SAVE-IT

SAfety VEhicles using adaptive Interface Technology (Task 7)

A Literature Review of Visual Distraction Research

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7.0 PROGRAM OVERVIEW

Driver distraction is a major contributing factor to automobile crashes. National Highway Traffic Safety Administration (NHTSA) has estimated that approximately 25% of crashes are attributed to driver distraction and inattention (Wang, Knipling, & Goodman, 1996). The issue of driver distraction may become worse in the next few years because more electronic devices (e.g., cell phones, navigation systems, wireless Internet and email devices) are brought into vehicles that can potentially create more distraction. In response to this situation, the John A. Volpe National Transportation Systems Center (VNTSC), in support of NHTSA's Office of Vehicle Safety Research, awarded a contract to Delphi Electronics & Safety to develop, demonstrate, and evaluate the potential safety benefits of adaptive interface technologies that manage the information from various in-vehicle systems based on real-time monitoring of the roadway conditions and the driver's capabilities. The contract, known as SAfety VEhicle(s) using adaptive Interface Technology (SAVE-IT), is designed to mitigate distraction with effective countermeasures and enhance the effectiveness of safety warning systems.

The SAVE-IT program serves several important objectives. Perhaps the most important objective is demonstrating a viable proof of concept that is capable of reducing distraction-related crashes and enhancing the effectiveness of safety warning systems. Program success is dependent on integrated closed-loop principles that, not only include sophisticated telematics, mobile office, entertainment and safety warning systems, but also incorporate the state of the driver. This revolutionary closed-loop vehicle environment will be achieved by measuring the driver's state, assessing the situational threat, prioritizing information presentation, providing adaptive countermeasures to minimize distraction, and optimizing advanced collision warning.

To achieve the objective, Delphi Electronics & Safety has assembled a comprehensive team including researchers and engineers from the University of Iowa, University of Michigan Transportation Research Institute (UMTRI), General Motors, Ford Motor Company, and Seeing Machines, Inc. The SAVE-IT program is divided into two phases shown in Figure i. Phase I spans one year (March 2003--March 2004) and consists of nine human factors tasks (Tasks 1-9) and one technology development task (Task 10) for determination of diagnostic measures of driver distraction and workload, architecture concept development, technology development, and Phase II planning. Each of the Phase I tasks is further divided into two sub-tasks. In the first sub-tasks (Tasks 1, 2A-10A), the literature is reviewed, major findings are summarized, and research needs are identified. In the second sub-tasks (Tasks 1, 2B-10B), experiments will be performed and data will be analyzed to identify diagnostic measures of distraction and workload and determine effective and driver-friendly countermeasures. Phase II will span approximately two years (October 2004--October 2006) and consist of a continuation of seven Phase I tasks (Tasks 2C--8C) and five additional tasks (Tasks 11-15) for algorithm and guideline development, data fusion, integrated countermeasure development, vehicle demonstration, and evaluation of benefits.

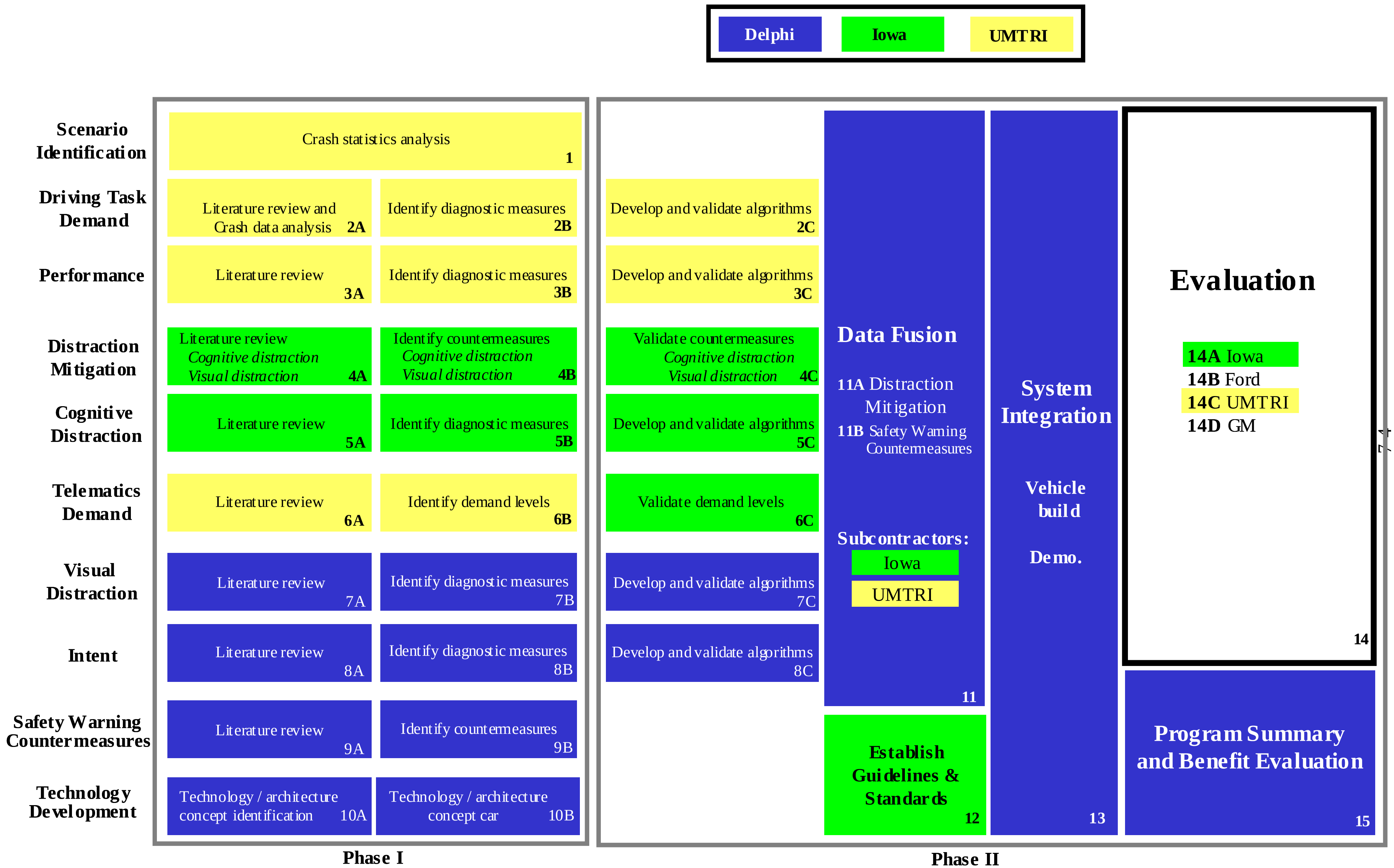

Figure i: SAVE-IT tasks

It is worthwhile to note the SAVE-IT tasks in Figure i are inter-related. They have been chosen to provide necessary human factors data for a two-pronged approach to address the driver distraction and adaptive safety warning countermeasure problems. The first prong (Safety Warning Countermeasures sub-system) uses driver distraction, intent, and driving task demand information to adaptively adjust safety warning systems such as forward collision warning (FCW) systems in order to enhance system effectiveness and user acceptance. Task 1 is designed to determine which safety warning system(s) should be deployed in the SAVE-IT system. Safety warning systems will require the use of warnings about immediate traffic threats without an annoying rate of false alarms and nuisance alerts. Both false alarms and nuisance alerts will be reduced by system intelligence that integrates driver state, intent, and driving task demand information that is obtained from Tasks 2 (Driving Task Demand), 3 (Performance), 5 (Cognitive Distraction), 7 (Visual Distraction), and 8 (Intent).

The safety warning system will adapt to the needs of the driver. When a driver is cognitively and visually attending to the lead vehicle, for example, the warning thresholds can be altered to delay the onset of the FCW alarm or reduce the intrusiveness of the alerting stimuli. When a driver intends to pass a slow-moving lead vehicle and the passing lane is open, the auditory stimulus might be suppressed in order to reduce the alert annoyance of a FCW system. Decreasing the number of false positives may reduce the tendency for drivers to disregard safety system warnings. Task 9 (Safety Warning Countermeasures) will investigate how driver state and intent information can be used to adapt safety warning systems to enhance their effectiveness and user acceptance. Tasks 10 (Technology Development), 11 (Data Fusion), 12 (Establish Guidelines and Standards), 13 (System Integration), 14 (Evaluation), and 15 (Program Summary and Benefit Evaluation) will incorporate the research results gleaned from the other tasks to demonstrate the concept of adaptive safety warning systems and evaluate and document the effectiveness, user acceptance, driver understandability, and benefits and weaknesses of the adaptive systems. It should be pointed out that the SAVE-IT system is a relatively early step in bringing the driver into the loop and therefore, system weaknesses will be evaluated, in addition to the observed benefits.

The second prong of the SAVE-IT program (Distraction Mitigation sub-system) will develop adaptive interface technologies to minimize driver distraction to mitigate against a global increase in risk due to inadequate attention allocation to the driving task. Two examples of the distraction mitigation system include the delivery of a gentle warning and the lockout of certain telematics functions when the driver is more distracted than what the current driving environment allows. A major focus of the SAVE-IT program is the comparison of various mitigation methods in terms of their effectiveness, driver understandability, and user acceptance. It is important that the mitigation system does not introduce additional distraction or driver frustration. Because the lockout method has been shown to be problematic in the aviation domain and will likely cause similar problems for drivers, it should be carefully studied before implementation. If this method is not shown to be beneficial, it will not be implemented.

The distraction mitigation system will process the environmental demand (Task 2: Driving Task Demand), the level of driver distraction [Tasks 3 (Performance), 5 (Cognitive Distraction), 7 (Visual Distraction)], the intent of the driver (Task 8: Intent), and the telematics distraction potential (Task 6: Telematics Demand) to determine which functions should be advised against under a particular circumstance. Non-driving task information and functions will be prioritized based on how crucial the information is at a specific time relative to the level of driving task demand. Task 4 will investigate distraction mitigation strategies and methods that are very well accepted by the users (i.e., with a high level of user acceptance) and understandable to the drivers. Tasks 10 (Technology Development), 11 (Data Fusion), 12 (Establish Guidelines and Standards), 13 (System Integration), 14 (Evaluation), and 15 (Program Summary and Benefit Evaluation) will incorporate the research results gleaned from the other tasks to demonstrate the concept of using adaptive interface technologies in distraction mitigation and evaluate and document the effectiveness, driver understandability, user acceptance, and benefits and potential weaknesses of these technologies.

In particular, driving task demand and driver state (including driver distraction and impairment) form the major dimensions of a driver safety system. It has been argued that crashes are frequently caused by drivers paying insufficient attention when an unexpected event occurs, requiring a novel (non-automatic) response. As displayed in Figure ii, attention to the driving task may be depleted by driver impairment (due to drowsiness, substance use, or a low level of arousal) leading to diminished attentional resources, or allocation to non-driving tasks[1]. Because NHTSA is currently sponsoring other impairment-related studies, the assessment of driver impairment is not included in the SAVE-IT program at the present time. One assumption is that safe driving requires that attention be commensurate with the driving demand or unpredictability of the environment. Low demand situations (e.g., straight country road with no traffic at daytime) may require less attention because the driver can usually predict what will happen in the next few seconds while the driver is attending elsewhere. Conversely, high demand (e.g., multi-lane winding road with erratic traffic) situations may require more attention because during any time attention is diverted away, there is a high probability that a novel response may be required. It is likely that most intuitively drivers take the driving-task demand into account when deciding whether or not to engage in a non-driving task. Although this assumption is likely to be valid in a general sense, a counter argument is that problems may also arise when the situation appears to be relatively benign and drivers overestimate the predictability of the environment. Driving environments that appear to be predictable may therefore leave drivers less prepared to respond when an unexpected threat does arise.

[1] The distinction between driving and non-driving tasks may become blurred sometimes. For example, reading street signs and numbers is necessary for determining the correct course of driving, but may momentarily divert visual attention away from the forward road and degrade a driver's responses to unpredictable danger evolving in the driving path. In the SAVE-IT program, any off-road glances, including those for reading street signs, will be assessed in terms of visual distraction and the information about distraction will be fed into adaptive safety warning countermeasures and distraction mitigation sub-systems.

