has expressed concerns about using a conventional eye-fixation recorder such as the NAC EMR-600 for rural roads but not the Takei system since it uses transparent goggles (Ishiwaka, 1992). Generally speaking, when targets are more than 30 degrees from the line of sight, a head movement accompanies eye fixations. However, for safe driving, a much larger field of view is needed.

What is the minimum illumination level the system can sense?

This is important for night-driving studies. It depends on the forward scene lens system and the image sensor. To keep on-the-head systems light, image intensifiers cannot be fitted to them.

Which sensing method should be used?

Specific comparative data on the systems of interest are not reported here. The only data available are from manufacturers' literature and are incomplete. For example, weights are typically reported only for components, not for representative assemblies. It is hoped that the author will be able to obtain such measurements directly in the next phase of this project. To give the reader a sense of how the various technologies differ, a summary from Goldberg (1980) is shown in the following table. (For additional details see Young and Sheena, 1975). It is the author's opinion that for corneal reflection systems the discomfort and cost are both moderate, not low as shown in the table. Also, visual interference for scleral systems tends to be low, not medium.

Table 1. Comparison of Eye Fixation Methods

Technique	Horiz. Meas. Range (deg.)	Horiz. Accuracy	Max. Res. Freq.	Visual Inter-ference	Subject Training	Calib. & Set-up Time	Subject Dis-comfort	Cost
Contact Lens	±20	2 arc sec.	500Hz	High	High	High	High	High
Electro-oculography	±50	0.5 arc sec.	15Hz	None	Low	High	Low	Low
Corneal Reflection	±30	10 arc min.	10Hz	Medium	Low	Low	Low	Low
Scleral Reflection	±15	15 arc min.	500Hz	Medium	Low	Low	Low	Low

Source: Adapted from Goldberg, 1980.

Note: Ishikawa (1992) has suggested that this table may be in error. Young and Sheena (1975) suggest vertical and horizontal accuracies of 2 and 1.5 degrees, respectively, for EOG-based systems.

An item of comparison not mentioned in this table is the influence of glasses and contact lenses. They are compatible with contact lens systems and create no problems for EOG systems. For scleral reflectance systems, some minor adaptations of the sensor may be required. As was noted earlier, they can cause significant problems for corneal reflection systems.

The author's view is that the basic choice is between EOG, corneal reflection, and limbus tracking. Other approaches are either invasive or have hazards that drivers will find unacceptable (e.g., aiming lasers at their eyes). Limbus tracking systems are simple and light weight, but have limited range and vertical accuracy. Corneal reflection systems require considerable headgear, limiting the wear duration, and are very costly. EOG systems can be difficult to calibrate and may be too slow. They are, however, inexpensive. Thus, no single approach is ideal.

Specific Recommendations

In summary, the ideal system would be off-the-head or, if on-the-head, very light weight (a few hundred grams), be easy to calibrate and not require periodic recalibration, and, of course, not cost very much. In brief, the basic decision boils down to whether an off-the-head system is required or not. To date, no experiments have been conducted to determine if wearing eye fixation gear of any type, let alone specific models, affects visual search behavior while driving. The choice of on- vs. off-the-head systems is often a budget question.

The author's view as to which system or systems are best for automotive applications has changed many times. If money is no object, an ASL 4000 system or one of the ISCAN products (possibly the RK-426 with a head tracker) should be considered. They have the necessary accuracy and reliability, and from what the author can determine from the literature and colleagues, provide good software support. Software for both data reduction and analysis is critical. The NAC EMR-600 is also a possibility but there are concerns about availability (in the U.S. and Europe) and field of view. The author cannot comment on the Takei Talk-Eye because so little is known about it.

One of the key problems with eye trackers is maintaining calibration, which usually requires two independent measures of gaze. One solution that has not been explored to date would be to use two systems such as an EOG system combined with a limbus or reflection tracker, especially inexpensive models such as the Ober-2 or the ASL model 210. The EOG data could be used to check the limbus output and would provide a wider range and more precise vertical data than from a limbus system alone. The basic drawbacks are a potentially complex set-up procedure (of calibrating the limbus tracker and placing electrodes) and the lack of software for such a system. Since absolute direction of gaze is desired, a head tracker would also be needed.

The author believes that weight would not be a problem for this combination. Again, the author's point of reference is the NAC-V. While part of the problem is neck discomfort associated with supporting and stabilizing that much weight (especially in rotation), the main problem is the clamping force on the head required to keep the headgear in position. Obviously, reducing headgear weight reduces the clamping force necessary, increasing comfort and wear duration. While off-the-head systems are strongly desired, in-car experience with them is limited and should be investigated.

It could be that for the initial development the cost of assembling the hardware and developing software could exceed the cost of a top of the line ASL or ISCAN product. Nonetheless, the author considers the idea worth further exploration.

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