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Driver Eye Glance Behavior During Car Following

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16. Abstract This report describes research that examined driver eye glance behavior away from the road scene ahead during car following. The results were based on data collected from 60 drivers and over 6,500 miles of driving on both highways and city streets. Results indicate the conditions in car following when drivers looked away from the road ahead, the distribution of glance durations when looking away, and the distribution of where drivers looked away from the road ahead. These data provide insights into the strategies used by drivers to manage their visual resources while car following. A key finding is that drivers appear to glance away from the road scene ahead during car following when the apparent optical expansion rate is zero, regardless of range. This strategy is reasonable provided the lead vehicle does not brake suddenly. It was also found that glance durations away from the road scene ahead during car following were, on average, shorter than those reported in other studies where car following was absent. This might be interpreted to indicate that the drivers were keeping their glances away short in case the driving situation should change.					
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EXECUTIVE SUMMARY

A study was undertaken to characterize driver eye glance behavior during car following. Participants drove an instrumented vehicle unaccompanied on public roads that included high speed highways as well as surface streets. The drivers were paid to participate in the study and had no time pressures placed on them. The data obtained represent a baseline database of what might be termed ‘safety -ideal’ eye glance behavior during car following. Key findings are summarized below.

There is remarkable consistency in the strategy with which drivers looked away from the road ahead during car following. Simply put, they generally looked away when the range rate was effectively zero. They did not, in general, appear to take range or time headway into account to any substantial degree. This strategy appears consistent with other research on the effective stimulus for braking behavior [1, 2]. It also implies that drivers assume that the lead vehicle will not brake abruptly, a belief reinforced by common driving experience. This strategy of deciding when it is safe to look away may explain why driver inattention is a leading contributing factor to rear-end crashes: driver expectations are sometimes violated and the driver has not allotted sufficient distance (range) to recover.

Driver eye glance durations away from road ahead during car following averaged 0.6 s with a standard deviation of 0.46 s. This pattern implies that drivers during car following are more cautious about how long they will look away from the road scene ahead. Furthermore, this finding suggests that future studies of the effects of in-vehicle technology on drivers should compare in-vehicle glance durations to both glance durations in an open-road environment and in a car following setting. The results should be substantially different except for the most simple of in-vehicle tasks.

The fact that driver eye glance durations were not predicted by range, range rate, or speed perhaps reflects a combination of the demand characteristics of the activity that prompted the glance away (unknown) and a well-learned strategy drivers have to keep glance durations below about 1.6 to 2 seconds [3, 4]. The distribution of glance locations was found to reflect both individual differences among drivers with respect to age and as a function of speed regime.

1.0 GENERAL INTRODUCTION

1.1 Background

The U.S. Department of Transportation's Intelligent Vehicle Initiative (IVI) attempts to enhance surface transportation safety, efficiency, and comfort by applying advanced technologies, including information processing, communications, control, and electronics, to the driving process. One goal of IVI is to reduce the number and severity of roadway crashes and related fatalities and injuries. Collision Warning Systems are, therefore, a focus of IVI research and development.

Rear-end collisions represented about 23% of all police-reported crashes in the U.S. in 1993 [6] and are among the most common crashes plaguing the U.S. driving population. Later analysis [7] indicates that the incidence of such crashes is going up. Rear-end crashes occur under two broad scenarios [8]. The lead-vehicle-moving (LVM) scenario involves a moving lead vehicle that is either slowing or traveling at a constant, though slower, speed than the following vehicle when a collision occurs. The lead-vehicle-stopped (LVS) scenario involves a lead vehicle that was stopped or moving very slowly (perhaps due to a traffic signal, stopped traffic, to make a left turn, etc.) for some period of time prior to being struck by the following vehicle. Regardless of subtype, the largest single contributing factor for rear-end crashes of either type is driver inattention [6].

Rear-end crash driver warning systems are being developed that monitor the forward path of the host vehicle. Warnings are provided if the car following time headway, closing rate, or other indications of separation with respect to a lead vehicle presents a potentially dangerous situation. The driver/system interface may consist of visual, auditory or haptic displays. The development of warning algorithms must be compatible with the driver's perceptual and psychomotor capabilities to react appropriately. This report describes the collection and analysis of car following data collected on public highways and city streets. A sample of civilian drivers spanning a wide range of ages and both genders were recruited to provide naturalistic data on normal car following behavior. As such, the data collected represent a valuable resource for ideal, safety-optimal, car following behavior.

1.2 Research Objectives

The objective of the research reported herein was to examine driver eye glance behavior away from the road scene ahead during car following. This is important for rear-end collision avoidance because it indicates the conditions under which drivers perceive it is safe to look away from the vehicle ahead. This type of information might be factored into rear-end collision warnings that are compatible with the perceptual means by which the driver will visually verify the hazard that prompts the warning.

2.0 LITERATURE REVIEW OF DRIVER BEHAVIOR DURING CAR FOLLOWING

2.1 Driver Eye Glance Behavior Away From The Road Ahead During Car Following

It is a truism that visual attention to the driving scene is primary in safe driving. To a first approximation, the driver may be considered to act like a limited-capacity single-channel information processor. In this framework, the driver has but a single foveal visual resource that must be moved about or time-shared to gather detailed information from the road scene ahead, mirrors, controls and displays within the vehicle, and other information sources [4]. This suggests that looks away from the road ahead during car following might be considered opportunities for rear-end crash occurrence.

A recent study by Summala, Lamble, and Laakso [5] illustrates the reduction in road scene object and event detection when looking away from the road scene ahead during car following. In their study, 28 drivers of varying degrees of driving experience (none; 1000-10,000 km; or 50,000 km or more lifetime driving experience) each followed a lead vehicle during daylight while driving an instrumented car on a new freeway not yet opened for traffic in Finland. Initial car following conditions consisted of the four combinations of either 15 m or 30 m initial headway distances while both vehicles traveled at either 30 km/hr or 60 km/hr. A digital display, which the driver was instructed to read, was located at the lower part of the windshield, at the speedometer area on the instrument panel, or in the mid-console area. The driver's task was to name all the fours and sevens from a random series of single digits that were presented at a frequency of three (3) Hz on the digital display. The confederate lead vehicle would brake with an average deceleration level of 2.1 m/s², sometimes with brake lights disabled and sometimes with brake lights operating normally. The brake reaction times of the following vehicle driver were measured after lead vehicle deceleration started. The results of the study indicated that detection of the brake lights was substantially impaired when the following vehicle driver was looking at the speedometer location. Whether brake lights were operational or not did not contribute at all to detection of the lead vehicle braking when the following vehicle driver was looking at the display in the mid-console area. Furthermore, driving experience had no effect on the outcomes of the study. This study strongly suggests that eye glances away from the road scene ahead during car following can lead to a substantial reduction in the ability to detect the braking of a moving lead vehicle.

Many studies have been conducted to examine the fine structure of driver eye movements to the road scene ahead while driving. Mourant and Rockwell [9] had eight test participants drive an instrumented car on public roads at 83.3 km/hr (50 mph) while following a confederate lead vehicle at a fixed distance of approximately 22.9 m (75 ft) to emulate steady-state car following. As compared to open road driving, there were fewer fixations per minute of driving while car following (221 versus 196, respectively). Fixations to the lane markers (center and right) increased almost twofold during car following, and there was a decrease in the sampling rate for road signs. The authors hypothesized that the slower visual sampling rate in car following might have been due to the judgments needed to maintain a fixed distance between the two vehicles.

Rockwell [10] summarized studies conducted by him and his colleagues at The Ohio State University which used eye movement recordings to capture the distribution of driver eye fixations during car following on public roads. They found, for example, that drivers in their studies driving at 100 km/hr (60 mph) looked at the lead vehicle and center of the travel lane ahead 71% of the time while car following at short headway distances (i.e., less than 45.7 m or 150 ft), and 68% of the

time while car following at long headway distances (i.e., greater than 45.7 m or 150 ft), a small difference. The drivers spent between 10 % and 12 % of the time in car following looking at the right lane marker for long headway conditions. Between 10 % and 11% of the time was spent looking at “other” locations (unspecified). Finally, between 8% and 10% of the time the driver’s eyes were out of view of the camera.

More recently, Veltri [11] examined driver eye fixations in a car following scenario in a fixed-based driving simulator. Four test participants drove at each of three constant speeds (7.5, 12.5, or 17.5 m/s). Each participant could choose his distance to the simulated car being followed, provided he did not lose sight of the vehicle, especially in tight curves. Each driver was, however, asked to keep his distance as constant as possible for each speed, once selected. The simulated route had numerous curves of various radii. At slower speeds, drivers were more varied in their technique of scanning the road scene ahead. These methods included on-car fixations, fixation on the tangent point on the inside of the curves, a combination of these, and looking halfway between the lead vehicle and the tangent point of the curve. As car speed increased, however, all test participants tended to look more off the car and towards the road (but not the tangent point), no matter what their original scan patterns. Two of the participants tended to look to the road ahead of the lead vehicle to acquire information while the remaining two participants look down from the lead vehicle onto the road right behind it to acquire information. This pattern of results indicates that driver eye glance behavior during car following can be influenced by travel speed, road geometry, and individual differences among drivers.

Liu and his associates [12,13] examined the fixation probabilities for various locations during simulated open road driving and during simulated car following, using the same fixed-base simulator as that reported by Veltri [11]. They found that, relative to open road driving, the presence of a lead vehicle substantially attracted driver eye fixations (probability of 0.34), while decreasing fixations to the sides of the road and just ahead of the following vehicle. These authors compared their simulator data to the on-road car following study data of Olson, Battle, and Aoki [14]. They also reported a significant fixation probability (0.37) to the lead vehicle, similar to the simulator results. However, the on-road study revealed a precipitous drop, relative to open road driving, in the probability of fixating the road far ahead but only very slight reductions in fixation probabilities to the sides of the road. These discrepancies were attributed to differences in the simulator driving scenario and the driving conditions present in the on-road study, again suggesting the influence of situational factors on driver eye fixations.

As indicated by this brief sampling from the literature, a number of published studies have examined where the driver looks in the road scene during car following. In contrast, not much has been published on the conditions under which the driver looks away from the road scene during car following. Numerous studies have been conducted in the area of driver workload and the visual demands imposed by various requested in-vehicle tasks [4]. However, these studies generally analyzed eye glance measures with respect to in-vehicle tasks, not car following parameters *per se*. Furthermore, safety considerations often lead to workload study tasks being requested only when there is no lead vehicle close by. The present study examined driver eye glance behavior during car following with a focus on driver eye glances away from the forward scene and no requested tasks in order to contribute to a better understanding of this behavior.

2.2 Primary Visual Cues in Car Following

How does a driver come to know that he or she must decelerate to avoid hitting another vehicle? Clearly, there are many cues that might prompt such a maneuver. Some of these cues are contextual in nature. The geometry of the driving scene can provide contextual cues. Examples of these include an upcoming intersection, an at-grade rail crossing, a hill, or a curve ahead, any of which may inform the driver of the need to slow down. Traffic control devices, signs, and pavement markings can also provide contextual cues, for instance, when the driver notices a traffic light ahead turns red and slows down accordingly. The presence of jersey barriers, earth movers, or road signs indicating road construction ahead might provide contextual cues to slow down. Many times, patterns of the traffic ahead of the vehicle immediately preceding the driver's own vehicle provide powerful cues to a driver on the need to decelerate. As interesting and important as these contextual cues to initiate braking may be, they are not the subject of inquiry for the present research and so are mentioned here only in passing.

A second class of cues that might prompt a deceleration response are the brake lights of a decelerating lead vehicle directly in front of the driver. Such a cue is referred to as an augmenting cue by Mortimer [15]. This term derives from the fact that such cues are synthetic signals used to provide information once their coding is learned. Depending on whether a lead vehicle driver is merely 'riding' the brake pedal or braking with some force, the brake light provides both alerting and informational cues. It is clear that many instances arise where such augmenting cues are not available. Examples include a parked vehicle, a stopped vehicle in the travel lane, or a vehicle traveling at a constant but lower speed than the subject vehicle closing in from behind. Augmenting cues are also not necessarily available for a vehicle that is slowing by means of throttle release, down-shifting, or the effects of road friction or drag. The crash record indicates that even if available, such augmenting cues may not be effective. Augmenting cues, and means to improve their alerting and informational properties, represent a substantial area of research. However, they also are not the subject of the present research and so are mentioned only in passing.