A safety system that mitigates the use of in-vehicle information and entertainment system (telematics) must balance both attention allocated to the driving task that will be assessed in Tasks 3 (Performance), 5 (Cognitive Distraction), and 7 (Visual Distraction) and attention demanded by the environment that will be assessed in Task 2 (Driving Task Demand). The goal of the distraction mitigation system should be to keep the level of attention allocated to the driving task above the attentional requirements demanded by the current driving environment. For example, as shown in Figure ii, “routine” driving may suffice during low or moderate driving task demand, slightly distracted driving may be adequate during low driving task demand, but high driving task demand requires attentive driving.

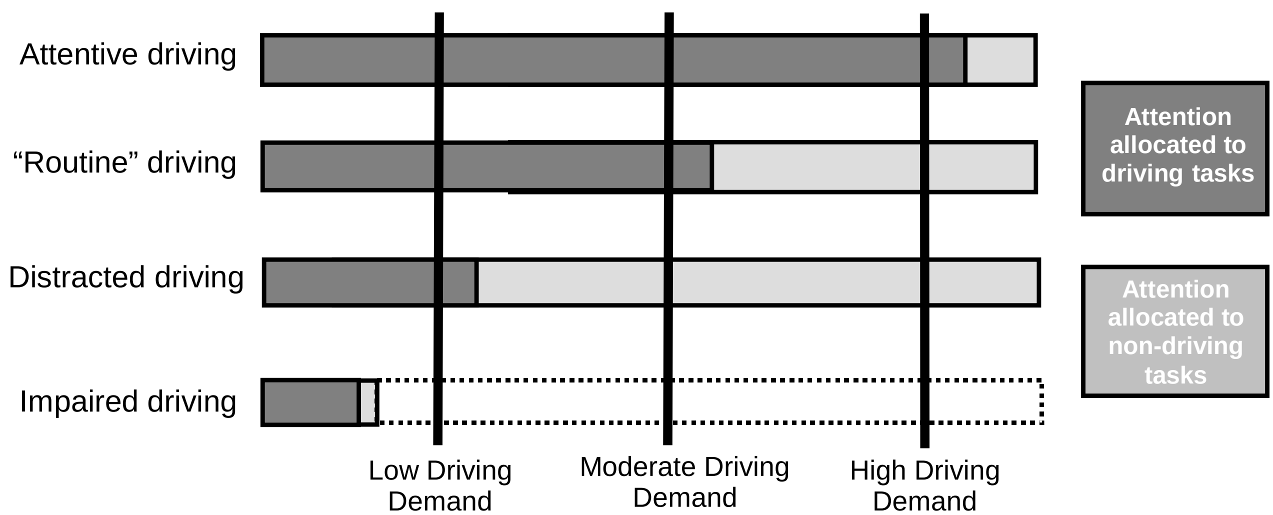

Figure ii. Attention allocation to driving and non-driving tasks

It is important to note that the SAVE-IT system addresses both high-demand and low-demand situations. With respect to the first prong (Safety Warning Countermeasures sub-system), the safety warning systems (e.g., the FCW system) will always be active, regardless of the demand. Sensors will always be assessing the driving environment and driver state. If traffic threats are detected, warnings will be issued that are commensurate with the real time attentiveness of the driver, even under low-demand situations. With respect to the second prong (Distraction Mitigation sub-system), driver state including driver distraction and intent will be continuously assessed under all circumstances. Warnings may be issued and telematics functions may be screened out under both high-demand and low-demand situations, although the threshold for distraction mitigation may be different for these situations.

It should be pointed out that drivers tend to adapt their driving, including distraction behavior and maintenance of speed and headway, based on driving (e.g., traffic and weather) and non-driving conditions (e.g., availability of telematics services), either consciously or unconsciously. For example, drivers may shed non-driving tasks (e.g., ending a cell phone conversation) when driving under unfavorable traffic and weather conditions. It is critical to understand this "driver adaptation" phenomenon. In principle, the "system adaptation" in the SAVE-IT program (i.e., adaptive safety warning countermeasures and adaptive distraction mitigation sub-systems) should be carefully implemented to ensure a fit between the two types of adaptation: "system adaptation" and "driver adaptation". One potential problem in a system that is inappropriately implemented is that the system and the driver may be reacting to each other in an unstable manner. If the system adaptation is on a shorter time scale than the driver adaptation, the driver may become confused and frustrated. Therefore, it is important to take the time scale into account. System adaptation should fit the driver's mental model in order to ensure driver understandability and user acceptance. Because of individual difference, it may also be important to tailor the system to individual drivers in order to maximize driver understandability and user acceptance. Due to resource constraints, however, a nominal driver model will be adopted in the initial SAVE-IT system. Driver profiling, machine learning of driver behavior, individual difference-based system tailoring may be investigated in future research programs.

Communication and Commonalities Among Tasks and Sites

In the SAVE-IT program, a "divide-and-conquer" approach has been taken. The program is first divided into different tasks so that a particular research question can be studied in a particular task. The research findings from the various tasks are then brought together to enable us to develop and evaluate integrated systems. Therefore, a sensible balance of commonality and diversity is crucial to the program success. Diversity is reflected by the fact that every task is designed to address a unique question to achieve a particular objective. As a matter of fact, no tasks are redundant or unnecessary. Diversity is clearly demonstrated in the respective task reports. Also documented in the task reports is the creativity of different task owners in attacking different research problems.

Task commonality is very important to the integration of the research results from the various tasks into a coherent system and is reflected in terms of the common methods across the various tasks. Because of the large number of tasks (a total of 15 tasks depicted in Figure i) and the participation of multiple sites (Delphi Electronics & Safety, University of Iowa, UMTRI, Ford Motor Company, and General Motors), close coordination and commonality among the tasks and sites are key to program success. Coordination mechanisms, task and site commonalities have been built into the program and are reinforced with the bi-weekly teleconference meetings and regular email and telephone communications. It should be pointed out that little time was wasted in meetings. Indeed, some bi-weekly meetings were brief when decisions can be made quickly, or canceled when issues can be resolved before the meetings. The level of coordination and commonality among multiple sites and tasks is un-precedented and has greatly contributed to program success. A selection of commonalities is described below.

Commonalities Among Driving Simulators and Eye Tracking Systems In Phase I
Although the Phase I tasks are performed at three sites (Delphi Electronics & Safety, University of Iowa, and UMTRI), the same driving simulator software, Drive Safety™ (formerly called GlobalSim™) from Drive Safety Inc., and the same eye tracking system, FaceLab™ from Seeing Machines, Inc. are used in Phase I tasks at all sites. The performance variables (e.g., steering angle, lane position, headway) and eye gaze measures (e.g., gaze coordinate) are defined in the same manner across tasks.

Common Dependent Variables An important activity of the driving task is tactical maneuvering such as speed and lane choice, navigation, and hazard monitoring. A key component of tactical maneuvering is responding to unpredictable and probabilistic events (e.g., lead vehicle braking, vehicles cutting in front) in a timely fashion. Timely responses are critical for collision avoidance. If a driver is distracted, attention is diverted from tactical maneuvering and vehicle control, and consequently, reaction time (RT) to probabilistic events increases. Because of the tight coupling between reaction time and attention allocation, RT is a useful metric for operationally defining the concept of driver distraction. Furthermore, brake RT can be readily measured in a driving simulator and is widely used as input to algorithms, such as the forward collision warning algorithm (Task 9: Safety Warning Countermeasures). In other words, RT is directly related to driver safety. Because of these reasons, RT to probabilistic events is chosen as a primary, “ground-truth” dependent variable in Tasks 2 (Driving Task Demand), 5 (Cognitive Distraction), 6 (Telematics Demand), 7 (Visual Distraction), and 9 (Safety Warning Countermeasures).

Because RT may not account for all of the variance in driver behavior, other measures such as steering entropy (Boer, 2001), headway, lane position and variance (e.g., standard deviation of lane position or SDLP), lane departures, and eye glance behavior (e.g., glance duration and frequency) are also be considered. Together these measures will provide a comprehensive picture about driver distraction, demand, and workload.

Common Driving Scenarios For the tasks that measure the brake RT, the "lead vehicle following" scenario is used. Because human factors and psychological research has indicated that RT may be influenced by many factors (e.g., headway), care has been taken to ensure a certain level of uniformity across different tasks. For instance, a common lead vehicle (a white passenger car) was used. The lead vehicle may brake infrequently (no more than 1 braking per minute) and at an unpredictable moment. The vehicle braking was non-imminent in all experiments (e.g., a low value of deceleration), except in Task 9 (Safety Warning Countermeasures) that requires an imminent braking. In addition, the lead vehicle speed and the time headway between the lead vehicle and the host vehicle are commonized across tasks to a large extent.

Subject Demographics It has been shown in the past that driver ages influence driving performance, user acceptance, and driver understandability. Because the age effect is not the focus of the SAVE-IT program, it is not possible to include all driver ages in every task with the budgetary and resource constraints. Rather than using different subject ages in different tasks, however, driver ages are commonized across tasks. Three age groups are defined: younger group (18-25 years old), middle group (35-55 years old), and older group (65-75 years old). Because not all age groups can be used in all tasks, one age group (the middle group) is chosen as the common age group that is used in every task. One reason for this choice is that drivers of 35-55 years old are the likely initial buyers and users of vehicles with advanced technologies such as the SAVE-IT systems. Although the age effect is not the focus of the program, it is examined in some tasks. In those tasks, multiple age groups were used.

The number of subjects per condition per task is based on the particular experimental design and condition, the effect size shown in the literature, and resource constraints. In order to ensure a reasonable level of uniformity across tasks and confidence in the research results, a minimum of eight subjects is used for each and every condition. The typical number of subjects is considerably larger than the minimum, frequently between 10-20.

Other Commonalities In addition to the commonalities across all tasks and all sites, there are additional common features between two or three tasks. For example, the simulator roadway environment and scripting events (e.g., the TCL scripts used in the driving simulator for the headway control and braking event onset) may be shared between experiments, the same distraction (non-driving) tasks may be used in different experiments, and the same research methods and models (e.g., Hidden Markov Model) may be deployed in various tasks. These commonalities afford the consistency among the tasks that is needed to develop and demonstrate a coherent SAVE-IT system.

The Content and Structure of the Report

The report submitted herein is a literature review report that documents the research progress to date (March 1--September 10, 2003) in Phase I. During the period of March-September 2003, the effort has been focused on the first Phase I sub-task: Literature Review. In this report, previous experiments are discussed, research findings are reported, and research needs are identified. This literature review report also serves to establish the research strategies of each task.

7.1 INTRODUCTION

For many drivers, driving a motor vehicle appears to be an automatic, effortless, and well-learned task that can be performed satisfactorily with a minimal level of attention. Occasionally, however, drivers may find themselves in a challenging environment that requires a high level of attention and concentration. Many drivers can probably recall that when they first learned to drive a motor vehicle, it was difficult to monitor road conditions and traffic events, coordinate the eyes, hands, and feet in order to keep the vehicle within the lane boundaries, and listen to the instructor or engage in a conversation with passengers, all at the same time. Observations of new drivers learning to drive a motor vehicle may also serve as a reminder that driving is not a trivial task and it is learned and improved over an extended period of time.

Driving a motor vehicle is a complex psychomotor task that requires the driver to process visual, auditory, and tactile information and translate this information into a complex, coordinated motor output. Driving entails a set of processes such as planning, perception, cognition, task selection, and motor response. These processes are not fully understood at this point, as pointed out by Green (1995).

> How people actually drive is not well understood. Most of the research has focused on what happens to people when they are involved in accidents and other matters pertaining to crashworthiness, not what happens beforehand (pre-crash). Further, very little is known about what behavior constitutes normal driving. (Green, 1995, p. 5)

Michon (1991) proposed the following two levels of driving activities.

- The "higher-level" tactical maneuvering: Maneuvers such as lane changing and overtaking are selected in order to meet the objectives and goals of driving (e.g., a target arrival time) and to satisfy the preferences of the driver under the constraints imposed by actual traffic and road conditions.
- The "lower-level" vehicle control and operation: The translation of the selected maneuvers into actual operations of steering, tracking, accelerating, and braking in order to maintain the vehicle within the lane boundaries and with preferred speeds and accelerations.

A successful completion of these activities requires frequent visual input to extract information from a changing environment. Human beings are visual animals because much information comes from the visual modality. Visual perception is of central importance in the driving task because drivers cannot operate a motor vehicle without vision. Whereas no hearing test is required, drivers are required to pass a vision test before a driver's license is issued. Wierda (1996) summarized the functions of visual search and perception in driving as follow.