There is a third class of cues to prompt deceleration that Mortimer [15] terms primary cues. These are defined as the natural visual cues available in a situation for distance or change-in-distance information. Since this report is concerned with driver perception of these primary cues in car following, they will be discussed in some detail.

It has been proposed by numerous researchers that key inputs for driver control in car following are the visual angle, angular rate of change of the lead vehicle subtended at the driver's eye, and various combinations or ratios of these (e.g., Lee, 1976 [16]; Regan, 1997 [17]; Flach, Standard, and Smith, 1997 [1]). The basic equations for visual angle $[\Theta(t)]$ as a function of time (in radians) and rate of change in visual angle as a function of time $[d\Theta/dt(t)]$ are derived below.

Visual angle subtended at the eye of the driver by a preceding vehicle is given by the following equation:

$$\theta(t) = \arctan\left[\frac{W}{R(t)}\right]$$

where: θ is visual angle in radians;

W is preceding vehicle width (nominal 6 ft. for passenger cars, 8 ft. for heavy trucks);

$R(t)$ is range (inter-vehicle distance) at time t , also in feet.

Note that visual angle is not generally a linear function of range, as implied by the small angle approximation $\hat{\theta}(t) \approx \frac{W}{R(t)}$.

Visual expansion rate is derived as follows:

Let
$$u = \frac{W}{R(t)}$$

Then
$$\frac{du}{dt} = \frac{R(t) \cdot 0 - W \cdot \dot{R}(t)}{R(t)^2} = \frac{-W \cdot \dot{R}(t)}{R(t)^2}$$

So
$$\dot{\theta}(t) = \frac{d\theta}{dt} = \frac{d[\arctan u]}{dt}$$

$$\frac{d[\arctan u]}{dt} = \frac{1}{1 + u^2} \cdot \frac{du}{dt}$$

$$\dot{\theta}(t) = \frac{1}{1 + u^2} \cdot \frac{du}{dt} = \frac{1}{1 + \left[\frac{W}{R(t)}\right]^2} \cdot \frac{-W \cdot \dot{R}(t)}{R(t)^2} = \frac{-W \cdot \dot{R}(t)}{R(t)^2 + W^2}$$

where: $\dot{\theta}$ is visual expansion rate;

\dot{R} is range rate (i.e., preceding vehicle velocity minus following vehicle velocity), in ft/s.

All other terms are previously defined.

Here it is important to note that $\dot{\theta}$ is a function of both R and \dot{R} .

When \dot{R} is less than zero, the range between the lead vehicle and following vehicle is getting smaller. Conversely, when \dot{R} is greater than zero, the range between the lead vehicle and the following vehicle is growing larger. From this, one can deduce that when $\dot{\theta}$ is greater than zero, the range between the lead vehicle and following vehicle is growing smaller and when $\dot{\theta}$ is less than zero the range between the lead vehicle and following vehicle is growing larger.

Drivers can only directly perceive \dot{R} if the range R is:

$$R(t)_{Threshold} < \sqrt{\frac{|-W \cdot \dot{R}(t) - \dot{\theta}_{Threshold} \cdot W^2|}{\dot{\theta}_{Threshold}}}$$

Mortimer (1990) [2] has indicated that the threshold for detection of angular rate of change, $\dot{\theta}$, in driving contexts is between 0.002 radians/s and 0.004 radians/s, with a nominal threshold value of 0.003 radians/s. By substituting 6 ft. for W and 0.003 radians/s for $\dot{\theta}_{Threshold}$, the following equation results for the maximum range at which the threshold can be detected.

$$R(t)_{Threshold} < \sqrt{2000 \cdot \dot{R}(t) - 6^2}$$

Table 1 below shows the maximum ranges required for various range rates with the assumptions provided above. In addition, the time-to-collision (TTC) values for each scenario are provided. The instantaneous time headways for 68 mph and 45 mph following vehicle travel speeds are also given. It can be seen that lower \dot{R} values (i.e., more gradual closing rates) require the following vehicle driver to be closer in range to the lead vehicle than higher \dot{R} values. A second observation is that the TTC values only depend on relative velocity and, for a moving lead vehicle, are independent of following vehicle travel speed. (Relative velocity and absolute velocity are identical only if the lead vehicle is stopped and all motion is accomplished by the following vehicle). Finally, instantaneous time headways at the threshold of direct perception of the visual expansion rate are a linear function of the reciprocal of the following vehicle travel speed. Thus, for the same R values and the same \dot{R} values, the threshold of perception will be different in units of time headway as a function of following vehicle travel speed. Put another way, the same driver response function to lead vehicle deceleration will be shifted along the time headway axis for different travel speeds simply by virtue of the manner in which time headway incorporates velocity.

Table 1 presents a set of \dot{R} values that represent a range of plausible closing rates for a car following situation, along with the calculated maximum “direct perception” ranges and associated instantaneous time headways if traveling at 88 ft/s (60 mph). A practical limitation in car-following studies is that the range of the car following (headway) sensor will be limited to perhaps 300 feet or so; at highway speeds, this implies that data collection on car following at greater than about 3 seconds of car following time headway will not be feasible.

Table 1. Representative Closing Rates, Minimum Calculated Ranges for Direction Perception, and Associated Time-to-Collision and Time Headway Values at 68 mph and 45 mph Travel Speeds

Closing Rate, \dot{R}	Maximum Range for Direct Perception of \dot{R}	Instantaneous Time-To-Collision at Maximum Range $TTC=R/\dot{R}$	Instantaneous Time Headway at Maximum Range, Given $V_{FV} = 100$ ft/s (i.e., 68 mph), $TH=R/V_{FV}$	Instantaneous Time Headway at Maximum Range, Given $V_{FV} = 66$ ft/s (i.e., 45 mph), $TH=R/V_{FV}$
$\dot{R} = 2.933$ ft/s (2 mph relative velocity)	76.35 ft	26.03 s	0.76 s	1.16 s
$\dot{R} = 7.33$ ft/s (5 mph relative velocity)	121 ft	16.51 s	1.21 s	1.83 s
$\dot{R} = 14.67$ ft/s (10 mph relative velocity)	171 ft	11.66 s	1.71 s	2.59 s
$\dot{R} = 22$ ft/s (15 mph relative velocity)	210 ft	9.54 s	2.10 s	3.18 s
$\dot{R} = 29.33$ ft/s (20 mph relative velocity)	242 ft	8.25 s	2.42 s	3.67 s
$\dot{R} = 36.67$ ft/s (25 mph relative velocity)	271 ft	7.39 s	2.71 s	4.11 s
$\dot{R} = 44$ ft/s (30 mph relative velocity)	296 ft	6.72 s	2.96 s	4.48 s
$\dot{R} = 51.33$ ft/s (35 mph relative velocity)	320 ft	6.23 s	3.2 s	4.85 s

Mortimer [15] pointed out that there are several candidates for the “effective stimulus” that serves as the primary cue (or cues) for deceleration. Most studies have used visual angle subtended by the leading vehicle. A second cue is the inter-vehicle range. Which one is actually used by the driver is difficult to discern. Mortimer argues in favor of inter-vehicle range on the following grounds. First, he points out that it is perhaps most fundamentally the variable that the driver is trying to influence in car following. Second, models based on visual angle or apparent width would have difficulty in explaining inter-vehicle separation in following a vehicle at night which displays a single light, such as a motorcycle. However, inter-vehicle distance and change in distance can still be appreciated under such conditions. Mortimer concludes that visual angle can nonetheless be important, as evidenced by the increase in driver sensitivity when rear-signaling systems that accentuate such cues are used in car following and braking studies.

Visual angle and angular expansion rate are frequently used as explanatory variables. Other times the inter-vehicle range and change in range over time are used as explanatory variables. Intuitively, it is also clear that one might attempt to use certain design and engineering means to make the lead vehicle’s visual angle and angular change over time more apparent (e.g., by means of rear-end lighting systems or conspicuity markings). These types of design interventions could be quite distinct from those that make the inter-vehicle distance or changes in inter-vehicle distance more apparent (e.g., by means of road markings or ground texture).

Studies of braking or deceleration during car following have been conducted to assess the reaction time distribution as well as the nature of the perceptual and decision processes involved. As

indicated earlier, brake lights provide symbolic information on a preceding vehicle's intent to slow down. To address safe car following distances that accommodate a worst-case scenario, one might assume that the lead vehicle does not show brake lights. This might arise, for example, upon encountering a vehicle traveling at a constant but slower speed than the following vehicle; a downshifting vehicle; a vehicle decelerating on an uphill; a vehicle with very dirty or snow covered brake lights, or a vehicle stopped in the travel lane with brake lights off. In these cases, drivers must react to changes in optical expansion rate, visual angle, range or range rate (or perhaps some combination of these). Further, even when brake lights do come on, other optical information provides the driver with information that allows for a more controlled response since brake lights only indicate that the following driver may need to brake.

Snider [18] carried out an early study of car following to examine driver perceptual sensitivity to changes in headway distance. Eight (8) male undergraduate student drivers drove an instrumented vehicle at 50 mph following a lead vehicle to which it was attached by means of a wire and take-up reel apparatus that provided range and range rate measurements. The alerted driver was told during trials to observe the lead vehicle which, at random times, decelerated at 0.006 g, 0.013 g, 0.019 g, and 0.025 g or 0.1 g at each at four different initial head ways: 60 ft, 120 ft, 180 ft, and 240 ft, each plus or minus 5 ft. The driver responded via a button press when he detected a change in headway and this headway change distance was the dependent variable in subsequent analyses. Regression modeling indicated that the headway change distance associated with detection could be predicted by knowledge of the initial headway alone; inclusion of a relative acceleration predictor variable had no appreciable effect on the goodness-of-fit of the linear regression model. The beta weight for the initial headway predictor varied from 0.021 to 0.085, indicating an average proportion of initial headway required for detection. However, using the criterion of a multiple R^2 of at least 0.5 (i.e., the regression model should account for at least half of the variability in the response), the range of beta weights was between 0.044 and 0.085.

Rockwell [19] summarized a number of studies into driver sensing capabilities conducted by him and his colleagues. Based on a study with 6 test participants (details not provided), he reported that the mean change in inter-vehicle distance for detection was 4 ft given an initial separation of 50 ft; 10 feet given an initial separation at 100 ft; and 15 ft given an initial separation of 200 ft. These amount to proportional changes in inter-vehicle distance of 0.08, 0.1, and 0.075, respectively. In one instance, the 5th percentile mean headway for detection change was 8 ft given an initial separation of 200 ft, yielding a proportional change of 0.04, indicative of relatively great sensitivity. However, these variations within and between test participants undoubtedly reflect variations in momentary attention to the lead vehicle as well as perceptual sensitivities.

Braunstein and Laughery (1964; as described in [2]) conducted research using vehicles and decelerations of 0.8 to 1.48 ft/s² and obtained proportions of initial headway needed for detection of 0.09 to 0.12 and proportions of change in initial visual angle of 0.08 to 0.14.

Mortimer [2] described a study he conducted in which 14 drivers drove a vehicle on an interstate highway while following a lead vehicle configured with different types of brake lighting systems. Each driver drove 50 mph at an initial separation of 200 ft. The lead vehicle then decelerated at 0.15 g, 0.25 g, or 0.35 g until a speed of between 30-35 mph was achieved. In conditions where the brake lights were not activated, the onset of following vehicle deceleration was estimated at 3.25 s, 2.13 s, and 1.91 s, respectively for 0.15 g, 0.25 g, and 0.35 g lead vehicle braking events. The associated mean changes in inter-vehicle distance at the time of response were 25.4 ft, 18.1 ft, and

20.4 ft, corresponding to proportional changes (from 200 ft initial headway) of 0.13, 0.09, and 0.10, respectively, for 0.15 g, 0.25 g and 0.35 g braking events.

Mortimer [2] also reported that, for the aforementioned study, the rates of change of visual angle of the lead vehicle "...at the instant of perception... (p.592)" were 0.0014 rad/s at decelerations of 0.15 g and 0.25 g and 0.0018 rad/s at decelerations of 0.35 g. Because these are below the threshold for perception of optical expansion (threshold of between 0.002 and 0.004 rad/s with a nominal threshold value of 0.003 rad/s), Mortimer presumed that closure was detected on the basis of the change in the headway or change in visual angle rather than the rate of change of these values. He also argues this is corroborated by the relatively constant Weber ratios (i.e., delta stimulus over baseline stimulus) which varied from 0.09 to 0.13.

From these studies, it appears that the proportional change in inter-vehicle distance, relative to an initial headway, needed for detection is in the range of 0.07 to 0.12, on average. Perhaps this serves as the primary cue when the closing velocity is rather low. At higher closing velocities and shorter ranges, optical expansion rate might serve as the primary cue, as will be seen below.

In terms of relative velocity cues, optical expansion rate (i.e., rate of change of visual angle with respect to time) has been identified as a key source of information. Mortimer [2], in his review, noted that an early study uncovered that at perception of closure, the proportion of inter-vehicle distance change to initial distance was approximately 0.02 to 0.03 while the rate of change of visual angle subtended by the lead vehicle at the following vehicle driver's eye was between 0.0028 and 0.0035. Because the inter-vehicle distance change at detection was below the threshold for detection, Mortimer concluded that the closure of the following vehicle on the lead vehicle must have been based on the optical expansion rate cue. The study was conducted at car following distances of 81 to 88 ft and lead car decelerations of 3 ft/s² (no travel speed information reported).

Hoffman and Mortimer [20] recently reported on the results of a study to examine driver sensitivity to changes in relative velocities between vehicles in a car following situation. Groups of 17, 13, and 18 test participants viewed film clips made from a following vehicle approaching a lead vehicle with several different relative speeds (0.54 to 7.23 m/s) while driving on a highway at a mean headway of 28 m. The apparent angular velocity was manipulated to span a range of 0.0013 to 0.017 rad/s. Participants were shown pairs of film clips for 4 s each. They were then asked to judge which clip showed the higher relative speed and to estimate the ratio of the two values. The results showed that only when the optical expansion rate exceeded 0.002 to 0.003 rad/s were the test participants able to scale the relative velocity. The relationship between subjective relative (closing) speed and objective relative speed was modeled with a power function (estimate = $\beta_0 * Actual^{\beta_1}$). A value for the exponent $\beta_1 = 0.8$ was found with 94% or more of the variance in subjective judgments accounted for. However, a simple linear regression model showed fit as good as that with the power law model. This equality of fit was interpreted to mean that within reasonable error in the experiment, the exponent has a value of 0.8 to 1.0.

Lamble, Laakso, and Summala [21] investigated the detection thresholds to lead vehicle deceleration as a function of the location of in-vehicle displays. The purpose of the research was to assess how readily a driver might detect a lead vehicle braking while using an in-vehicle device located various distances from the driver's straight ahead line-of-sight. Twelve drivers between 19 and 27 years of age drove either 20 m or 40 m behind a lead vehicle which traveled at 50 km/hr and suddenly decelerated at 0.7 m/s² without warning. The investigators found that Time-To-Collision

(calculated as $TTC = \{(V_{\text{relative}}^2 + 2aR)\}^{1/2}/a$, where V_{relative} is relative velocity, a is following vehicle deceleration, R is range) decreased significantly as the eccentricity of in-vehicle display location increased. Furthermore, the TTC at detection was significantly shorter in the 20 m initial headway distance condition than in the 40 m initial headway distance condition. Also of interest was the finding that drivers were more sensitive to the visual expansion when closer to the lead vehicle. Mean detection threshold for the visual expansion rate when looking straight ahead were 0.00377 rad/s at 20 m and 0.00215 rad/s at 40 m. The authors speculated that this was probably due to the larger retinal size of the lead car, which made the detection of a change in size more obvious. These values are close to the thresholds for detection of a closing object of 0.003 rad/s reported by Hoffman and Mortimer [20]. Thus, available evidence from actual car following scenarios suggests that the threshold for detecting optical expansion rates is approximately from 0.002 to 0.004 rad/s, with a nominal value of 0.003 rad/s.

From these studies, one can conclude that drivers are sensitive to optical expansion rates above a certain threshold. This threshold, while driving, appears to be in the range of about 0.002 rad/s to 0.004 rad/s. If the closing rate is rather slow, the driver may nonetheless notice the closure based on a proportional change in headway with respect to some initial inter-vehicle distance. One difficulty in applying the proportional distance change thresholds to naturalistic open road driving is that the “initial separation distance” required for the calculation is generally indeterminate. Experimenters in past studies on the subject told the drivers what inter-vehicle distance to drive initially, yet such stipulations are not present in naturalistic driving studies. Presumably, this proportional change in inter-vehicle distance requires at least short-term memory of an initial headway with which current headway is mentally compared for its successful application. On the other hand, the instantaneous optical expansion rate may, with suitable range and range rate instrumentation, be determined from knowledge of the lead vehicle width, inter-vehicle distance (range) and relative velocity (range rate). When the optical expansion rate threshold is exceeded, so likely will be the threshold for detection of a change in separation distance, even though the opposite is not necessarily true.

Once a change in optical expansion rate exceeds threshold, the driver may react. The nature of that reaction, once initiated, will also be driven by optical variables and the driver’s experience with the dynamics of the host vehicle. Lee (1976)[16] (see also Lee, 1980 [22]) proposed the optical version of time headway, τ or Tau, as a critical aspect of the car following situation the driver uses to manage deceleration. In Lee’s small-angle approximation, τ is defined as the visual angle subtended by the vehicle ahead divided by the optical expansion rate, i.e., $\tau = \theta / \dot{\theta} = [W/R]/[(W \cdot \dot{R})/R^2] = R/\dot{R}$ if closing on a lead vehicle is signified by $\dot{R} < 0$, where W is lead vehicle width, R is range of headway distance, and \dot{R} is range rate or relative velocity. In his analysis, Lee pointed out that if a driver is closing on an obstacle at a distance $R(t)$ with a travel speed $\dot{R}(t)$, then a deceleration, a , applied will be adequate to avoid contact if and only if $\dot{R}^2(t)/2a \leq R(t)$. By rearranging terms, this relationship implies that $R(t)a/\dot{R}^2(t) \geq 1/2$ must be true if the lead vehicle is not to be struck. Lee determined that the dimensionless time derivative of τ , i.e., $\dot{\tau} = [(R(t) \cdot a)/\dot{R}^2(t)] - 1 = 1/2 - 1 = -0.5$, fully captures this safety requirement and the driver should brake. If the $\dot{\tau}$ value at a given moment is greater than -0.5, then the driver should apply an acceleration to keep pace in the travel lane. Application of this model to empirical braking data of test drivers showed excellent agreement. However, Flach, Stanard, and Smith [1] have recently completed a meta analysis of various published studies and arrayed evidence to suggest that the optical expansion rate may alone be what is used for controlling braking maneuvers, i.e., τ is not used as Lee [16] had expected.

It was mentioned earlier that brake lights can prompt a driver response, even though perceptual information is needed to manage the nature of that response. Liebermann, Ben-David, Schweitzer, Apter, and Parush [23] conducted a field study of braking responses during close car following. Drivers were 45 young athletes (ages 21 to 30 years, 9 women, 36 men). Drivers drove a vehicle behind a confederate lead vehicle at either 60 km/hr or 80 km/hr on a public roadway in Israel. Car following distance was either 6 m or 12 m, which translates into 0.36 s and 0.72 s of car following time headway at 60 km/hr, respectively, or 0.27 s and 0.54 s of car following time headway at 80 km/hr, respectively. At randomly timed intervals, the lead vehicle made either real braking maneuvers (described as a ‘maximal deceleration’ with brake lights functional, but level of braking and duration not reported) or “dummy” braking maneuvers (i.e., brake lights activated but no deceleration). After the driver’s brake response was recorded, the lead vehicle driver would immediately reaccelerate and prepare for the next event.

Liebermann et al. [23] reported the following results. At shorter following distances, drivers had shorter accelerator release times and shorter movement times to move the foot from the accelerator to the brake pedal. Driving speeds had no significant effects, though the researchers suggested this might be due to the similar travel speeds employed. Drivers reacted to the onset of brake lights on 83% of trials in the dummy condition and 97% of trials when real braking was applied by the lead vehicle. This was interpreted to indicate that the onset of brake lights alone is sufficient to trigger a preventative response, but that the optical expansion of the lead vehicle in real braking events is also used as a cue to modulate braking movement. Real braking without brake lights was not included in the study, thus precluding an assessment of the effect of optical expansion alone on driver braking maneuvers.

Probst [24] also found driver reaction times to be independent of travel speed. Probst had 11 drivers (6 females, 5 males, ages 20 to 41 years) follow a lead vehicle at 20 or 40 m separation while traveling at either 50 km/hr or 70 km/hr. Thus, initial car following time headways were either 1.44 s or 2.88 s of time headway, respectively, at 50 km/hr or 1.02 s or 2.05 s of time headway, respectively, at 70 km/hr. At random times, the lead vehicle would suddenly accelerate or decelerate, always without brake lights, such that the relative velocity was between 2 km/hr and 8 km/hr. The driver’s task was to press a button on the steering wheel as soon as a change was detected, and also indicate the direction of motion.

Probst [24] reported that average times required to report changes in inter-vehicle distance varied from $0.96s \pm 0.4 s$ for the short distance and lower speed (20 m and 50 km/hr) and $2.06 s \pm 1.00 s$ for the long distance and higher speed (40 m and 70 km/hr). Detection times were found to be independent of absolute travel speed. Lower detection times were reported for closing as opposed to receding maneuvers. . A non-linear model was fitted to the data but no goodness-of-fit data were provided and the plots in the article do not contain empirical data points with which to make a visual comparison. The model was of the form:

$$t_{detect} = t_{pureRT} + aV_R^b$$

where t_{detect} = The detection time after lead vehicle acceleration or deceleration;

t_{pureRT} = Pure reaction time, i.e, reaction time independent of relative velocity; and

V_R = Relative velocity.

In general, these results might suggest to some a general trend toward greater vigilance or attention to the vehicle ahead as a function of car following distance. This is encouraged by commonsense intuitions about driver behavior in close car following. However, the attentional interpretation is, in itself, problematic for several reasons worthy of discussion. For example, the driver has relatively fewer degrees of freedom in space and time when following a lead vehicle closely. The following vehicle driver must react relatively more quickly (or more aggressively) or else a collision might occur. Thus, a driver following a lead vehicle closely might be no more attentive than a driver following a lead vehicle farther back. Reaction time data that show faster responses to lead vehicle deceleration when following more closely may be due simply to sensitivity to physical constraints and not to greater attentiveness.

Apart from fewer degrees of freedom to respond to lead vehicle deceleration when following closely as opposed to following farther back, another reason why the driver following closely might respond more quickly is because the driver may more readily perceive the deceleration of the lead vehicle. This greater perceptual sensitivity may be in terms of variations in range, range rate, visual angle, or optical expansion rate. For example, Mortimer [2] reported that drivers perceive changes in headway or visual angle as small as about 0.12 in these variables. Thus, at an initial 100 ft. of headway distance, the driver may perceive a change in inter-vehicle distance after closing approximately 12 ft. At 50 ft, the driver needs only a change of 6 ft to detect the change in inter-vehicle distance, all else being equal. It is also clear that sensitivity to optical expansion rate covaries with range. For a given range rate or closing relative velocity, smaller expansion rates may be detected at shorter headway ranges which would go undetected at farther ranges. This would allow for earlier detection of a deceleration based on closer car following, not because of any real difference in attention to the vehicle ahead.