- Determination of lateral and longitudinal position, speed, and acceleration
- Determination of vehicle heading
- Detection of obstacles and hazards

- Reading of route indications (e.g., traffic signs and lights) and recognition of traffic situations and road users (e.g., other vehicles and pedestrians)

Drivers do not always devote the full attention to the primary task of driving. They frequently engage in secondary (non-driving) tasks, for example, listening to music and news, or conversing with passengers. The non-driving tasks are known as driver distraction, which can divert attention away from the driving task. Royal (2003) conducted a nationally representative survey of 4,010 drivers in the U.S. and collected useful data on the nature and scope of the distracted driving problem in the public's eyes. The key findings are that on at least some driving trips, the vast majority of drivers engage in two distracting behaviors, namely, talking with other passengers (81% of the responders), and changing radio stations or looking for CD or tapes (66% of the responders). Nearly half of the responders eat or drink while driving, and a quarter of drivers make outgoing phone calls, take incoming phone calls, or deal with children in the rear seat, respectively.

Other activities include reading maps or directions (12%), personal grooming (8%), reading printed material (4%), responding to a beeper or pager (3%), and using wireless remote Internet access (2%). Because many of these activities involve a visual component, they could compete with the driving task for the same resource, therefore creating visual distraction. It is worth noting that drivers engage in both technology-based (e.g., radios, CD, tapes, cell phones, pagers, and navigation systems) and non-technology-based distraction activities (e.g., dealing with children in the back seat, looking at maps, directions, or printed materials).

Driving is commonly a dual task. "Drivers must continuously allocate attention to competing tasks, both driving-related and non-driving. Most of the time, they do this quite well" (Westat, 2000, p. 26). Satisfactory performance of multiple tasks is feasible because full attention may not always be required for the driving task. Hughes and Cole (1986) suggested that 30%-50% of a driver's visual attention could be allocated to activities unrelated to the driving task. Antin, Dingus, Hulse, and Wierwille (1990) estimated that drivers could spend one third of time looking inside a vehicle and engaging in non-driving tasks. Because humans have only one foveal vision that can be deployed to examine objects serially, they cannot direct the visual resource to multiple locations or objects simultaneously. In other words, drivers tend to adopt a time-sharing strategy in the allocation of visual resource.

Time-sharing is clearly demonstrated in Barr, Yang, and Ranney (2003). In comparison to the non-distracted condition, the amount of time spent looking at the forward roadway decreased and the glance durations to the windows and in-vehicle objects increased when subjects were tuning the radio, engaging in a conversation, or talking on the phone. When drivers are distracted, eye glances are taken away from the forward roadway and allocated to other target regions such as the windows and interior locations.

7.2 OVERVIEW OF THE REPORT

Because visual perception is pivotal to the driving task and visual distraction can pose a major risk to safety, a large amount of research has been conducted on visual distraction. In this report (SAVE-IT Task 7A), the visual distraction research in the literature will be reviewed and summarized. This report is not intended to be a comprehensive coverage of all studies in the area of visual distraction. Readers are referred to other excellent reviews on visual distraction research, for example, Green (1999a). Instead, this report will focus on research findings with respect to potentially diagnostic measures of visual distraction and the performance impact of visual glance behaviors, in particular, as they are related to measurements and mitigations of visual distraction using adaptive interface technologies with automatic eye tracking systems. The determination of diagnostic measures and their performance impact, especially in terms of driver reaction time, will be an important part of driver state determination. For the SAVE-IT program, the state of the driver should be assessed in real time. The driver state information can be fed into both SAVE-IT countermeasure sub-systems ("Distraction Mitigation" as in Lee, 2003a, and "Safety Warning Countermeasure" as in Smith & Zhang, 2004) to help reduce distracted-related crashes and enhance the effectiveness of collision warning systems.

The remainder of this report is divided into eight sections. Section 7.3 provides a taxonomy of driver distraction comprising of four types of distraction. Along with cognitive distraction, visual distraction is a major type of driver distraction. In Section 7.4, potential measures of visual distraction are defined. In Section 7.5, recent reports of crash statistics analyses are examined in order to establish a strong link between visual distraction and automobile crashes.

Sections 7.6 and 7.7 are the central part of the report. These sections cover human factors findings regarding eye glance behaviors (e.g., glance duration and frequency) during the performance of conventional and other technology-based tasks. In particular, the link between visual distraction and automobile crashes will be examined further, effects of visual distraction and gaze eccentricity on driving performance, reaction times, and task completion times will be discussed, effects of driving task demand, task complexity, driver age and experience on measures of visual distraction will be described. In Section 7.8, human factors guidelines and principles that have been proposed to guide product designs are explained. These guidelines are pertinent because many of them deal with visual glance behaviors and a large body of visual distraction research has been carried out in order to substantiate the guidelines. In Section 7.9, theoretical developments and the methods for measuring visual distraction, especially the use of automatic eye tracking systems, are briefly described. In the final section (Section 7.10), the key findings from previous sections are summarized and directions for future SAVE-IT studies are offered.

7.3 TYPES OF DRIVER DISTRACTION

Driver distraction is clearly recognized as one of the major contributing factors to automobile crashes on U.S. highways. According to NHTSA, "driver distraction is a broad subject area that includes everything from radios and fast food to Internet connections and on-board navigation systems" (Millman, 2000). Driver distraction may be technology-related (e.g., cell phones), or non-technology-related (e.g., conversing with passengers). NHTSA's current focus is on technology-related problems (Westat, 2000, p. 10), including the use of cell phones, route guidance systems, and wireless Internet services.

Driver distraction is defined as the allocation of attention to tasks and events irrelevant to the primary task of driving. Based on the type and modality of attention, NHTSA has defined four categories of distraction: visual distraction, cognitive distraction, auditory distraction, and biomechanical distraction (psychomotor or manual distraction) (Ranney, Mazze, Garrott, & Goodman, 2000). In this report, visual distraction is defined as eye glances away from the forward roadway and onto in-vehicle or roadside objects and events. Cognitive distraction is defined as thinking about events or tasks irrelevant to driving, or being lost in thought. Auditory distraction is defined as listening to messages or events irrelevant to driving. Manual distraction is defined as taking the hands off the steering wheel and shifting the body out of the normal driving posture.

Many distracting activities that drivers engage in can involve multiple categories of distraction. Among the distraction categories, visual distraction and cognitive distraction are especially important. It is self-evident that visual distraction will increase the risk involved in driving if important events (e.g., lead vehicle braking) are missed because of off-road glances. One cannot drive for long with eyes closed, or looking at off-road objects. Visual distraction is arguably the type of distraction most detrimental to driving safety. Similarly, because central information processing is required for safe driving, mental slippages (cognitive distraction) can be detrimental to driving safety.

Auditory distraction and manual distraction tend to overlap with visual distraction and cognitive distraction. Manual distraction often coincides with visual and cognitive distraction because when drivers manually manipulate dials and buttons, they typically look at the dials and buttons and think about appropriate actions. The most detrimental effect of manual interaction with an interface appears to be the glance at the dials and buttons and the cognitive load of carrying out the function. Similarly, auditory distraction often goes hand in hand with cognitive distraction because when drivers listen to radio broadcast or Internet news, they typically need to think about the contents and make appropriate decisions. Because driving is not an auditory task, it can be argued that the most distracting component of auditory messages is the cognitive load of processing the auditory material.

Because of their utmost importance in driving safety, the SAVE-IT program will focus on visual distraction (this report) and cognitive distraction (Lee, 2003b). An attentive driver typically looks at the forward roadway, keeps both hands on the steering wheel, and focuses the attention on driving ("attentive driving" in Table 7.1). Although eye movements during visual search and instrument monitoring may be modeled as random or stratified random sampling with replacement, evidence exists to suggest that randomness does not completely account for the pattern of information seeking (Ellis & Stark, 1986). Statistical dependency seems to exist among eye movements. Stark and Ellis (1981) proposed three steps in visual search: "look without seeing" (eyes fixating at objects but the mind not processing the information) using habitually preferred eye movement patterns, "see without looking" (forming an internal model), and "look and see" (verifying the internal model) that requires foveal fixations on salient features. Even though dissociation between eye movements and attention has been demonstrated, eye movements and attention are typically linked (Rizzolatti, Riggio, & Sheliga, 1994). Most researchers would agree that eye movements reflect a driver's thought processes and main areas of interest (Liu, 1998). When a driver looks at off-road objects (visual distraction), the driver is usually processing the information associated with the objects (cognitive distraction). To be consistent with the literature, the label "visual distraction" (see Table 7.1) will be used to designate this condition. Because of the dissociation between eye movements and attention, it is possible, though infrequent, that a driver looks away from the forward road momentarily and still thinks about the driving task. This condition is labeled as "visual distraction only" in Table 7.1. In agreement with the literature, we assume that eye movements reflect a driver's attention and areas of interest and therefore we will not make a distinction between these two conditions.

Table 7.1. Relationship between visual distraction and cognitive distraction

		Visual Distraction	
		Present	Absent
Cognitive Distraction	Present	Visual Distraction (Eyes off road, mind off driving)	Cognitive Distraction (Eyes on road, mind off driving)
	Absent	Visual Distraction Only (Eyes off road, mind on driving)	Attentive Driving (Eyes on road, mind on driving)

Further, it is conceivable that a driver looks at the forward road (e.g., no visual distraction) but thinks about work issues or family matters (e.g., cognitive distraction). This condition is labeled as "cognitive distraction" in Table 7.1 and will be studied in another SAVE-IT task (Lee, 2003b). It can be illustrated with the "change blindness" phenomenon (Rensink, O'Regan, & Clark, 1997). They presented subjects two successive frames of an original image A (e.g., statue with a background wall), followed by two successive frames of a modified image A' (e.g., statue with the wall removed). The presentation of the images lasted for 60 s in the order A, A, A', A', A, A, A', A', etc., or until subjects reported the change between images A and A'. They discovered that observers might look at objects (no visual distraction), yet if the mind is not driving (cognitive distraction), objects/changes in their field of view may not be noticed or detected. The key factor for the perception of changes is attention, without which observers appear to be blind to the changes. This phenomenon illustrates the importance of cognitive distraction because a driver may look at the forward road, yet the mind may not be on driving. It may explain the high incidents of "looked but did not see" crashes frequently reported in the crash databases.

7.4 DEFINITION OF VISUAL DISTRACTION MEASURES

Despite the paramount importance of measuring visual distraction, there is no universally-agreed yardstick for such measurements. This sentiment has been echoed many times. "At present there is no common basis for determining when an activity represents a distraction" (Westat, 2000, p. 1). "We don't have a good measure of distraction" (Edwards' statement at the NHTSA public meeting, 2000, p. 207).

Kantowitz (2000) stated that "there is no single best measure of driver distraction" (Llaneras, 2000, p. 59). Diagnostic measures of driver distraction are probably "those which are theory-driven, reliable, objective, and generalizable" (Llaneras, 2000, p. 3). Heeding the advice, we will consider multiple measures in this report. Because one objective of the SAVE-IT program is to use eye glance behaviors via automatic eye tracking systems to determine visual distraction in real time, only eye glance measures will be defined in this section. This decision is reasonable because during the process of standard development (e.g., J2364 and CAMP Workload Study), human factors professionals have indicated that eye glance behaviors are the ideal measures of safety and usability.

Below is a list of visual distraction measures and their definitions.

- Peak glance duration: It is defined as the time (in s) of the longest glance at a target area (e.g., an in-vehicle display) during the performance of a task. For example, a subject may make several glances at the radio area while tuning the radio, and the time of the longest glance is the peak glance duration for the radio-tuning task.
- Mean glance duration: It is defined as the mean amount of time (in s) of all the glances at a target area (e.g., an in-vehicle display) during the performance of a task (e.g., radio tuning).
- Number of glances (glance frequency): It is defined as the number of glances at a target area (e.g., an in-vehicle display) during the performance of a task (e.g., radio tuning).
- Total glance duration (total eyes-off-road time): It is defined as the cumulative time elapsed (in s) for all glances at a target area (e.g., in-vehicle display) during the performance of a task (e.g., radio tuning). Frequently, it is calculated by multiplying the mean glance duration by the number of glances for the performance of a particular task.
- Mean time between glances: It is defined as the cumulative time elapsed (in s) looking away from a target area (e.g., an in-vehicle display), divided by the number of glances away from the target area.
- Type 1 eyes-off-road exposure: It is defined as a product of three variables, namely, mean glance duration, number of glances, and frequency of use per week, for a task or device (e.g., the radio). The mean glance duration and the number of glances are defined above. The frequency of use per week is defined as the average number of times a task (e.g., radio tuning) is performed in a week.

- Type 2 eyes-off-road exposure: It is similar to Type 1 eyes-off-road exposure and defined as a product of three variables, (mean glance duration)$^{1.5}$, number of glances, and frequency of use per week, for a task or device (e.g., the radio). The first variable, mean glance duration, is given a heavier weight to reflect its higher importance.

These measures are not necessarily independent of each other. For example, if a task requires a 10-s total glance duration, the number of glances would be 10 with short 1-s mean glance duration, but 7 with longer 1.4-s mean glance duration. In other words, the mean glance duration and the number of glances may be inversely correlated.

It is worthwhile to note that the measures defined above (e.g., peak and mean glance duration, glance frequency) are broad and can cover many different situations. For example, if the target area is an in-vehicle device, the glance duration and glance frequency on the device would indicate the level of visual distraction to interior objects (e.g., adjusting radio, cassette, CD, climate controls, using or dialing a cell phone). If the target area is an exterior object, the glance duration and glance frequency measures would indicate the level of visual distraction on exterior objects (e.g., looking at an outside person, event, or signs). If the target area is the forward road, the glance duration and glance frequency measures would indicate the level of attention allocated to the driving task, which is inversely related to the level of visual distraction.

7.5 VISUAL DISTRACTION AND AUTOMOBILE CRASHES

It can be probably argued that visual distraction is the most risky type of driver distraction. Most human factors experts hold the opinion that driver distraction, especially visual distraction, increases the risk of automobile crashes. Shelton (2001) stated, "to drive safely, a driver needs to give priority attention to the driving task. Even a momentary distraction can lead to a crash." Dingus (2000) argued that there is "strong evidence that diverting visual attention away from the roadway results in an increased risk of crashes." Millman (2000) made the following statement.

> Distraction degrades driver performance. Multiple distraction and more complex distractions degrade driving performance even more…increasing distractions increase risk and, in turn, lead to unintended consequences…the nature of distraction-related crashes is that they often occur under conditions where the driver may not be exhibiting overtly negligent behavior – they occur when unexpected events happen.

Wierwille and Tijerina (1998) argued that any time the driver's visual resources are allocated to in-vehicle devices, there is an increase in the likelihood of an accident. If a driver spends a substantial amount of time looking at and manipulating an in-vehicle interface, the time available to look at the road is reduced, increasing the crash risk. The longer the driver looks away from the road scene, and the further away from the road scene that glances are directed, the more likely the driver will miss some safety critical information from the road ahead.

Surveys of the driving public are in agreement with the experts' opinions. After surveying 4,010 drivers, Royal (2003) revealed that one in four drivers (26%) reported an involvement in a motor vehicle crash in the past 5 years. Among those drivers who reported involvement in a motor vehicle crash, 14% attributed the crashes to driver distraction. The distraction activities reported by the respondents included: looking for something inside or outside the car, dealing with children or other passengers, another driver, personal thoughts, looking at an animal outside of the car, radios, and cell phones. Many of these distractions were visual in nature. It is worthwhile to point out that this distraction list included both technology-based and non-technology-based activities, and non-technology-based activities were more pervasive.

Royal (2003) also reported drivers' perception of distracting actions. Most drivers who were surveyed believed that reading printed materials such as books, newspapers, or mail items, using wireless remote Internet equipment, personal grooming, and looking at maps or directions were very distracting. Nearly half of the drivers believed that making outgoing phone calls, taking incoming phone calls, answering or checking a pager or a beeper, and dealing with children in the back seat were distracting. Again, many of these activities were visual in nature, and included both technology-based and non-technology-based activities.

The experts' opinion and the driving public's perception are further collaborated by the crash statistics. Wang, Knipling, and Goodman (1996) analyzed the National Automotive Sampling System Crashworthiness Data System (henceforth, CDS) 1995 data and found that for the crashes analyzed, 13.8% of the drivers were distracted (including 6.9% reported distractions, 5.1% reported "looked but did not see", and 1.8% reported sleepy), 46.5% of the drivers were attentive or not distracted, and in 39.7% of cases the driver state was unknown (including "no driver was present"). Similar results were shown with percentages of crashes. In particular, 23.8% of the crashes involved driver distraction/inattention (including 11.7% distractions, 8.9% "looked but did not see", and 3.1% sleepy), 28.9% of crashes involved drivers who were attentive or not distracted, and 47.4% of crashes involved unknown driver states.

These percentages must be regarded as conservative estimates because of the large number of unknowns. Redistributing the "unknown" percentages of drivers, 22.89% of drivers were distracted (including 11.44% distracted, 8.46% "looked but did not see", 3% sleepy). Similarly, redistributing the "unknown" percentages of crashes, 45.25% of crashes involved driver distraction/inattention (including 22.24% distracted, 16.92% "looked but did not see", and 5.89% sleepy). Clearly, driver distraction is involved in a significant number of crashes (23%-45% after redistributing the unknowns).

Stutts, Reinfurt, Staplin, and Rodgman (2001) analyzed the overall 1995-1999 CDS data, and concluded that 48.6% of the drivers were identified as attentive at the time of the crash, 8.3% were identified as distracted, 5.4% as "looked but did not see", and 1.8% as sleepy or asleep, and the remaining 35.9% were coded either unknown or "no driver present". The sum of the total, including "distraction", "looked but did not see", and "sleepy" categories, was 15.5% without redistributing the unknowns. After redistributing the unknowns, the sum was 24.18%. Redistributing the unknowns, the percentage of drivers identified as distracted increased to 12.9%. These percentages of driver distraction were likely under-reported because they were based on police reports and drivers may be fearful of fully disclosing distraction status to police officers.

The distraction type and associated percentages, as reported in Stutts et al. (2001), are presented in Table 7.2. It is clear from Table 7.2 that visual distraction (e.g., visual-manual component) is a major source of distraction.

In spite of the strong correlation, the relationship between driver distraction and automobile crashes is not necessarily causal. There are many factors attributing to a crash, and it may not be possible to account for all the variables. Even if all the variables are accounted for, we can only predict general patterns and tendencies, but not specific crash occurrence at a particular location and time. In all likelihood, crash occurrence is chaotic and probabilistic. Tijerina (1996) contended the following.

> One general finding of the crash problem studies … is that driver inattention is a key contributor to crashes on the highway. Crashes may indeed occur when the driver is not paying attention to the driving scene, but drivers who do not pay attention to their driving do not always have crashes. Crashes occur when a set

of circumstances come together in space and time to jointly yield an unfortunate outcome. (p. 36)

Table 7.2. Distraction type and percentages reported in Stutts et al. (2001)

Distraction Type	Percentage
Outside person, object or event	29.4%
Adjusting radio, cassette, CD	11.4%
Other occupant in vehicle	10.9%
Moving objects in vehicle	4.3%
Other device/object brought into vehicle	2.9%
Adjusting vehicle/climate controls	2.8%
Eating or drinking	1.7%
Using/dialing cell phone	1.5%
Smoking related	0.9%
Other distraction	25.6%
Unknown distraction	8.6%
Total	100%

Heinrich's safety triangle, depicted in Figure 7.1, appears to capture the relationship between driver distraction and automobile crashes. Driver errors include the loss of vehicle control, wrong driver decisions, and driver distraction. Although driver errors increase the likelihood of crashes, crashes do not always occur whenever drivers make errors, for example, deviating from the lane boundary, changing lane without checking the blind spot, or looking at the radio for a long duration. Most driver errors do not lead to crashes because driver errors often occur without the presence of hazards. Yet, driver errors do increase the crash risk, and crashes are likely when both driver errors and hazards are present.

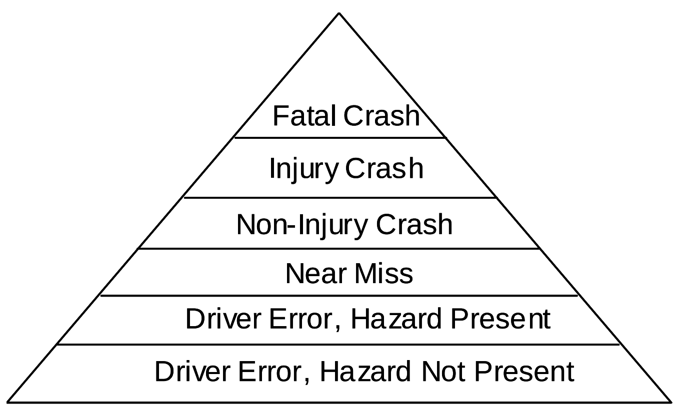

Figure 7.1. Heinrich's safety triangle

Table 7.3 may be used to illustrate the relationship between driver distraction and automobile crashes. Based on crash data analysis (e.g., Wang, Knipling, & Goodman, 1996), NHTSA estimated that 25% of crashes are attributable to driver distraction. In other words, the probability of driver distraction given a crash, p(distraction/crash), is

0.25, and the probability of non-distraction given a crash, p(no distraction/crash), is 0.75 (1-0.25).

Table 7.3. Relationship between driver distraction and automobile crashes

		Driver Distracted?	
		Yes	No
Crash Occurred?	Yes	Distraction and Crash	Crash but No Distraction
	No	Distraction but No Crash	No Distraction and No Crash

The reverse probabilities, the probability of a crash given the occurrence of driver distraction, p(crash/distraction), and the probability of a crash given non-distraction, p(crash/no distraction), are not known. Neither are the probability of non-crash given driver distraction, p(no crash/distraction), and the probability of non-crash given non-distraction, p(no crash/no distraction). Because crashes are low-probability events, p(crash/distraction) may be a small number, which could be the reason for falsely thinking that driver distraction is not a major factor of crashes. The absolute values can be misleading, however. Relative ratios should be more informative. If the probability of a crash given the occurrence of driver distraction, p(crash/distraction), is significantly larger than the probability of a crash given non-distraction, p(crash/no distraction), it must be concluded that driver distraction significantly increases the likelihood of crashes.

Heinrich's safety triangle is frequently used in hazard analysis. The logic behind this analysis is as follow. Crashes are rare and this makes crashes impractical for predictive safety evaluations. However, there exists a hierarchy of incidents that occur more frequently. These incidents are related to crashes. Therefore, it is possible to measure these incidents in small-scale evaluations and then extrapolate to estimate the rare crash events to arrive at safety estimates. Dingus, McGehee, Hulse, Jahns, Manakkal, Mollenhauer, and Fleischman (1994) proposed measures of unsafe driving behaviors, some of which are listed below.

- Peak glance duration of single glances to displays greater than 2.5 s
- Abrupt lateral and braking maneuvers (acceleration of 3.9 m/s^2, or 0.4 g)
- Unplanned lane deviations
- Unplanned speed variation of over 16 km/h (10 mph)
- Dangerously close headways

Tijerina (1996) described a workload safety paradox to explain the major factors leading up to crashes. As shown in Figure 7.2, three factors are at work: driving task demand, non-driving task demand, and driver discretion to use in-vehicle device. Drivers tend to adjust their attention and driving behavior based on their understanding of driving conditions and their personal motivations. If driving task demand is perceived as high, drivers will be less likely to divert attention away from the driving task. If the driver can exercise discretion about when or whether to use an in-vehicle device, the driver will be less likely to engage in non-driving distraction tasks. If the driver cannot exercise discretion, or if device use is mandatory (e.g., because of the device design), however, the total demand, including both driving task demand and non-driving task demand, will increase, and the relative crash hazard levels will increase accordingly.