While intuition suggests that closer car following is associated with greater attention paid to the lead vehicle in close car following, there is contradictory evidence in a study conducted on normal and last-second braking by Kiefer and his associates [25]. In a series of three studies, drivers each drove an instrumented car on a test track under car following conditions with various forms of a forward collision warning system. They were instructed to car follow a surrogate lead vehicle (artificial car towed by a towing vehicle by means of a boom arm) at a self-determined "comfortable" following distance. On what were termed "surprise" trials, the surrogate lead vehicle suddenly braked without warning and with brake lights disabled. An analysis was conducted of the correlation between time headways and brake reaction time at the start of lead vehicle braking (an associated forward collision warning onset followed closely in time). Across these three studies of this type, the correlation coefficients were all extremely low, with sample correlation coefficients of 0.07, -0.18, and -0.18, respectively.

It is clear from the research of Liebermann et al. [23] and others that drivers often react to brake lights alone. This complicates the picture somewhat since driver sensitivity to a light source is generally much greater than the threshold for optical expansion (or range rate) and is relatively constant over the range of following distances and closing rates considered in normal car following. This implies that any on-road naturalistic driving studies will produce data that contain somewhat noisy data relative to a simulator or laboratory study. Still, it is possible that there will be sufficient structure in the driver's braking behavior to allow for an assessment of the optical cues drivers use in determining what to do and when to do it.

Most recently, Brackstone, Sultan, and McDonald [26] reported on an on-road study that investigated the approach process between two vehicles where lead vehicle braking was presumably not an issue. Three test participants between the ages of 25 and 35 each drove an instrumented vehicle equipped with sensors for range and range rate (i.e., relative speed) measurement, as well as host vehicle travel speed and video of the road scene. Drivers had about 30 minutes of driving to become familiar with the test vehicle. Drivers were then instructed to drive at a cruising speed of their choice (somewhere between 24 and 35 m/s) and if their path were to become blocked by a slower moving vehicle, they were to decelerate as they saw fit and follow. Approximately 70 such approaches were captured, of which approximately 60 approaches were analyzed. One analysis examined the optical flow and time-to-collision models as applied to braking ‘action points’, i.e., instances when the driver started to decelerate by braking.

Brackstone et al. [26] fitted linear regression lines for each of the test participants in two different models. One model examined a critical optic flow, defined by those authors as a critical optical expansion rate. The fitted linear model predicted range rate (acting as a surrogate for optic flow) as a linear function of inter-vehicle range. The fitted models had R^2 (proportion of variance accounted for) values of 0.66, 0.56, and 0.70 for each of the three drivers respectively. The paper does not report the statistical significance of the intercept and slope coefficients but the R-squared values indicate the slopes are significantly different from zero and the intercepts are all substantially different from zero by inspection. While Brackstone and his associates claim these models represent a poor fit, the high R^2 values (especially given samples of between 16 and 22 observations) appear to provide a surprisingly good fit for field data. They nevertheless do not lend support to a driver strategy based only on a critical expansion rate.

Brackstone, et al. [26] also fitted linear regression models to predict time headway as a function of range rate. Interestingly, this second model had R^2 values of 0.64, 0.47, and 0.63 for each of the three test participants, respectively. These results suggest that there was a relationship between time headway and range rate at which a braking action was initiated. A more useful relationship would reverse the roles of time headway and range rate at brake onset to perhaps discern if the driver is braking at lower values of range rate given closer car following. Such a model, however, presumes, that one knows the strategy for braking is a critical range-rate.

3.0 METHOD

3.1 TEST PARTICIPANTS

Data were analyzed on a sample of sixty (60) test participants recruited from the licensed driver population of central Ohio and paid to participate in the study. Recruitment was done by advertising in several daily newspapers based within seventy miles of the Transportation Research Center Inc. in East Liberty, OH. Equal numbers of males and females were recruited in each of three age categories: Younger (18 to 25 years of age); Middle (35 to 55 years of age); and Older (65 to 75 years of age). Each participant had a valid driver's license, proof of insurance, had driven at least 3,000 miles in the past year, had not had any Driving Under the Influence convictions or more than three moving violations within the preceding five years, and did not report any major medical problems.

3.2 INSTRUMENTED VEHICLE

The test vehicle used in this study was a 1996 Chrysler Concorde which contained the Micro-Data Acquisition System for Crash Avoidance Research (MicroDAS) instrumentation package [27, 28]. This instrumentation package included various sensors that recorded the dynamics of the test vehicle during its operation. Sensors were used to record the magnitude, direction and range of steering inputs, lateral and longitudinal accelerations, vehicle speed, headway distance and closing rate, lane position, brake applications, and Global Positioning System (GPS) coordinates. In addition, MicroDAS instrumentation included an ADC ODIN-4 headway sensor system for primary capture of range and range rate data collected at approximately 10 Hz. Additional, redundant headway sensor systems mounted in the vehicle included a ControlLaser CL200 (operating at approximately 10 Hz) and an Eaton-Vorad EVT200 (operating at approximately 10 Hz), both equipped with serial data ports for output to MicroDAS files.

A video record of the test was made with MicroDAS. Video cameras collected data both inside and outside of the vehicle. Two interior cameras were used: one to record test participants' eye glance locations and durations, the other to record steering motions, turn signal applications, and hand-off-wheel events. A camera was installed inside a dashboard-mounted spherical compass to conceal it. (Note that this modification of the compass rendered it non-functional.) Two cameras were mounted on the exterior of the test vehicle: one camera recorded the forward road scene and one camera recorded lane boundary lines. These cameras relayed images to a quad-video multiplexer that combined the video signals so that they could be recorded on single video frames using digital in-vehicle video data recorders with a 30 Hz frame rate. The multiplexed video frame was synchronized with real-time vehicle performance information including vehicle speed, headway distance and closing rate, turn signal activation, lateral and longitudinal acceleration, and the distance from the start point of the drive. The test participant was informed of this data collection prior to participation, but both the data collection process and the system itself were designed to be unobtrusive.

3.3 TEST ROUTE AND SCHEDULE

The test participants were asked to drive an approximately three-hour route on public roadways (approximately 1.5 hours of driving outbound and 1.5 hours of driving to return). The route included both highway and city driving segments between the Transportation Research Center Inc. in East Liberty, OH and the Columbus, OH area. Highway driving segments were composed of

U.S. Route 33, Interstate 270, and a small segment of Interstate 71. These highways had posted speeds of 88 to 105 kph (55 mph to 65 mph). The city driving segment was on Morse Rd. in Columbus, OH. This was a four-lane divided road with posted speed limits which varied between 56 and 72 kph (35 and 45 mph) and had numerous traffic lights.

Data collection runs were scheduled Mondays through Thursdays during both rush hour (7-9 a.m., 4-6 p.m.) and non-rush hour (10 a.m.-12 noon; 1 p.m.-3 p.m.) to capture variations in driver car following behavior that might be associated with variations in traffic density. Each test participant drove either in the morning or in the afternoon and each participant drove both a rush-hour route and a non-rush-hour route. The route began and ended at the Vehicle Research and Test Center (VRTC) near East Liberty, OH. The morning and afternoon test participants drove basically the same route, but the order of segments varied in order to locate the test participant in the urban area during the appropriate morning or afternoon rush hour. Upon completing half of the route, participants were instructed to wait in a shopping mall until the rush/non-rush hour change had occurred. The participant then departed the shopping area for the return half of the trip. Each test participant drove only one day for approximately 175 km (110 miles).

3.4 PROCEDURE

Upon arrival at the facility, the experimenter described the test agenda and general purpose, and summarized the Test Participant Information letter (i.e., informed consent form). Participants were instructed that, during this testing, test participants were expected to perform actions typical of normal driving, such as making turns, making lane changes, and using the radio and other vehicle equipment. They were not asked to perform any abnormal or dangerous tasks. Note that a special interest in car following or driver eye glance behavior was NOT mentioned. The experimenter stated that the test participant was to drive as he or she normally would. The experimenter orally and via the letter emphasized the test participant's responsibility for safe operation of the test vehicle. The test participant was instructed to carefully read the Test Participant Information letter and resolve with the experimenter any questions before signing the attached forms. The test participant was reminded, as stated in the letter, that safe operation of the vehicle was the test participant's highest priority. The test participant was instructed to not perform any actions that he or she believed to be unsafe. Test participants were reminded that they could stop the testing at the earliest safe opportunity should the driving situation worry them or should they experience any discomfort.

Once the informed consent form was signed, the participant received more detailed orientation. Test participants were provided with detail and overview maps of their route, as produced using the Street Atlas 97 mapping software. Test participants also received typed turn-by turn instructions in Times New Roman 14 point font mounted on a clipboard. These instructions also included a toll-free telephone number and instructions for contacting the experimenter via the cellular telephone in the event of an emergency. The experimenter showed the test participant the route maps and the turn-by-turn instructions. The experimenter pointed out and named the roads and streets they would be driving on, and pointed out the turns, exits, and entrances to be made. The experimenter made every effort to ensure that the test participant understood and was comfortable with the route.

The experimenter then led the test participant to the test vehicle. The test participant was shown the test vehicle and familiarized with the headlight switch and dimmer, four way warning flashers, horn, windshield wiper/washer controls, and controls/adjustments for the heater/air conditioning,

seat, mirrors, and steering wheel. The test participant was advised that the vehicle's cruise control and compass did not work. After making sure they had all positions and controls adjusted to their satisfaction, the experimenter showed the test participant the cellular phone located in the glove box, demonstrated its use and pointed out the experimenter's phone number on the turn-by-turn instructions. The experimenter pointed out the location of the first aid kit and maps. The test participant was reminded that smoking was not permitted in the vehicle, and instructed to wear their seat belt while driving. They were instructed not to wear sunglasses during their drive. During this process, the MicroDAS technicians checked that the test participant's face was in clear view of the camera. The orientation was also used to distract the test participant while these adjustments were made. The experimenter accompanied the test participant in a five-mile drive on TRC's private access road in order to orient them to the vehicle as well as to evaluate their fitness for the task before sending them onto public roadways. The test participant then drove the public roads portion of the test session unaccompanied. They were instructed to return to their departure point, where the experimenter would meet them.

When the test participant returned, the experimenter completed the post-test portion of the test participant information form and recorded the test participant's answers to the a set of debriefing questions, and gave them the check for their participation. The experimenter thanked the test participant and escorted them to their vehicle.

4.0 RESULTS

Car following behavior was characterized in terms of car following “epochs.” A given car following epoch was operationally defined to begin with a valid sensor return from the ODIN-4 system for a given lead vehicle ahead in the same travel lane as the following (host) vehicle (identified through inspection of the concurrent road scene video). The given car following epoch was operationally defined to end when a) the lead vehicle left the travel lane ahead of the following vehicle, b) the following vehicle changed lanes, c) another vehicle cut in between the lead vehicle and the following vehicle, or d) the vehicles were separated by a range greater than the range of the ODIN-4. Note that a cut-in initiated a new car following epoch if it resulted in a valid sensor return from the ADC headway sensor system. A total of 2,913 car following epochs, identified by means of these operational rules, were analyzed.

4.1 GLANCE DATA RESULTS

For each of the 2,913 car following epochs, the eye glance video (when available) was manually reduced to identify driver eye glance behavior (glance location and duration). Data reductionists examined the eye glance video between the start time and end time of each car following epoch and entered the start and end time for each glance to each of the following pre-defined locations: Left Shoulder glance, Left Mirror, Road Ahead, Interior of vehicle (i.e., head-down), Center Mirror, Right Mirror, and Right Shoulder glance. A total of over 77,000 eye glances were reduced for this analysis.

To capture more or less ‘normal’ car following, a decision was made to screen out data for which the range was less than one car length (taken to be less than 5 m) and for which the host vehicle travel speed was less than 12 m/s or about 27 mph. The data were also filtered for drop outs, data entry errors, and anomalous records for which no explanation could be found. All glances to the road scene were dropped in order to concentrate the analysis only on the glances away from the road scene. On average, drivers spent approximately 86% of the time, per car following epoch, with eyes on road ahead (mean = 86.3%; SD = 9.8%).