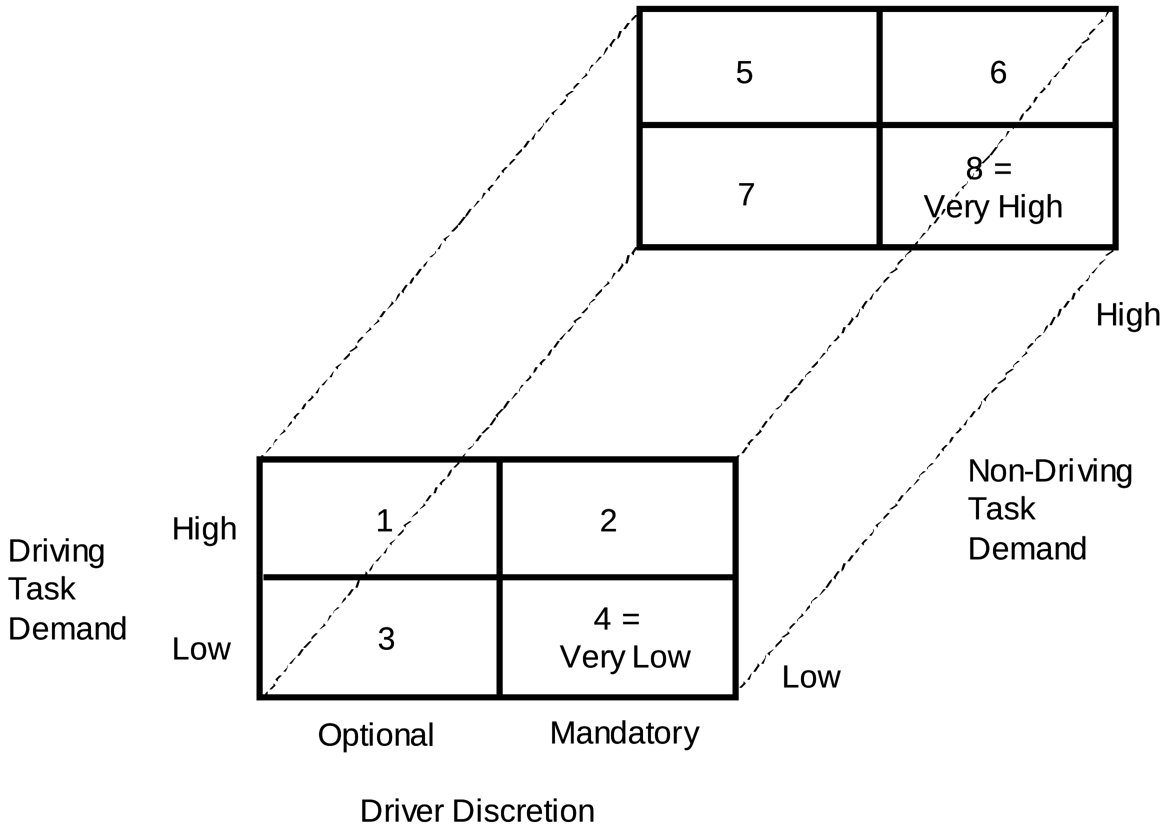

Figure 7.2. A workload safety paradox showing hypothetical level of relative crash hazard as a function of driving task demand, non-driving task demand, and driver discretion to use in-vehicle device (from Tijerina, 1996).

If driving task demand is perceived as low, drivers will be more likely to divert attention away from the driving task and engage in non-driving distraction tasks. If unpredicted events occur under this circumstance, drivers may not be prepared to respond in a timely manner. This may be why many crashes occur under conditions of low driving task demand, e.g., in daylight and on dry pavement.

Tijerina (1996) proposed several reasons why in-cab device use may be mandatory rather than discretionary. First, human operators may have an intrinsic drive to interact with some types of technology (e.g., answering a phone call) in a mandatory manner. Second, drivers may be tempted to use navigation systems (high non-driving task demand) near intersections in which traffic behavior is unpredictable (high driving task demand). Third, operating practices of the heavy vehicle drivers may require drivers to enter trip data into a recorder shortly after crossing a state line.

7.6 EFFECT OF VISUAL DISTRACTION ON DRIVING PERFORMANCE AND CRASHES

Next we will summarize major human factors findings that have been reported in the literature. Although all type of statistics, including the mean and variance, will be examined, it should be noted that the bulk of the research findings that are reviewed in this report will focus on the mean results. Because the amount of research in the area of visual distraction is considerable, research findings will be reviewed in two sections (Sections 7.6 and 7.7). In this section (Section 7.6), the focus will be on the relationship between visual distraction and its effect on driving performance and crashes. In this case, the level of visual distraction will be treated as an independent variable, and its effects on safety-relevant dependent variables including driving performance and crash rate will be investigated. In Section 7.7, the review will focus on the factors that can influence the levels of visual distraction in the driving environment. In this case, the level of visual distraction will be treated as a dependent variable.

Section 7.6 is divided into four sub-sections. In Section 7.6.1, results of crash database analysis will be reviewed to reveal the relationship between visual distraction and automobile crashes. In Sections 7.6.2, effects of visual distraction on driving performance variables such as lane departures and task completion time will be examined. In Section 7.6.3, effects of visual distraction on reaction times for hazard and event detection will be investigated. In Section 7.6.4, visual glance behaviors and associated performance will be examined as a function of gaze eccentricity.

7.6.1. Crashes Predicted From Measures of Visual Distraction

Wierwille and Tijerina (1996) analyzed the North Carolina 1989 and 1992 crash narrative databases that were provided by the police. With key word search on these databases, they generated a list of hits. After deleting the hits that were irrelevant to visual allocation and workload, they generated 2,816 citations. Of these citations, visual allocation into the vehicle was clearly noted in 1,562 cases, visual allocation outside the vehicle was clearly noted in 661 cases, and unspecified visual allocation was noted in 593 cases (whether it was inside or outside was not specified in the narratives).

Using the North Carolina 1989 data on accident occurrence for various interior sources as reported in Wierwille and Tijerina (1996), Wierwille and Tijerina (1998) established a strong connection between in-vehicle visual demands (as the independent variable) and accident occurrence (as the dependent variable). The dependent variable, the number of crashes attributed to eye glances to various interior sources (e.g., radio, speedometer, etc.), was obtained from Wierwille and Tijerina (1996). The independent variable, the in-vehicle visual glance behavior for various interior sources, was expressed in terms of Type 1 and Type 2 eyes-off-road exposures, and calculated using three parameters, frequency of use per week, mean glance duration, and glance frequency.

Wierwille and Tijerina (1998) estimated the frequency of weekly use for various devices from three previous studies that involved both on-road testing and questionnaire data. The frequency data from these studies were combined to produce the frequency of weekly use for interior devices such as speedometer, radio, and mirror, while the vehicle was in motion. The mean glance duration and number of glances for in-vehicle devices were estimated from three other studies: Rockwell (1988), Bhise, Forbes, and Farber (1986), and Dingus, Antin, Hulse, and Wierwille (1989). The combined data for frequency of use per week, mean glance duration, and number of glances are presented in Table 7.4. Wierwille and Tijerina (1998) calculated Type 1 and Type 2 eyes-off-road exposures, using estimated frequency of use per week, mean glance duration, and glance frequency. These calculations are presented in Table 7.4.

Table 7.4. Eye glances, exposures, and crashes (from Wierwille & Tijerina, 1998)

Category	Mean glance duration	Number of glances	Frequency of use/week	Type 1 eyes-off-road exposure	Type 2 eyes-off-road exposure	Number of crashes
Speedometer	.62	1.26	300	234.36	184.54	17
Mirrors	1.0	1.0	250	250	250	101
Standard radio	1.2	3.5	56	235.2	257.65	104
Climate controls	1.1	1.75	37	71.23	74.70	15
Smoking/lighting	1.5	4.0	32	192	235.15	79
Wiper/washer	1.1	1.2	29	38.28	40.15	12
Fuel gage	1.3	1.2	25	39	44.47	2
High beam indicator	.62	1.0	24	14.88	11.72	3
Clock	.83	1.26	15	15.69	14.29	2
Vents	.62	1.83	15	17.02	13.40	3
Heater & AC	1.1	1.75	15	28.88	30.28	7
Lock, side window	1.4	1.6	15	33.6	39.76	2
Visor	.8	2.0	12	19.2	17.17	5
Gearshift	1.5	1.75	10	26.25	32.15	17
Defroster/ Defogger	1.1	1.2	7	9.24	9.69	5
Seat belt	1.5	2.0	5	15	18.37	13
Seat	1.5	2.5	3	11.25	13.78	10
Personal timepiece	.83	1.26	3	3.14	2.86	1
Map	1.7	5.0	1	8.5	11.08	21

Note. The number of crashes is correlated with mean glance duration (r=0.192), the number of glances (r=0.396), and the frequency of use/week (r=0.436).

Although a particular variable such as off-road glance duration, glance frequency, or frequency of use on a weekly basis alone has low to moderate level of correlation with the frequency of crashes, these variables together in a combined manner, as expressed in terms of Type 1 and Type 2 exposures, are strongly correlated with the frequency of crashes. The correlation coefficient was 0.898 for Type 1 eyes-off-road exposure, and

0.941 for Type 2 eyes-off-road exposure. With the removal of an outlier, the correlation coefficient was increased to 0.982, for both Type 1 and Type 2 eyes-off-road exposures. These results provided the empirical support for the commonly-accepted claim that an increase in the off-road glance time leads to an increased crash risk.

It should be pointed out that crash data and exposure data were obtained from different databases, and many variables, for example, vehicle make and model, location of vehicle displays, were not controlled across studies. The crash reports relied heavily on the police reports and driver's honesty. They were based on one state (i.e., North Carolina) and one year (i.e., 1989) only. Because of these factors, Wierwille and Tijerina's results should be treated as tentative.

Wierwille and Tijerina's (1998) method has been applied to estimate crash probabilities for new technologies (Dingus, 2000; NHTSA public meeting, 2000, p. 86). The mean glance duration, number of glances, and estimated frequency of week per week were shown in Table 7.5. These values were used to calculate Type 1 eyes-off-road exposure, which was in turn converted into crash rates. After normalizing the crash rate for looking at the fuel gage, the relative crash rate for performing complex radio task such as inserting a CD or manual tuning was 6.3, that for navigation with traffic information device was 4.46, that with new in-vehicle task of low complexity was 7.18, that with new in-vehicle task of moderate complexity was 14.77, and that with new in-vehicle task of high complexity was 32.31.

Table 7.5. Glance, exposure, and crash rate from Dingus (2000)

Task	Glance Duration (s)	Number of Glances	Frequency of Use/Week	Type 1 Exposure	Crash Rate
Check fuel gage	1.3	1.2	25	39	1
Complex radio task	1.1	4.0	56	246.4	6.3
Navigation with traffic information	1.5	5.8	20	174	4.46
New in-vehicle task of low complexity	1.4	10.0	20	280	7.18
New in-vehicle task of moderate complexity	1.6	18.0	20	576	14.77
New in-vehicle task of high complexity	1.8	35	20	1276	32.31

Note. New in-vehicle tasks of low-, moderate-, and high-complexity did not represent a particular device or task. For these tasks, glance values were those typically seen across many tests, and two tasks per commute trip and ten commute trips per week were assumed for the frequency of use/week.

Wierwille and Tijerina's (1998) analysis has been extended by Green (1999a, 2000) to predict the number of deaths attributable to a particular device, using the following equation,

$$Y = 1.109 \times (X - 1989) \times P \times (-0.133 + 0.0447 \times D^{\frac{3}{2}} \times N \times F)$$

Y is the number of deaths in U.S. in a particular year (X). X is a year after 1989. P represents the market penetration fraction, which is defined as the fraction of vehicles on the road that have a feature. D represents mean glance duration, N represents the number of glances, and F represents the frequency of use/week.

7.6.2. Driving Performance Predicted From Measures of Visual Distraction

Although the connection between visual distraction and automobile crashes is commonly acknowledged, it cannot be assessed in advance (before crash occurrence). Alternatively, driving performance measures such as lane keeping, speed maintenance, car following performance, driver reaction to objects and events are frequently regarded as safety measures. Lateral deviation is a good measure of crashes and safety because even a deviation of a few feet could be fatal (Zwahlen, Adams, & DeBald, 1988). As pointed out by Green (1999a, 2003), non-distracted and distracted conditions produce different driving performances. In the following paragraphs, the relationship between measures of visual distraction and driving performance is examined separately for three dependent variables: standard deviation of lane position or SDLP, number of lane departures, and task completion time.

7.6.2.1. Standard Deviation of Lane Position (SDLP)

The effects of visual distraction on SDLP have been studied for many years. Zwahlen and DeBald (1986) carried out a study investigating the lateral lane keeping performance as a function of time (or travel distance) that the eyes were closed or looked away from the forward road. Twelve subjects drove either a small or a large car on an airport runway, at 48 km/h (30 MPH). The lateral lane position was measured with liquid dye, contained in a can that was attached to the rear bumper, dripping regularly onto the pavement when the car was driven. Mounted midway in the center console were either article clippings or sections of a road map. When they reached the starting point (called the zero point), subjects were asked to drive normally, with their eyes closed, or while reading text inside the car.

Zwahlen and DeBald's (1986) results are presented in Figure 7.3. At the zero point, SDLP was the same for all conditions and it was not equal to zero. For the "normal driving" condition, SDLP remained flat throughout the entire drive. Statistical analysis revealed that there were no significant differences in SDLP among the conditions, for the first 50 ft of the drive (1 s at 30 MPH). As shown in Figure 7.3, beyond 50 ft, the "eyes closed" and "in-vehicle reading" conditions had a higher SDLP than did the "normal driving" condition. It seemed that reading in-vehicle text for 2 s (at 90 ft) raised the SDLP from the initial value ("normal driving" condition), and reading for 3 s (at 135 ft) raised the SDLP noticeably. There was no difference in the lateral variance between the "eyes closed" and "in-vehicle reading" conditions for up to 225 ft (5 s at 30 MPH). As shown in Figure 7.3, beyond 225 ft, the "eyes closed" condition had a larger SDLP than did the "in-vehicle reading" condition. Analogously, Zwahlen, Adams, and DeBald (1988) found that longer eyes-off-road time was significantly correlated with greater lane deviations.

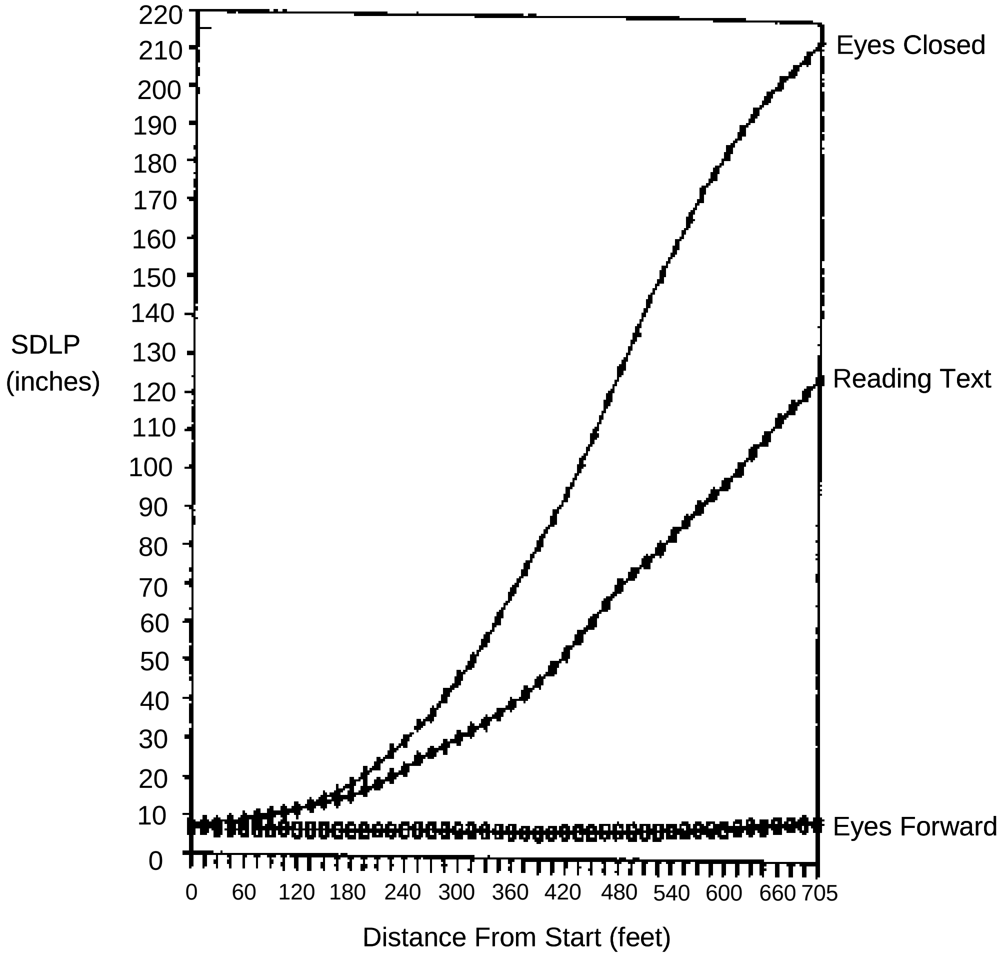

Figure 7.3. SDLP versus travel distance (from Zwahlen & DeBald, 1986).

Zwahlen and DeBald (1986) proposed the following equation for SDLP.

$$SDLP = k \times D \times T^{0.5}$$

K is a constant, set at 0.076 (averaging across car sizes) for the "eyes closed" condition, or 0.041 for the "in-vehicle reading" condition. D is the distance traveled at constant speed with driver's vision occluded (either with eyes closed, or with reading). T is the time of visual occlusion (either with eyes closed, or with reading).

The studies by Zwahlen and his colleagues are important in several respects. First, they demonstrated that visual distraction, as measured in terms of eyes-off-road time, is clearly related to SDLP. Second, once SDLP is calculated, the probability of lane departures can be calculated. Assuming that vehicle lateral positions within the lane are normally distributed with a mean of zero (at the center of the lane), knowing the lane width (W) and the standard deviation of the distribution (SDLP), a Z score corresponding to the lane boundaries can be computed with the following equation,

$$Z = \pm \frac{W}{2 \times (SDLP)}$$

The Z-score can be translated to a probability of lane departures, using a normal probability table, summing the probability under both tails.

This calculation was carried out in Zwahlen, Adams, and DeBald (1988). Zwahlen, Adams, and DeBald (1988) found an SDLP of 7.2-10.4 in. when drivers looked ahead continuously (baseline). Averaged across all the distraction conditions (e.g., while the driver was operating the radio and climate control functions on the CRT touch panel), the average SDLP was 16 in. The maximum SDLP was 22 in. Assuming vehicle lateral positions were normally distributed, an average SDLP of 16 in. was translated into a 3% probability of lane departures on 12-ft roads and a 15% probability of lane departures on 10-ft roads. These probabilities are much larger than those from the baseline. Assuming vehicle lateral positions were normally distributed, the SDLP at the baseline, (7.2+10.4)/2, or 8.8 in., was translated into a 0.006% probability of lane departures on 12-ft roads and a 0.6% probability of lane departures on 10-ft roads.

The correlation between visual glances and SDLP was demonstrated by Popp and Farber (1991). A turn-by-turn display or a list display was positioned at either a central position (15^0 below the horizon), or a peripheral position (30^0 from the focus of expansion, near the radio area). The number of glances to the display was higher for the peripheral position than for the central position, and higher for the list display than for the turn-by-turn display. The total glance duration to the display was longer for the peripheral position than for the central position (17.5 vs. 14 s), and longer for the list display than for the turn-by-turn display. The mean glance duration was approximately 1 s for both the peripheral and central locations. The lane keeping performance appeared to correspond to the eye glance behavior. The SDLP increased when mean glance duration and the number of glances was increased.

The correlation was also revealed in NHTSA's "Heavy Vehicle Driver Workload Assessment" study (Tijerina, Kiger, Rockwell, & Tornow, 1996). In their study, 16 professional truck drivers drove an instrumented truck while reading 1-, 2-, or 4-line-long text messages that were presented on a CRT screen. The mean number of glances to the CRT screen was greater for the 2-line displays (4.58 glances) and 4-line displays (7.38 glances) than to the 1-line displays (1.14-2.01 glances). Analogously, they found a strong correlation between the eye glance behavior and driving performance. The mean SDLP was 0.118 and 0.16 m for 2-line and 4-line messages, and ranged from 0.064-0.109 m for 1-line messages.

7.6.2.2. Lane departures

The number of lane departures is another performance measure. Dingus, Hulse, McGehee, Manakkal, and Fleischman (1994) performed the TravTek Camera Car project. The project goal was to demonstrate an in-vehicle route guidance and information system supported by traffic and incident information in the Orlando, Florida area. The TravTek information was presented on a 6-in. diagonal in-dash CRT with touch screen controls that was located on the horizontal center of the dashboard. The touch screen controls were available while the vehicle was stopped, and steering wheel controls, supplemented with a voice system, were used while the car was in motion. Thirty novice TravTek users of 16-73 years of age (18 visitors, and 12 local Orlando residents) drove an instrumented vehicle to the same unfamiliar location in the Orlando area six times while performing one of the following six tasks.

- TravTek "turn-by-turn with voice"
- TravTek "turn-by-turn without voice"
- TravTek "route map with voice" (moving map)
- TravTek "route map without voice" (moving map)
- Textual "paper direction" list with large legible font
- A conventional "paper map"

Dingus, Hulse, McGehee, Manakkal, and Fleischman (1994) reported a mean glance duration of 1 s or smaller for the "turn-by-turn with voice" and "turn-by-turn without voice" conditions, and about 1.1 s for the "route map without voice", "paper direction", and "paper map" conditions. The difference was statistically significant. The number of unplanned lane departures was lower (about 20) for the "turn-by-turn with voice" or "turn-by-turn without voice" condition, and higher for other four conditions (about 30). There seemed to be a connection between the mean glance duration and the number of lane departures. For most conditions, half of the lane deviations were attributed to eye glances to the display. For the "route map without voice" condition, approximately 85% of lane deviations were attributed to eye glances to the display (Dingus, McGehee, Hulse, Jahns, Manakkal, Mollenhauer, & Fleischman, 1994). Overall, the turn-by-turn display, with or without voice, was better than the moving map (route map), or conventional paper map.

A strong correlation between mean glance duration and lane departure was not always obtained. Green (1999a) analyzed the ETAK data that were collected by Wierwille and his colleagues. He found a direct relationship between the mean glance duration and number of glances. Importantly, he revealed a high correlation (r=0.78) between the number of glances to a device and the number of lane departures. Although the number of lane departures increased with the mean glance duration, the lane departure variance accounted for by the mean glance duration was only 5%.

The weak correlation between mean glance duration and lane departure was also documented in Tijerina, Parmer, and Goodman (1999) and Blanco (1999). In Blanco (1999), truck drivers drove on real roads, while performing in-vehicle tasks. Although the number of eye glances to in-vehicle display was directly correlated with the number of lane deviations, mean glance duration was not significantly correlated with the number of lane deviations. Total glance duration was directly correlated with the number of lane deviations.

However, the low correlation for mean glance duration could be attributed to a ceiling effect. Because most drivers find it intolerably unsafe to look away from the road for a long duration while driving (Rockwell, 1988; Wierwille, 1993a), mean glance durations are typically shorter than 2 s. As discussed previously, Zwahlen and DeBald (1986) discovered that the SDLP remained stable within 2-s off-road glance duration, and it increased considerably with longer duration. It is conceivable to attain a stronger correlation with a larger range of mean glance durations.

In contrast, a strong correlation has been consistently documented between the number of glances to a device and the number of lane departures. Green (1999a) revealed a high correlation of 0.78. Dingus (2000) illustrated a direct correlation, while manipulating tasks (e.g., the conventional task, the search task, the search-plan task, the search-plan-compute task, the search-plan-interpret task, the search-compute task, and finally the search-plan-interpret-compute task), presentation format (e.g., graph with icons, table, graph with text, and paragraph), and information density (e.g., low, medium, and high).

Tijerina (1996) and Tijerina, Kiger, Rockwell, and Tornow (1996) reported the results of NHTSA's "Heavy Vehicle Driver Workload Assessment" study. Their original objective was the development of a heavy vehicle driver workload assessment protocol including methods, baseline data, and guidelines that can be used by product designers to evaluate the effects of high technology in-cab systems on a driver's ability to safely carry out the primary task of driving. It was intended to develop protocols that may serve as a standard during the test and evaluation of driver workload and distraction issues, similar to the "Good Laboratory Practices", "Good Manufacturing Practices", and "Good Ergonomic Evaluation Practices". The original objective was not achieved because absolute assessments of driver workload that predict crash occurrence were not feasible, and only relative assessments were feasible. However, the project was successful in establishing the sensitivity of the workload measurement system to variations in heavy vehicle driver workload.