4.1.1 Conditions in Car Following When Drivers Look Away

Of primary interest in this study is a characterization of when, during car following, drivers look away. Table 2 presents summary statistics for initial range, range rate, time headway, and travel speed when there was a look away from the road scene, presented by age group and overall for the approximately 28,234 glances away from the road ahead analyzed in this study. Inspection of the table reveals a more or less orderly progression toward more conservative driver eye glance behavior during car following as the driver’s age increases. On average, younger drivers in this study looked away at closer range, at shorter headways, and while closing on the lead vehicle more than did the middle or older drivers. This pattern of behavior is consistent with the greater involvement of drivers in this age range as the striking vehicle driver in a rear-end crash [1].

Table 2. Statistics on Initial Car Following Measures Upon Glance Away From Road Ahead by Age Group.

Age Group	Measures	Mean	Median	Std. Dev.	5 %-ile	95 %-ile
Younger (18 to 25 yrs) N=10878 glances	Range, m	44.0	36.2	27.5	12.7	100.1
	Range Rate, m/s	-0.42	-0.14	1.87	-4.00	2.11
	Time Headway, s	1.67	1.47	0.96	0.49	3.49
	Speed, m/s	26.4	28.6	5.5	15.0	32.4
Middle (35 to 55 yrs) N=10039 glances	Range, m	49.6	43.1	28.3	14.1	104.8
	Range Rate, m/s	0.00	0.11	1.81	-3.19	2.69
	Time Headway, s	1.90	1.68	1.00	0.60	3.84
	Speed, m/s	26.1	28.4	5.3	14.7	31.7
Older (65 to 75 yrs) N=7441 glances	Range, m	56.3	52.4	26.3	20.6	104.5
	Range Rate, m/s	0.20	0.17	2.01	-3.00	3.47
	Time headway, s	2.19	2.06	0.97	0.84	3.90
	Speed, m/s	25.8	27.7	4.8	15.0	30.6
All Drivers N= 28358	Range, m	49.2	43.0	27.9	14.2	103.2
	Range Rate, m/s	-0.11	0.0	1.91	-3.47	2.75
	Time Headway, s	1.89	1.71	1.01	0.57	3.75
	Speed, m/s	26.2	28.1	5.3	15.0	31.9

Note: Negative range rate signifies a closing of the gap between the two vehicles; positive range rate signifies an opening of the gap between the two vehicles.

Figures 1 and 2 contain plots of the initial range versus range rate at the start of a glance away from the road ahead for the cases in which the lead vehicle is a light vehicle (passenger cars, sport utility vehicles, and vans) and a heavy truck, respectively. Each plotted point represents a glance away from the road ahead. Points in Figure 1 form an elliptical area ranging horizontally from approximately 5 to 130 meters and vertically between -5 meters and 5 meters. Figure 2 is similar in shape, but with many fewer points and with vertical range limited to approximately +/-3 meters. These figures provide some insights into the decision strategies of the drivers in determining when to look away. When the preceding vehicle is a light vehicle, drivers generally look away when the range rate is around zero. Furthermore, this strategy is used consistently across the entire span of ranges recorded in this study. Regression analysis indicated that the trend line has zero slope ($p = 0.4087$). Thus, drivers acted as though insensitive to the range between them and the lead vehicle and relied exclusively on range rate to decide if it was safe to look away. This is a reasonable strategy provided that the lead vehicle does not brake suddenly.

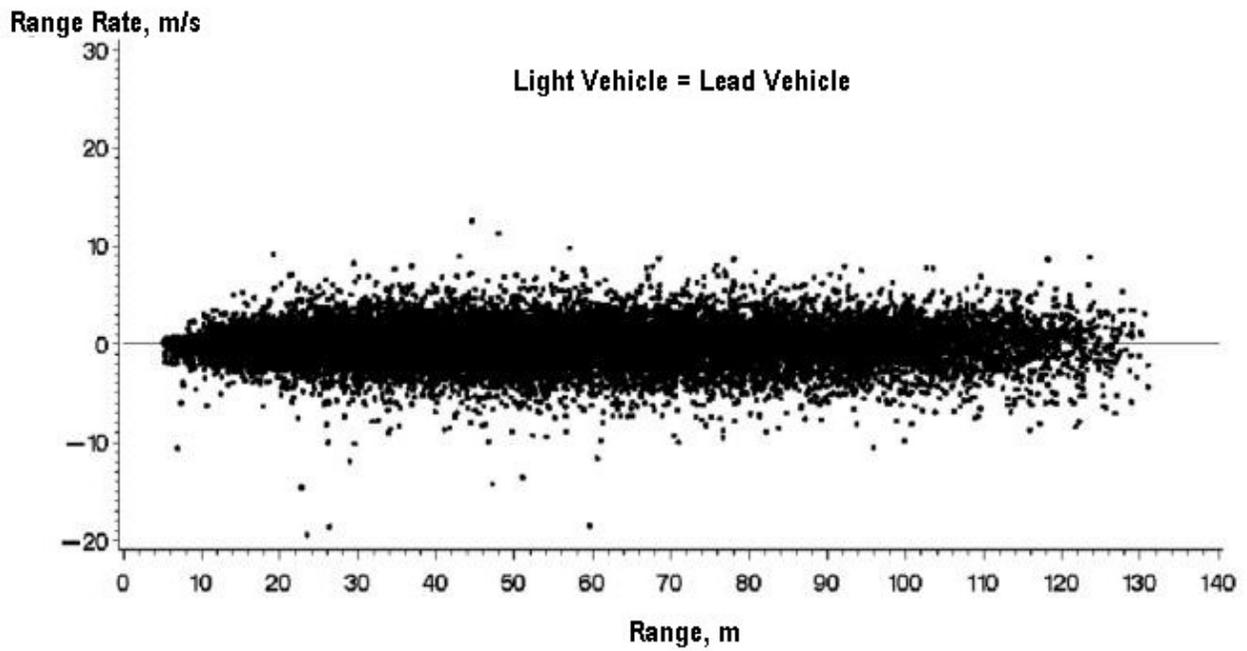


Figure 1. Initial Range Versus Range Rate Upon Glance Away From the Road Ahead During Car Following Where Lead Vehicle is a Light Vehicle

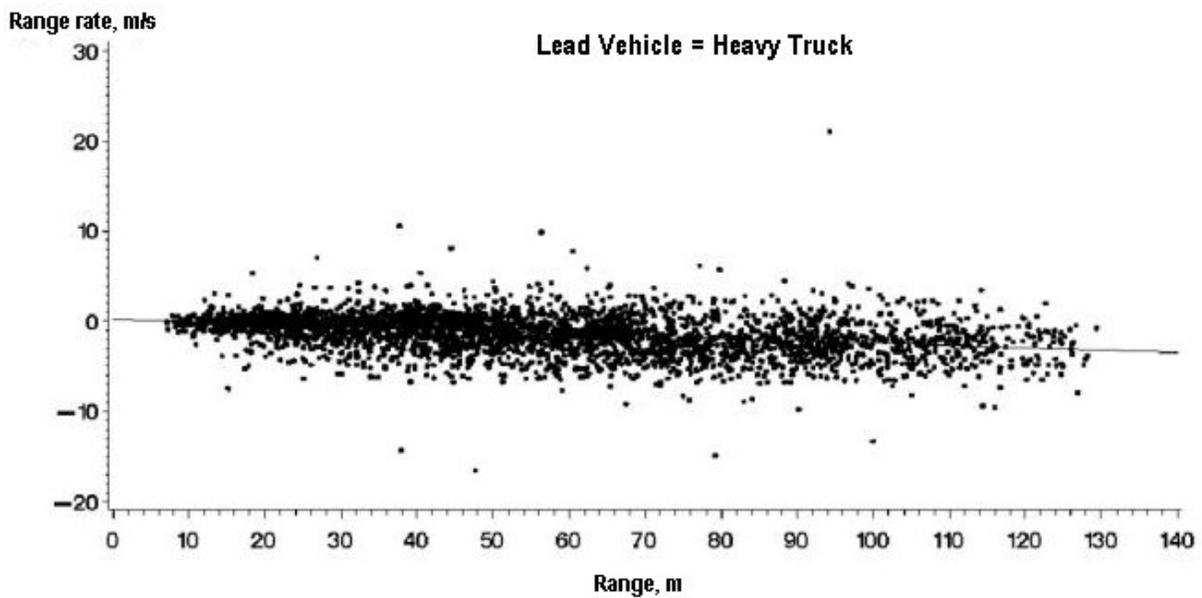


Figure 2. Initial Range Versus Range Rate Upon Glance Away From the Road Ahead During Car Following Where Lead Vehicle is a Heavy Truck

When following heavy trucks, one might suppose that a lack of preview for the driving conditions ahead of the lead vehicle might prompt a compensatory strategy between range rate and range when deciding if it is safe to look away. Figure 2 provides only mild support for this hypothesis. There is a slight downward trend such that higher closing rates (i.e., higher negative range rates) are compensated slightly by greater ranges. Simple linear regression produced the following results:

$$\dot{R}_{est} = 0.1546 - 0.026R \quad (\text{where } p < 0.0001, R^2 = 0.12, SE = 2.03)$$

Thus, only about 12 percent of the variability in initial range rate upon a glance away from the road scene was accounted for by the initial range. This shows that when following heavy trucks that do not allow for the same preview of driving conditions ahead of the lead vehicle that might be possible with light vehicles, drivers still rely predominantly on range rate centered about zero to decide to look away.

Plots as a function of age category, gender, rush hour versus non-rush hour, and speed regime (travel speeds of 50 mph or more versus travel speeds less than 50 mph) all looked essentially the same as those in Figure 1. Individual driver plots showed some variability but again the general trend was a horizontal scatter plot centered close to zero range rate. This set of findings supports the assertion of Flach, Standard, and Smith in 1997 [13] and of Mortimer in 1990 [14] that drivers are predominantly using the optical analogue of range rate, i.e., optical expansion rate, to guide their look-away decisions. It appears that no adjustment for range was used to a significant degree, especially when following light vehicles. It should be kept in mind, of course, that other motivations were undoubtedly involved in the glances away from the road scene and that these contributed to the spread about the zero range rate.

To obtain better insights into the nature of glances taken away from the road scene when the gap between lead and following vehicle was closing, a simple analysis of the optical expansion rate upon glance away was carried out. Specifically, the optical expansion rate ($\dot{\theta}$) was calculated for each glance away when the range rate was negative according to the formula:

$$\dot{\theta}(t) = \frac{-W \cdot \dot{R}(t)}{R(t)^2 + W^2}$$

In this formula $\dot{\theta}(t)$ represents the optical expansion rate in radians/s. W represents lead vehicle width. This width was assumed to be a fixed value of 1.829 m (6 ft) for a light vehicle and 2.438 m (8 ft) for a heavy truck. \dot{R} and R signify range rate and range, respectively, upon glance away. As previously discussed, Mortimer (1990)[14] presents a threshold value for $\dot{\theta}$ of 0.003 radians/s above which a driver can detect that the gap between him and a lead vehicle is closing. Of the 14,237 glances taken away from the road ahead when the range rate was negative (indicative of a closing of the between-vehicle gap), 81% of these were below the threshold. This reinforces the view that drivers generally looked away when the range rate (or its optical analogue, $\dot{\theta}(t)$) was effectively zero. However, this leaves 19% of such glances taken when the driver should have been able to tell that the gap between the vehicles was closing. At least a portion of these glances are thought to have been associated with preparing to overtake or pass the lead vehicle, but no analyses were performed to determine if this were the case.

Car following behavior has traditionally been indexed in terms of time headway, i.e., the ratio of range divided by following vehicle travel speed. Figure 3 presents a scatter plot of range and travel speed at which glances were taken away from the road ahead. Each plotted point represents a glance. Unlike the range-range rate plots, there is much less structure in Figure 3. Horizontally points range from 12 to approximately 35 m/s, while vertically points range from approximately 10 to 130 m. A simple linear regression analysis indicated the following trend:

$$R_{est} = 3.2 + 1.76 * V \quad (\text{where } p < 0.0001, R^2 = 0.11, SE = 26.3)$$

This indicates that there is a small tendency to adjust the range at which a glance is taken away by the travel speed, but this relationship only accounts for about 11 percent of the variability in ranges at which drivers looked away from the road ahead during car following. This implies that time headway does not appear to be a critical variable in predicting when people will look away during car following.