The bulk of Tijerina's (1996) research was conducted with an empirical evaluation of heavy vehicle operation with professional drivers in an actual heavy vehicle on the road. In one experiment, 30 truck drivers drove an instrumented truck (without the use of high technology device) over a 459-km test route for about 4 hr. Road type (e.g., freeway, rural roads) and ambient light levels (e.g., night/daylight driving) were varied. Drivers were occasionally requested to execute in-cab conventional tasks. The results are shown in Table 7.6.

It was concluded that visual allocation measures (e.g., mean glance duration and the number of glances) were sensitive to driving conditions and requested tasks. Lane keeping measures and speed measures were also sensitive to variations in driving conditions and requested tasks. Of the driving conditions, road type had the most pronounced effect, and light had a minimal effect. The effect of driving condition was generally additive with effect of secondary task (e.g., requested tasks).

In another experiment (Tijerina, Kiger, Rockwell, & Tornow, 1996), a high-technology experiment was performed in which a prototype text message system and cellular phone system were chosen for evaluation. Sixteen professional truck drivers drove an instrumented truck for 4 hr on public roads under conditions of ambient lighting (e.g., day/night), traffic density (e.g., light/heavy), and road type (e.g., divided/undivided). Drivers were asked to read text messages of varied length, on a CRT screen. The mean glance duration to the CRT screen was not significantly different among the eight text messages, indicating that drivers on average took their eyes off the road for a narrow range of glances (1.35-1.71 s). On the other hand, the number of glances to the CRT screen was significantly different among the eight text messages. The mean number of glances to the CRT screen was greater for the 2-line (4.58 glances) and 4-line displays (7.38 glances) than to the 1-line displays (1.14-2.01 glances). The 2-line radio tuning message and 4-line message were those that took eyes off the roadway the longest and took the longest to complete.

Table 7.6. Visual glance results from Tijerina (1996): Mean (SD)

Requested task	Glance duration	Number of glances
Read digit clock	1.20 (0.43)	1.03 (0.17)
Read air pressure	1.57 (0.71)	1.16 (0.46)
Adjust radio volume	0.77 (0.40)	1.10 (0.54)
Tune radio	1.22 (0.41)	5.62 (3.15)
Left mirror – detect	1.21 (0.55)	1.05 (0.28)
Right mirror – detect	1.37 (0.59)	1.05 (0.22)
Tune CB	0.96 (0.34)	3.23 (1.33)

In short, Tijerina (1996) and Tijerina, Kiger, Rockwell, and Tornow (1996) found that reading 2-line and 4-line text messages increased the time looking away from the road scene and shortened the glances to the road scene. Correspondingly, the incidence of unplanned lane departures was greater when reading 4-line text messages (17 lane deviations) than when reading 1-line or 2-line messages (7-14 lane deviations). Steering reversals were significantly different, with more reversals on average for the 2-line (12.08) and 4-line messages (17.67) than for the 1-line messages (3.95-7.12). Most steering reversals occurred in tasks with long glance duration. Hence, Tijerina (1996) recommended to limit text messages to 1-line display of 55 characters.

Tijerina, Parmer, and Goodman (1998) and Tijerina, Johnston, Parmer, Winterbottom, and Goodman (2000) tested 16 subjects driving a 1993 Toyota Camry at 7.5-mile test track at Transportation Research Center (TRC). Four commercially available route guidance systems were used, three using visual-manual input with a visual display, and a fourth using voice input and output without any visual display. Three navigation tasks (address, intersection, and point-of-interest or POI entry) were used, and the POI data were reported. There were two additional tasks: tuning the radio to a specific band and frequency with the "SEEK" function, and manually dialing 10-digit phone numbers using a cordless phone.

Mean number of glances to in-vehicle device during the POI entry ranged from 22 to 33 for the visual-manual route guidance systems, and was considerably lower for voice-based system (5 glances), manual phone dialing (9 glances), and radio tuning (6 glances). The mean glance duration to the in-vehicle device during the POI entry was 2.5-2.7 s for the visual-manual route guidance systems, 3.1 s for manual phone dialing, 2.7 s for radio tuning, but considerably lower for the voice-based system (1 s). The mean glance durations to the in-vehicle device were unusually long. Conversely, mean glance duration to the forward road ranged from 0.7-1.1 s for manual phone dialing, radio tuning, and visual-manual route guidance systems, but was considerably longer for the voice-based system (2.8 s). Importantly, lane departure data appeared to mirror the eye glance data. In particular, the number of lane departures was 0.8-0.9 per trial for two out of three visual-manual route guidance systems, and 0.25 per trial for the third visual-manual route guidance system. It was 0.05 per trial for phone dialing, 0.2 per trial for radio tuning, and 0 per trial for the voice-based system. These results appeared to suggest that both the number of glances and the mean glance duration were contributing factors of lane departures.

The correlation between the number of glances and lane departures was also documented in a simulator experiment by Jenness, Lattanzio, O'Toole, Taylor, and Pax (2002). Twenty-four subjects drove for 10 min while performing either a voice- or manual-dialing task. The number of glances away from the road was 1.0 without a secondary task, 34.7 for the voice dialing condition, and 79.7 for the manual dialing condition. Correspondingly, the number of lane departures was 19.8 without a secondary task, 24.8 for the voice dialing condition, and 31.6 for the manual dialing condition. The correspondence between the number of glances away from the road and the number of lane departures was evident.

A similar correlation was found for total glances by Jenness, Lattanzio, O'Toole, and Taylor (2002). Twenty subjects drove two 2.23-mile laps, while performing one of the following secondary tasks.

- Voice dialing task: Subjects dialed phone numbers with voice recognition repeatedly and continuously (a low level of visual/manual distraction, and a high level of cognitive distraction)
- Eating task: Subjects ate cheeseburgers and drunk pops continuously (a high level of manual distraction, and a moderate level of visual distraction)
- CD task: Subjects operated a CD player continuously (a high level of visual/manual distraction)
- Reading task: Subjects read directions continuously (a high level of visual distraction)

Jenness et al. (2002) discovered that on average, the number of glances away from the forward road was 146.42 (SD of 43.02) for the reading condition, 77.27 (SD of 22.16) for the CD condition, 19.57 (SD of 13.77) for the eating condition, 20.54 (SD of 11.44) for the voice dialing condition, and 1.96 (SD of 3.10) for the baseline condition (no secondary tasks). Importantly, a similar pattern was discovered for the lane departure results. On average, lane deviations were 25.31 (SD of 13.27) for the reading condition, 21.19 (SD of 11.14) for the CD condition, 13.62 (SD of 10.19) for the eating condition, 13.62 (SD of 10.10) for the voice dialing condition, and 8.23 (SD of 7.24) for the baseline condition. Clearly, the total number of off-road glances was correlated with the number of lane deviations.

To summarize, it is clear that the number of lane departures increases with the number of glances and the total glance duration to in-vehicle device. The results with mean glance duration are mixed. It appears that the mean glance duration to an in-vehicle display typically does not exceed 2 s and that its limited range weakens its effect on the number of lane departures (e.g., a ceiling effect).

7.6.2.3. Task completion time

Task completion time is another performance measure that is commonly used to assess the impact of visual distraction. A strong correlation between task completion time and number of glances to the in-vehicle display was revealed by Tijerina, Parmer, and Goodman (1999) and Gellatly and Kleiss (2000). Furthermore, Tijerina et al. (1999) found that both task completion time and number of glances to the display were moderately correlated with the number of lane departures.

As discussed above, Dingus, Hulse, McGehee, Manakkal, and Fleischman (1994) found that the mean glance duration was about 1 s or lower for the "turn-by-turn with voice" and "turn-by-turn without voice" conditions, and about 1.1 s for the "route map without voice", "paper direction", and "paper map" conditions. Other benefits were demonstrated with the TravTek system. Comparing to the conventional "paper map", the TravTek system significantly reduced the time required to plan the trip (750 vs. 100 s), the drive time to the destination (2,250 vs. 1,400 s), and the number of times getting lost while navigating (10 vs. 0-4). Dingus, McGehee, Hulse, Jahns, Manakkal, Mollenhauer, and Fleischman (1994) reported that comparing to the conventional "paper map", the TravTek system resulted in fewer stops (13 vs. 10) and shorter time of stops (350 vs. 200 s). In summary, the TravTek system seemed to be beneficial because it reduced the plan time, the drive time, and the number of navigation errors.

Blanco (1999) found that an increase in peak glance duration, total glance duration, or number of glances to in-vehicle display was associated with a decrease in mean speed, an increase in speed variance, and an increase in secondary task completion time. The mean glance duration was not significantly correlated with any performance measures.

Jenness, Lattanzio, O'Toole, and Taylor (2002) demonstrated a direct relationship between visual distraction (e.g., off-road glance time) and travel time. The average time for completion of 2 laps was 459.35 s (SD of 92.30 s) for the reading condition, 455.81 s (SD of 84.51 s) for the CD condition, 386.80 s (SD of 68.68 s) for the eating condition, 381.96 s (SD of 66.70 s) for the voice dialing condition, and 351.97 s (SD of 68.67 s) for the baseline condition. This pattern of drive time results corresponded to the pattern of eye glance results that were presented previously. This experiment also indicated that when pitting visual distraction (e.g., the reading condition) against manual distraction (e.g., the eating condition) or cognitive distraction (e.g., the voice dialing condition), visual distraction led to more driver errors and slower drive time.

Analogously, Jenness, Lattanzio, O'Toole, Taylor, and Pax (2002) demonstrated a direct relationship between visual distraction and drive time, as shown in Table 7.7.

Table 7.7. Jenness, Lattanzio, O'Toole, Taylor, and Pax's (2002) results: Mean (SD)

	No Secondary Task	Voice Dialing	Manual Dialing
Number of off-road glances	1.0 (1.1)	34.7 (9.4)	79.7 (23.7)
Drive times (s)	507.03 (91.32)	560.69 (114.2)	578.38 (123.4)
Dialing errors		3.8 (3.9)	1.4 (1.5)

In summary, when engaging in secondary tasks, subjects took more glances away from the forward road, drove more slowly, and took more time to complete the driving course. This result supports the hypothesis that a compensatory mechanism is at work—When performing a secondary task (with increased workload), subjects tend to slow down to reduce the overall workload. This compensation may not be perfect because more driving errors (including lane deviations) occur when secondary tasks are performed.

7.6.3. Hazard and Event Detection Reaction Times Predicted From Measures of Visual Distraction

Although it is commonly believed that performance measures such as SDLP and lane departures during task execution are fundamentally safety-relevant, Tijerina et al. (2000) pointed out that they may not be sufficient. Other recommended measures include hazard and event detection performance such as a driver's reactions to lead vehicle braking, road hazards, or incursions into the travel lane. In Section 7.6.3, the relationship between visual distraction and reaction time to roadway hazards and events is examined.

Hancock, Simmons, Hashemi, Howarth, and Ranney (1999) instructed subjects to stop at intersections when the traffic light was changed to red from green. They revealed that when subjects were distracted with a simulated cell phone task (with visual and cognitive components), brake reaction time was slower (0.93 s) than was for the non-distracted condition (0.61 s). Without distraction, drivers stopped the vehicle 35.3 ft before the finish line, but with distraction, they stopped the vehicle 26.3 ft before the finish line. In other words, distracted drivers stopped the vehicle 25% later than did the non-distracted drivers.

Lamble, Laakso, and Summala (1999) investigated drivers' ability to detect a decelerating car ahead when drivers' visual attention was focused on a display located at different positions around the interior of the vehicle. This study was unique because it studied drivers' response when drivers focused their visual attention inside the vehicle during a critical event on the road ahead. Six male and six female students of 19-27 years old were asked to drive an instrumented vehicle (1994 Mitsubishi Galant) on a 1.2-km long and 2.5-m wide straight and level roadway near an airfield, while following a

1988 Lada Samara. Subjects' use of controls, vehicle speed, and inter-vehicle distance were measured. Cameras were used to record the forward road and subjects' face for subsequent analysis.

A 10 mm by 7 mm red LED display, mounted in a 35 mm by 35 mm by 20 mm black box, was used for the in-car foveal task. The LED was mounted in 8 positions: 4°, 21°, or 34° below the focus of expansion, two dashboard locations (17° or 24° to the right of and 4° below the focus of expansion), the rear-view mirror area, the right-side mirror area, and the right window area. Subjects were required to focus solely on the LED display rather than the vehicle ahead, and orally name all the fours that appeared on the display as random digits. Despite the instructions, subjects looked at the forward road occasionally. As a result, some trials were discarded. A control condition required subjects to focus on the forward road (0°).