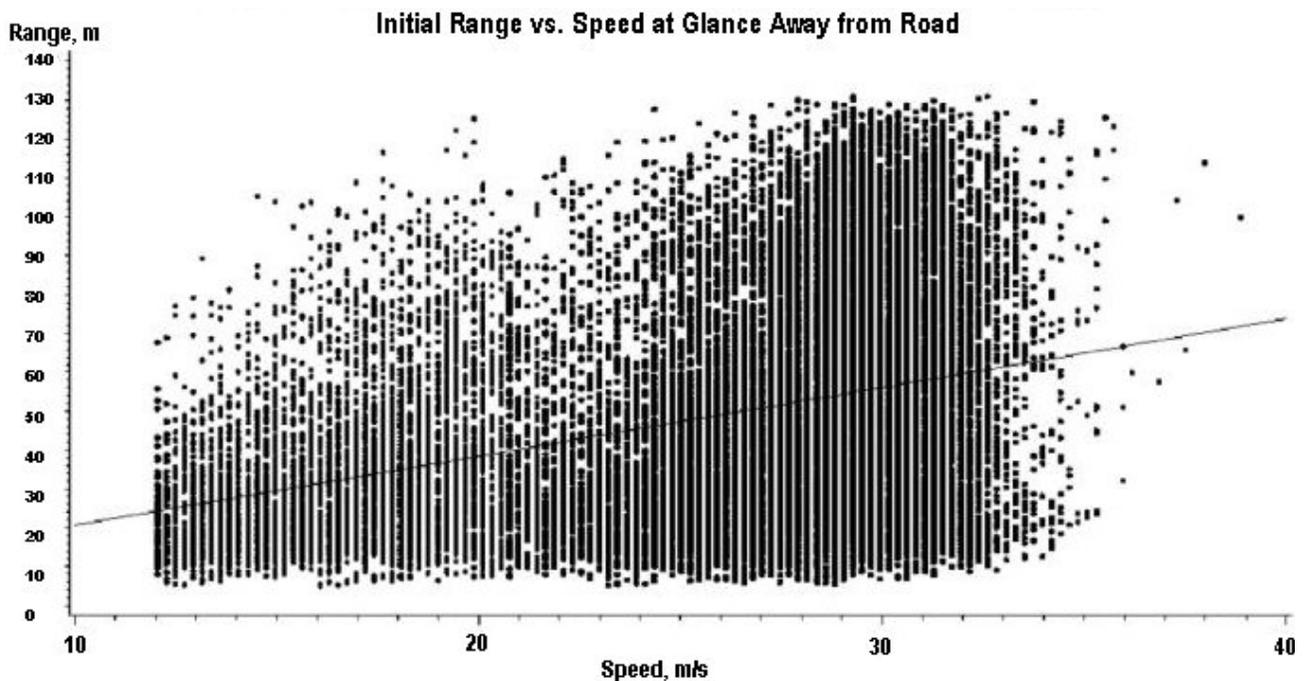


Figure 3. Scatter Plot of Range vs. Travel Speed at Glance Away From the Road Ahead

Figure 4 presents a scatter plot of the number of glances away from the road ahead per car following epoch as a function of epoch duration. As can be seen, there is a trend for the number of glances away from the road ahead during a car following epoch to go up with the duration of the epoch. The results of a simple linear regression confirmed that estimated glance frequency = $1.84 + 0.17(\text{epoch length})$, $p < 0.0001$, $R^2 = 0.6051$, $SE = 7.33$. This trend appeared stable regardless of age, gender, lead vehicle type, or rush hour versus non-rush hour driving.

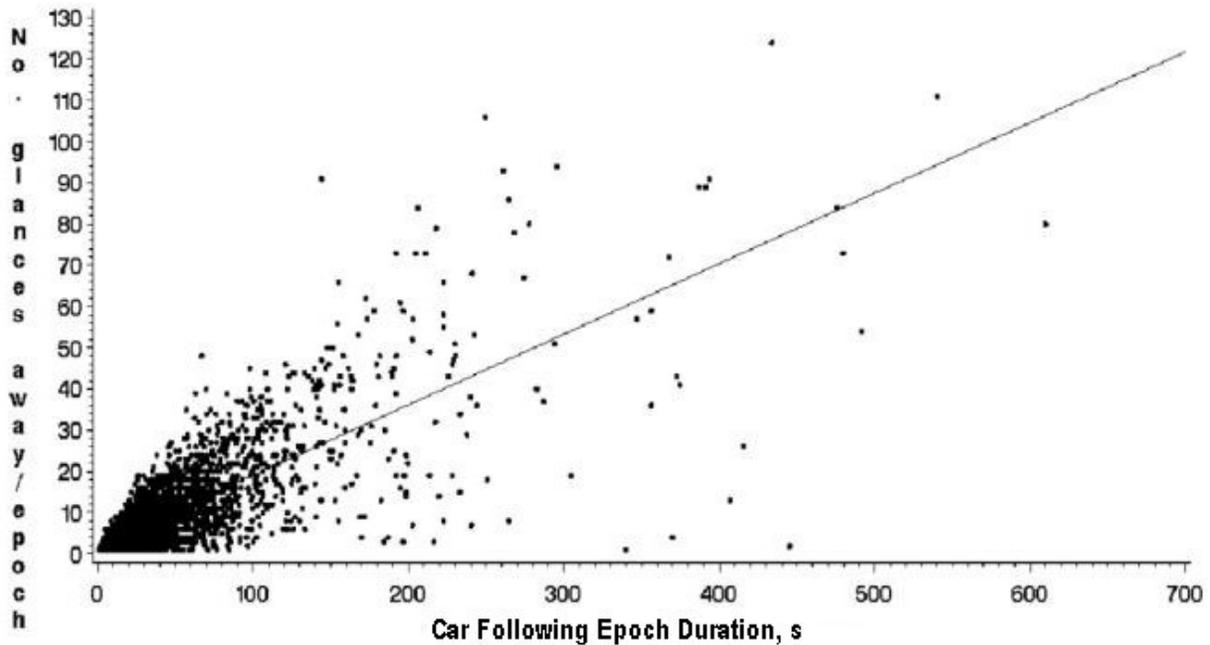


Figure 4. Scatter Plot of Number of Glances Away From the Road Ahead by Car Following Epoch Duration

A mixed-model analysis of variance was carried out on the glance away frequency per epoch to assess the influence of driver age category, gender, and rush hour versus non-rush hour driving. The only statistically significant differences in average number of glances away per epoch was across age categories ($p < 0.0001$). The results revealed that younger and middle-age drivers averaged more glances away per car following epoch than the older drivers (means of 11.5, 11, and 8 glances respectively; standard deviations of 14.4, 12.9, and 9.3 glances, respectively). Again, this pattern of results is consistent with the generally more conservative driving habits of older drivers.

4.1.2 Durations of Glances Away from Road Ahead During Car Following

In addition to the incidence or frequency of glances, eye glance durations are also of interest in characterizing driver eye glance behavior during car following. Figure 5 presents the distribution of glance durations observed during car following in this study. The mean glance duration is 0.6 s; the 5th percentile value was 0.17 s and the 95th percentile value was determined to be 1.47 s; the distribution is positively skewed. These data are shorter than the glance durations collected by the author in an unpublished study of mirror sampling behavior prior to lane change execution. Furthermore, they are shorter in duration than the glance duration data reported in Rockwell [10]. During that study, eye glance data were generally collected during open road driving, i.e., with no lead vehicle present.

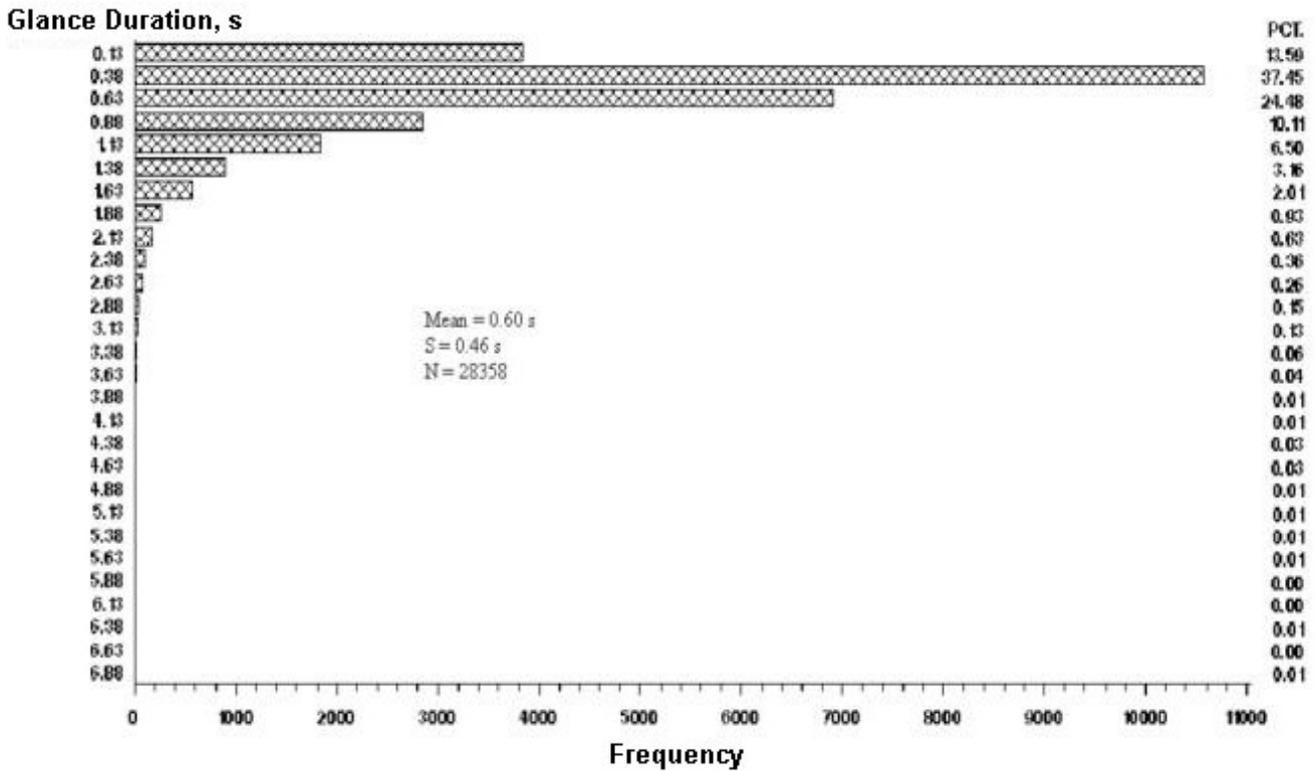


Figure 5. Distribution of Duration of Glances Away from the Road Ahead During Car Following

Rockwell [10] reported on the glance durations to the left mirror and a car radio collected in a series of three studies carried out over a period of six years. Figure 6 presents the glance duration distribution for left mirror glances during car following in the present study with the distribution of glance duration data reported in Rockwell [10] shown in Figure 7. It is clear that, while the shape and spread of the distributions are similar, the mean of the distribution during car following is reduced by about one-half. In a subsequent personal communication with Rockwell, the author discovered that these data generally reflect conditions of open road driving, not car following. It appears, then, that glance durations are sensitive to the presence of a lead vehicle.

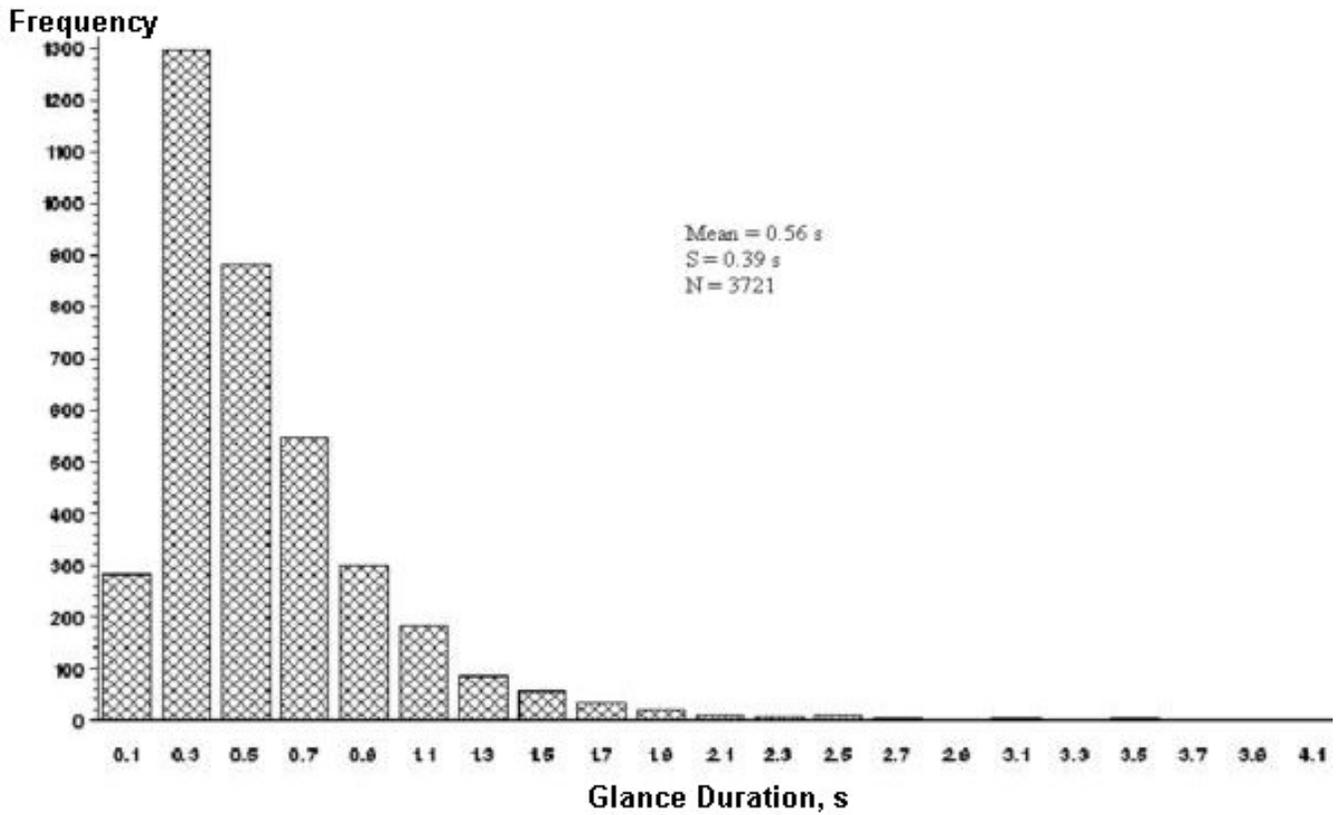


Figure 6. Distribution of Glance Durations to the Left Mirror, Current Study

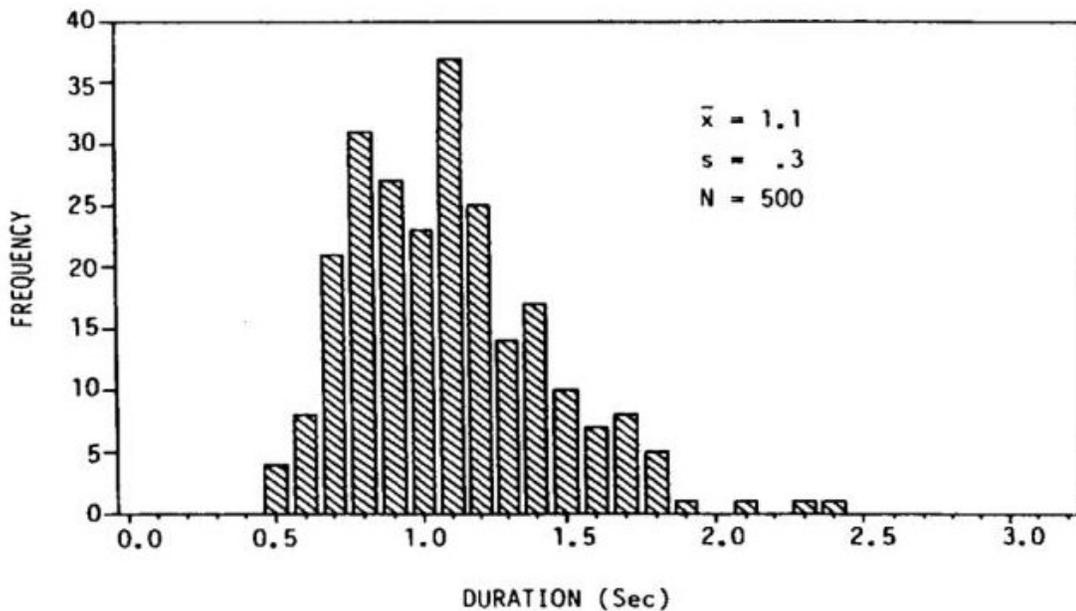


Figure 7. Distribution of Glance Durations to the Left Mirror, Rockwell Study (1988)

A regression analysis was conducted to determine if glance duration could be predicted by range and range rate, and travel speed. The regression modeling results did not produce significant results. Bivariate scatter plots of glance durations with range, range rate, or travel speed are provided in Figures 8, 9, and 10, respectively. These plots reinforce the conclusion that how long drivers looked away from the road ahead during car following was less driven by the car following parameters just mentioned than by other factors.

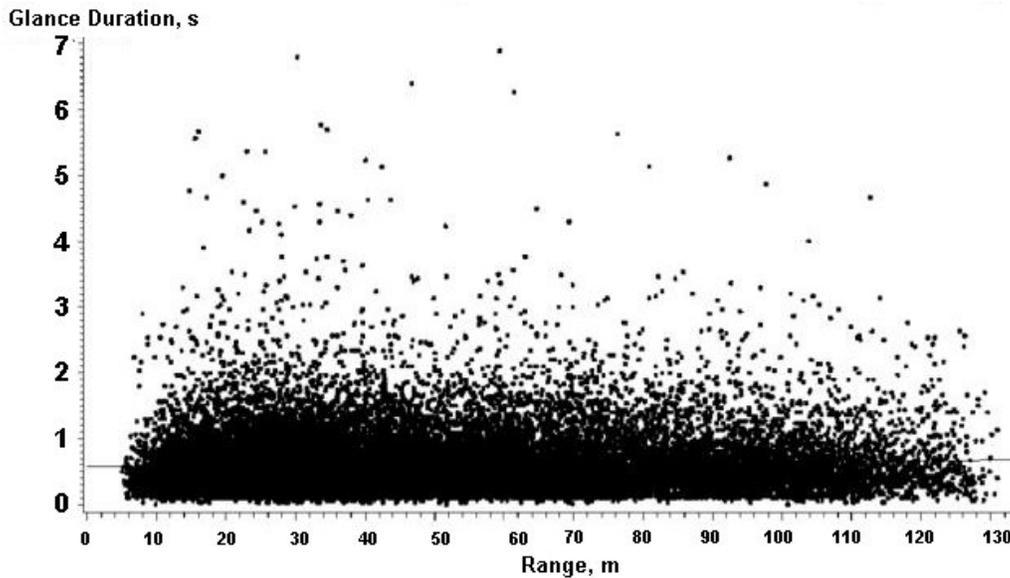


Figure 8. Scatter Plot of Glance Durations Away from the Road Ahead During Car Following, versus Initial Range

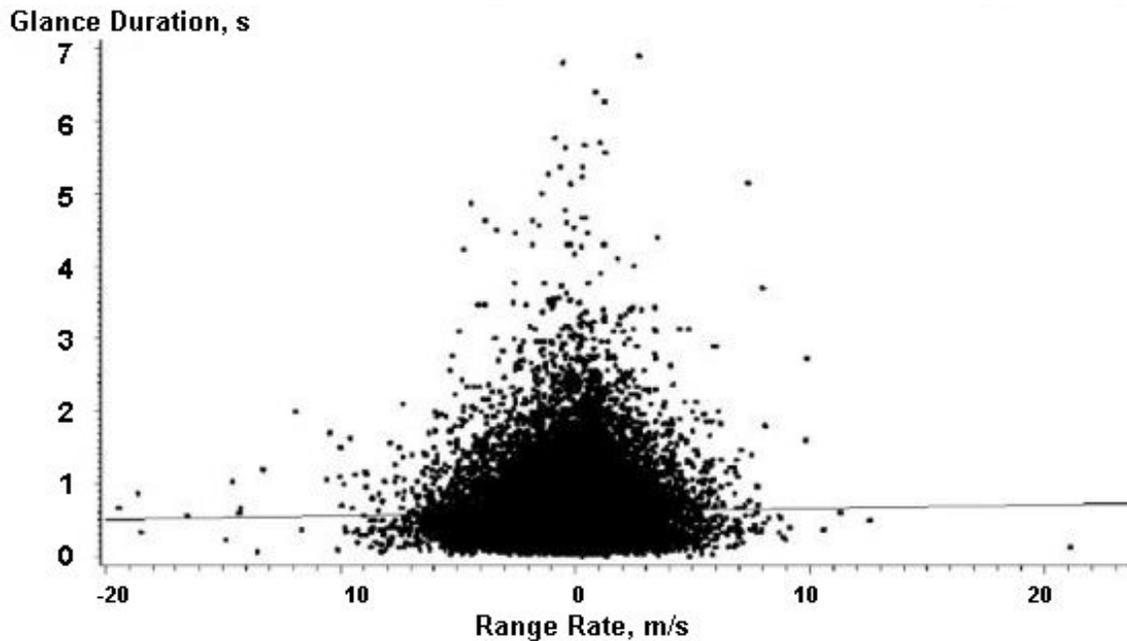


Figure 9. Scatter Plot of Glance Durations Away from the Road Ahead During Car Following versus Range Rate

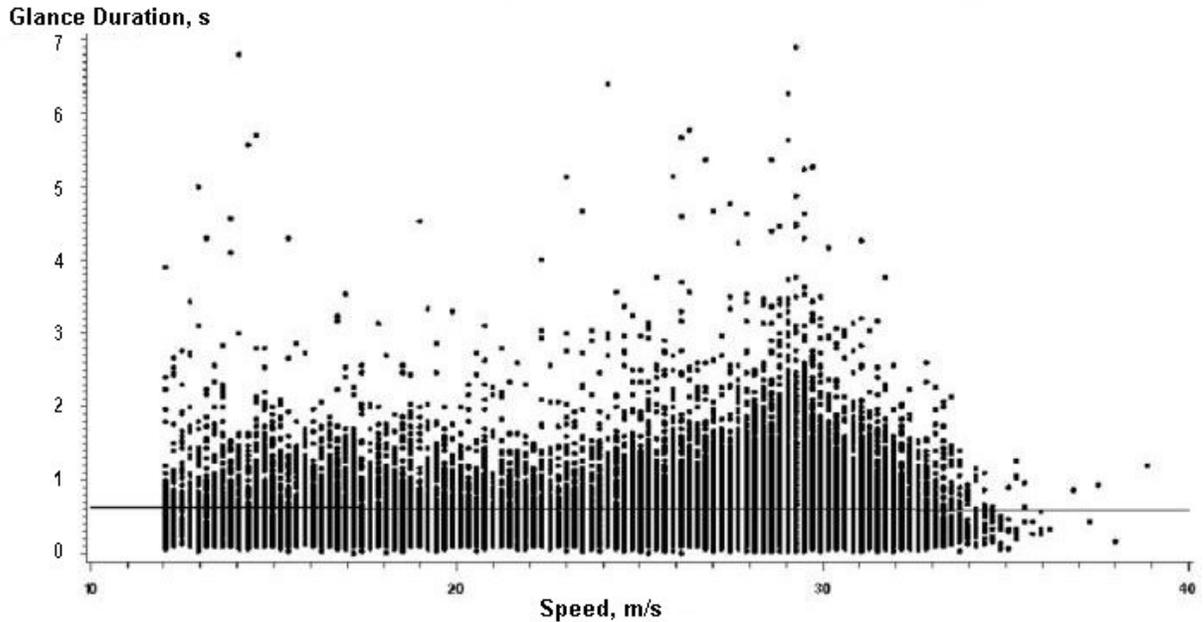


Figure 10. Scatter Plot of Glance Durations Away During Car Following versus Travel Speed

4.1.3 Locations of Glances Away During Car Following

In addition to the incidence or frequency of glances and their durations, where the driver looks is of interest in characterizing driver eye glance behavior during car following. Figure 11 shows the distribution of eye glance locations away from the road scene as a function of the following driver age categories: Younger (18 to 25 years of age), Middle (35 to 55 years of age), and Older (65 to 75 years of age). The histogram frequency of glances away from the road ahead are organized in terms of the following glance locations: center mirror (Cntrmirr), head-down (Headdown, i.e., any glance to the interior of the vehicle), left mirror (Lmirror), left over-the-shoulder glance (Lshouldr), right mirror (Rmirror), and right over-the-shoulder glance (Rshouldr). In general, the Younger and Middle age groups appear similar to one another and different from the Older age group. Specifically, the older drivers made relatively fewer head-down glances as compared to the Younger and Middle age drivers. The older drivers also tended to take direct glances over the left shoulder more frequently than they glanced to the left mirror. This might suggest a greater cautiousness in the older driver that manifests itself in less reliance on the left mirror and more reliance on direct looks for traffic in the left (passing) lane. Finally, it is interesting to note the greater frequency of center mirror use than side mirror use across all three age groups.

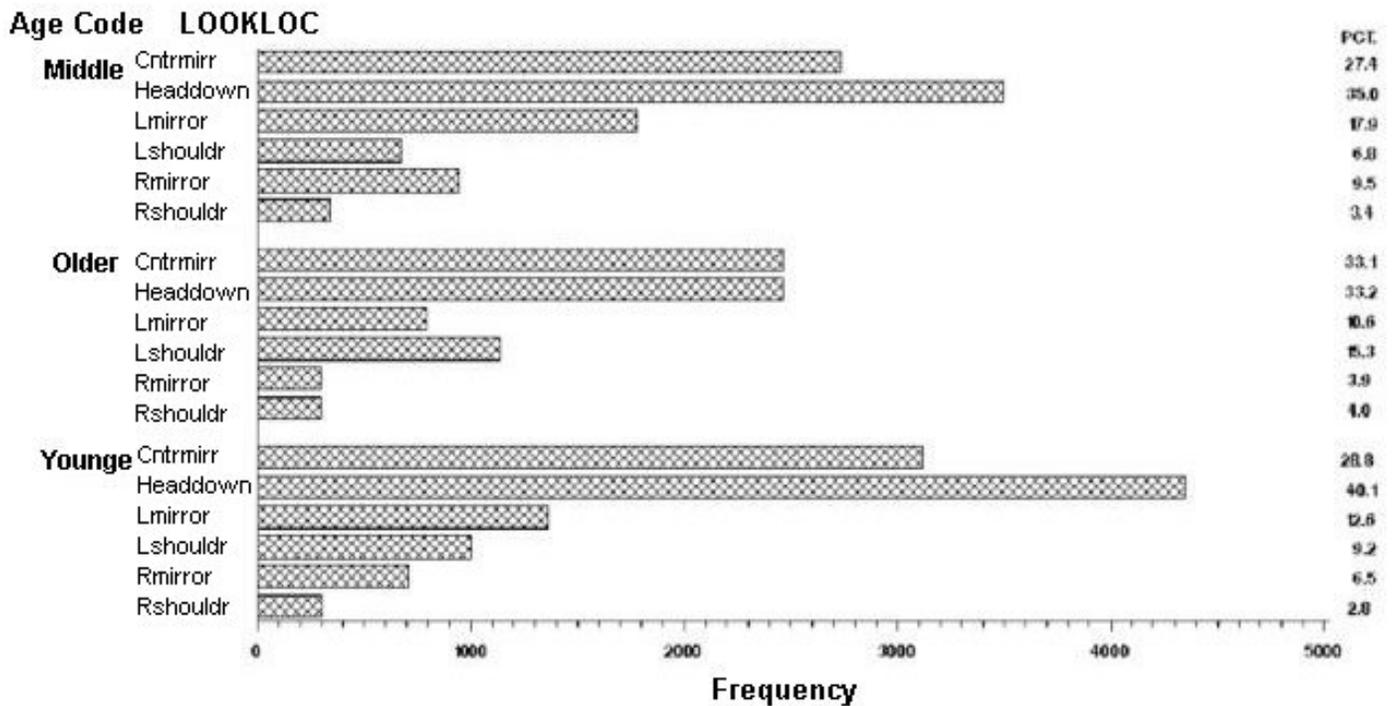


Figure 11. Distribution of Initial Glance Locations Away From the Road Ahead by Age Group

Figure 12 presents the histograms of driver eye glance locations as a function of speed regime. High speed driving (Hispd) was operationally defined as driving greater than 22.3 m/s or 50 mph; low speed driving (Lowspeed) was defined as driving at less than 22.3 m/s or driving less than 50 mph. The overall greater frequency of glances under high speed driving conditions is an artifact of the test route being composed predominantly of highways with posted speeds of 65 mph. However, it is interesting to note that the relative incidence of head-down glances is greater in high speed driving than in low speed driving. This may reflect the presumed greater predictability of driving on highways as opposed to surface streets or driving in congested traffic. Frequency distributions revealed no noticeable differences in where drivers looked away during car following as a function of driver gender, whether the lead vehicle was a light vehicle or a heavy truck, or between rush hour and non-rush hour driving.

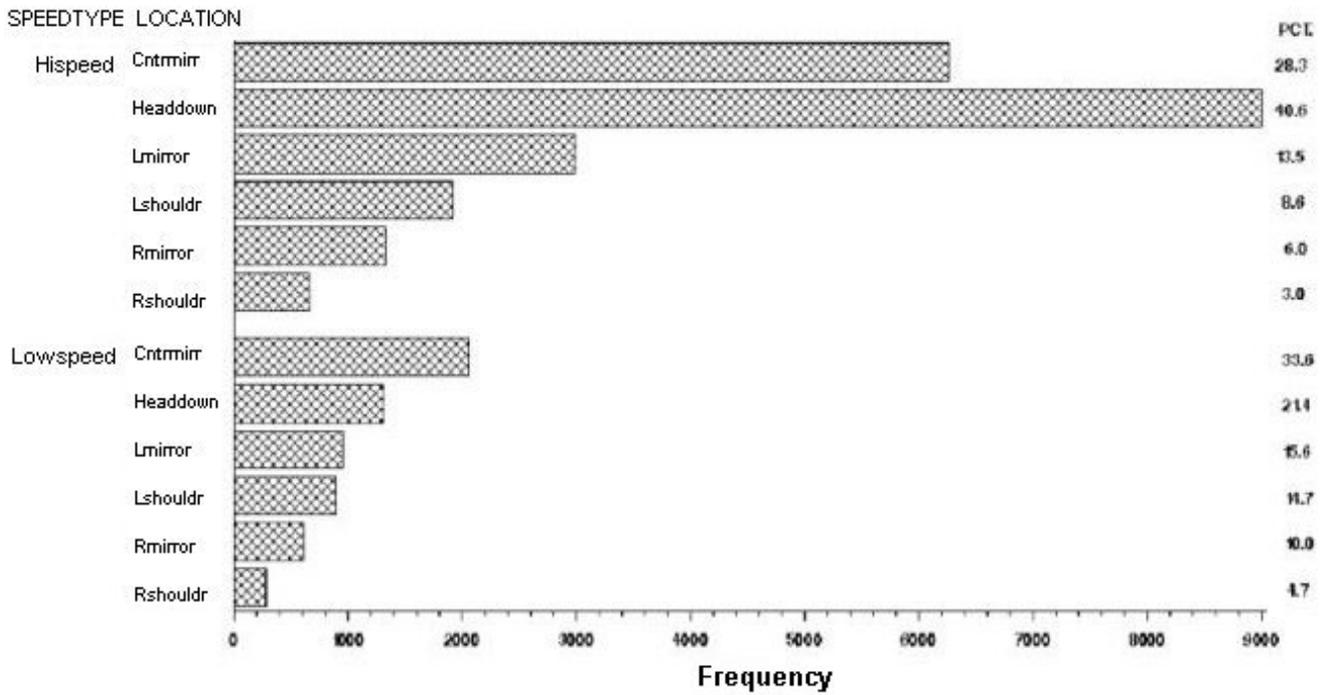


Figure 12. Distribution of Initial Glance Locations Away From the Road Ahead by Speed Regime (see text for explanation)

5.0 CONCLUSIONS

This study was undertaken to characterize driver eye glance behavior during car following. As such it produced results which may be used in a variety of contexts. In this study, participants drove an instrumented vehicle unaccompanied on public roads that included high speed highways as well as surface streets. Safety had been emphasized and drivers were given no requested tasks to perform. They could check mirrors, review the route directions, adjust the radio or climate control settings, etc., at their discretion. The drivers were paid to participate in the study and had no time pressures placed on them. They appeared in every respect to be alert and motivated to complete their participation safely. These data, then, represent a baseline database of what might be termed 'safety -ideal' eye glance behavior during car following.

There is remarkable consistency in the strategy with which drivers looked away from the road ahead during car following. Simply put, they generally looked away when the range rate was effectively zero. They did not, in general, appear to take range or time headway into account to any substantial degree. This strategy appears consistent with other research on the effective stimulus for braking behavior [13], [14]. It also implies that drivers assume that the lead vehicle will not brake abruptly, a belief reinforced by common driving experience. This strategy of deciding when it is safe to look away may explain why driver inattention is a leading contributing factor to rear-end crashes: driver expectations are sometimes violated and the driver has not allotted sufficient distance (range) to recover.

Driver eye glance durations away from road ahead during car following averaged 0.6 s with a standard deviation of 0.46 s. This distribution of data is shifted downward from eye glance distribution data reported by Rockwell [10] and that of an unpublished study of the author on driver eye glance behavior prior to lane change execution. This pattern implies that drivers during car following are more cautious about how long they will look away from the road scene ahead. Furthermore, this finding suggests that future studies of the effects of in-vehicle technology on drivers should compare in-vehicle glance durations to both glance durations in an open-road environment and in a car following setting. The results should be substantially different except for the most simple of in-vehicle tasks.

The fact that driver eye glance durations were not predicted by range, range rate, or speed perhaps reflects a combination of the demand characteristics of the activity that prompted the glance away (unknown) and a well-learned strategy drivers have to keep glance durations below about 1.6 to 2 seconds [4], [10]. The distribution of glance locations was found to reflect both individual differences among drivers with respect to age and as a function of speed regime. The high-speed driving situation appears to have less variability and so the driver will engage in more head-down glances than while driving on surface streets. However, as the data of Summala et al. [5] indicate, even glances to the area of the speedometer can lead to significant increases in response latency to lead vehicle braking events.

Age was found to have interesting effects on glance behavior. All three age groups exhibited a greater frequency of center mirror use than side mirror use. In general, the Younger and Middle age groups appeared similar to one another and different from the Older age group. Specifically, the older drivers made relatively fewer head-down glances as compared to the Younger and Middle age drivers. The Older drivers also tended to take direct glances over the left shoulder more frequently than they glanced to the left mirror. This might suggest a greater cautiousness in the older driver

that manifests itself in less reliance on the left mirror and more reliance on direct looks for traffic in the left (passing) lane.

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