Lamble, Laakso, and Summala (1999) explicitly instructed subjects to follow the lead vehicle and brake as soon as they noticed the lead vehicle decelerating. The lead vehicle could decelerate with the removal of the foot from the accelerator pedal while driving at 50 km/h in second gear, resulting in a deceleration rate of 0.7 m/s^2 (0.07 g). The initial headway could be 20 or 40 m (1.44 or 2.88 s time headway). Lamble, Laakso, and Summala (1999) calculated the time to contact (TTC) at the moment of host vehicle braking. They found that TTC decreased significantly as the eccentricity of the foveal task increased, with an r^2 of 0.60 at 20-m headway and 0.673 at 40-m headway. Because TTC is inversely related to brake reaction time, their results suggested that brake reaction time increased with the eccentricity of the foveal task.

Summala, Lamble, and Maakso (1998) studied the reaction time impact of visual distraction as related to gaze eccentricity. Twenty male and eight female subjects of 20-43 years of age drove a 2-km freeway section. An LED display was located at three locations: lower windscreen area (16° below the focus of expansion, slightly to the right), near the speedometer (27° below the focus of expansion), and near the radio area (50° eccentricity). Again, subjects followed a lead vehicle while looking at the LED and were explicitly told to brake in response to lead vehicle braking. The lead and host vehicles were the same as those used in Lamble, Laakso, and Summala (1999). The lead vehicle braking occurred at an average deceleration of 2.1 m/s^2, with the brake lights either working normally or switched off. The independent variables were as follow.

- Four initial distance/speed conditions
    - 15 m at 30 km/h (1.8 s time headway)
    - 30 m at 30 km/h (3.6 s time headway)
    - 30 m and 60 km/h (1.8 s time headway)
    - 60 m at 60 km/h (3.6 s time headway)
- Two brake-light conditions (lights on or off)
- Two replications
- Three levels of subject experience (beginner, novice, experienced)

Summala, Lamble, and Maakso (1998) found that for every distance condition, brake reaction time increased from 1 s to 5-6 s as gaze eccentricity increased. As compared to the control condition, the average delay in brake reaction time, across the four distance conditions and all subjects, was 0.9 s for the lower windscreen position, 2.1 s for the speedometer position, and 2.9 s for the radio position. Driving experience did not have an effect on reaction time, suggesting that detecting closing-headway situations with peripheral vision does not improve with driving experience as lane-keeping does. In conclusion, they found a substantial delay in brake reaction times when a driver looked away from the lead car that braked, regardless of whether the driver was a novice or more experienced driver.

There are conflicting reports regarding which component of cell-phone use is most distracting. A Japanese study showed that the majority of mobile phone related crashes occurred during dialing or receiving calls, whereas a US report indicated that the majority of mobile phone related crashes occurred during conversations. Toward a resolution on this issue, Lamble, Kauranen, Laakso, and Summala (1999) made a head-to-head comparison between the visual distraction component (dialing and receiving) and the cognitive distraction component (conversation) using reaction time measure in a car following situation. A number keypad task, mounted on the dashboard just to the right of the steering wheel at an average of 35° eccentricity, was used to simulate dialing a phone number (visual distraction condition). Subjects were asked to key in a series of 3 random integers on the keypad. A memory and addition task (non-visual attention) was used to simulate cognitive load associated with phone conversations.

Nineteen subjects (10 males and 9 females) drove an instrumented car on a 30-km roadway. Subjects were instructed to follow a lead vehicle, with their right foot positioned above the brake pedal, and brake as soon as they noticed the lead vehicle decelerating. The lead vehicle could brake at 0.47 m/s^2. Lamble, Kauranen, Laakso, and Summala (1999) discovered that compared to the control condition (with eye gaze on the forward road), brake reaction time was increased by 0.48 and 0.50 s in the visual and cognitive distraction conditions, respectively. The reaction time increase could be more pronounced if subjects were not explicitly told to respond to lead vehicle braking, and if their right foot was not positioned above the brake pedal. Effects of visual and cognitive distraction appeared similar, and both delayed response times.

Lee, McGehee, Brown, and Reyes (2002) studied the reaction time impact of driver distraction in the context of forward collision warnings. In their first experiment, subjects were distracted. They were asked to press a button near the rearview mirror when a tone sounded. The button press triggered a display above the mirror that presented a changing series of single-digit numbers at a rate of 4 Hz. Similar to Lamble, Laakso, and Summala (1999), subjects were asked to watch these numbers and report the number of times the digit 4 appeared. Examinations of subjects' glance behaviors confirmed that subjects indeed looked away from the road during the distraction period. When subjects were distracted, the lead vehicle could brake quickly and imminently, which would require the driver to make an immediate response in order to avoid crashes. Brake reaction time was measured.

In their second experiment, drivers were not distracted. Again, the lead vehicle could brake imminently, and brake reaction time was measured. A comparison of results from the two experiments indicated that the foot-off-accelerator time was 0.4-s longer when subjects were distracted than when they were not distracted. The movement time from the accelerator pedal to the brake pedal did not vary with distraction. The time from the initial brake application to maximum depression of the brake pedal was shorter for distracted subjects than for non-distracted subjects, indicating that distracted subjects pressed the brake pedal faster than did non-distracted subjects.

In conclusion, the previous studies consistently documented that visual distraction slowed down brake reaction times to lead vehicle braking. The delay in brake reaction time could be in the range of 0.4-0.5 s. These studies, however, did not investigate how particular measures of visual distraction, for example, mean glance duration and glance frequency, affected brake reaction times.

7.6.4. Effects of Gaze Eccentricity

In the preceding discussion, it has been implicitly assumed that visual perception cannot be achieved without foveal vision. This assumption may be valid only to the first approximation. In Section 7.6.4, we will demonstrate that visual perception is possible, albeit degraded, with peripheral vision. Gaze eccentricity has been manipulated with two methods. One method is asking subjects to direct their foveal vision to the forward road and to determine whether they can detect event changes at a peripheral location. The other method is asking subjects to direct their foveal vision to an in-vehicle location (e.g., the radio area) and determine whether driving performance, including lane keeping performance, is degraded. Studies employing both methods are reviewed in this section.

Mourant and Rockwell (1970) reported results in support of the hypothesis that peripheral vision is used to monitor other vehicles and lane markers in order to direct the fovea for closer examinations when the situation demands it. Other studies revealed that the peripheral vision plays a large role in vehicle velocity estimation because angular velocity is greater in the peripheral area than in the foveal area.

An old tenet in the traffic safety community is that although foveal vision is needed for lane keeping, drivers learn to use peripheral vision in lane keeping. This is substantiated by Summala, Nieminen, and Punto's (1996) discovery that experienced drivers were able to utilize para-foveal or peripheral vision to maintain lane position. They asked 27 subjects to drive an instrumented car on a straight road. The lane boundaries were painted white continuously with a 3-m lane width. Subjects were instructed to accelerate from a full stop to 30 km/h within 50 m and drive a 210-m road segment using only peripheral vision for lane keeping.

In Summala et al.'s (1996) study, subjects were asked to direct their foveal vision to an off-road area steadily. Digits were shown at three eccentricities (7° or 23° below the focus of expansion, and 38° from the focus of expansion near the radio area), and subjects were asked to name the digits aloud, add a constant to the digits, or add the last two digits. Importantly, subjects were capable of lane keeping with peripheral vision. Lane keeping performance, however, declined with increasing gaze eccentricity. The distance that drivers were able to drive properly within the lane boundaries decreased as a function of gaze eccentricity. Despite the instruction of keeping their gaze on the in-vehicle display, subjects "cheated" and looked at the forward road occasionally. The number of cheating glances increased with eccentricity.

To investigate the effect of gaze eccentricity on reaction time, Osaka (1991) presented a red object at several different locations when subjects fixated at the center of the road. Subjects were asked to press a key when they detected the red light. Reaction time was shortest for detecting objects at the center of the fixation, and increased as the eccentricity increased. Reaction time for detection of peripheral objects at 15˚ (horizontal) was 14%-25% longer.

Faerber and Ripper (1991) displayed three types of large stimuli (simple arrows, icons, and alphanumeric signs) on a CRT screen located at 15° directly below the focus of expansion (15°/0), or 15° below and 30° to the right of the focus of expansion (15°/30°). Subjects were asked not to move their head or eyes and use their peripheral vision to detect the visual stimuli. Mean detection RT was 930 ms at 15°/0° and 1,050 ms at 15°/30°, a difference of 120 ms. Although peripheral vision can be used to detect complex stimuli such as icons, reaction time was longer with peripheral vision.

Similar results were obtained by Mourant, Tsai, Al-Shihabi, and Jaeger (2000). Ten young drivers (23-46 years old) and ten older drivers (58-76 years old) drove a 1985 Dodge Caravan. They were asked to report digits on an in-vehicle display (located at 18° below and 32° to the right of the focus of expansion), or digits superimposed on the driving scene. The percent correct of reporting the digits varied with display type. With 1-s inter-stimuli interval, the percent correct was 69.4% for the superimposed display and 62.1% for the in-vehicle display. This finding showed an advantage of showing visual information near the focus of expansion.

In a study by Labiale (1993), thirty-six 18-76 years old subjects drove an instrumented vehicle on a 26-km test course in heavy traffic. A 3.2-cm by 0.9 cm red warning lamp could be turned on at four different locations: (1) near the speedometer, (2) about 5-10° to the right of the driver, on top of the dashboard, (3) near the center of the dashboard, and (4) near the left A-pillar. Subjects were asked to operate a lever located to the right of the steering wheel as soon as they detected the operation of the warning lamp. They were not told about the exact location of the warning lamp. Labiale (1993) found that the average detection time was 2.09-2.32 s for the first two locations and 3.60 s for other two locations. Subjective preference measures collaborated the reaction time results. This finding indicated that horizontal eccentricity was a major factor of reaction time.

In Sprenger's (1993) study, 36 male subjects drove VW Passats twice along an 87-km test route. One Passat was equipped with a HUD that was located 10° below the focus of expansion, with a virtual reflection image at 280 cm. In this condition, subjects were asked to read the digital speed. The other Passat was not equipped with HUD, and subjects were asked to read speed with the conventional speedometer. Sprenger (1993) found that speed on HUD was read more frequently than that on the conventional speedometer. Subjective reports showed that it was easier to read the HUD image than the speedometer. Furthermore, mean glance duration was longer for the speedometer (713.4 ms) than for the HUD (608.8 ms), indicating the effect of vertical eccentricity on display recognition time.

Lamble, Laakso, and Summala (1999) investigated the effect of horizontal and vertical eccentricity on the detection of lead vehicle decelerating. They found that detection thresholds were higher in the vertical locations than in the horizontal positions. This could be explained by the fact that the human eye is not spherical and the resolution is smaller in the vertical periphery than in the horizontal periphery. They also found that the TTC in response to the lead vehicle braking was longer when in-vehicle LED was located on top of the dashboard just to the right of the steering wheel (17°) than in the speedometer area (21° below the focus of expansion). This result suggested that future vehicle design should consider using the area above the dashboard, just to the side of the steering wheel, for mounting visual displays.

To summarize, in spite of the fact that experienced drivers can keep their vehicle in the lane with peripheral vision, the lane keeping performance becomes degraded as gaze eccentricity increases. The degradation is considerably more pronounced for detection of objects such as signs and icons and detection of traffic events such as lead vehicle braking or decelerating. When gaze eccentricity is increased horizontally or vertically, reaction time becomes markedly longer.

7.7. Visual Distraction and Characteristics of Driving Tasks, Non-Driving Tasks, and Driver Experience

In Section 7.7, we will treat the level of visual distraction as a dependent variable and examine the independent variables that influence the level of visual distraction in the driving environment. The baseline glance behavior will also be investigated. Although there are some recent studies on roadside distractions such as the eye glances at roadside advertising signs (Beijer, Smiley, & Eizenman, 2004; Smiley, Beijer, & Eizenman, 2004), most of the research has been focused on eye glances at in-vehicle devices. Therefore, we will focus on the eye glance behaviors at in-vehicle devices.

This section is divided into four sub-sections. In Section 7.7.1, visual glance behaviors while performing conventional or navigation tasks will be studied to establish a baseline. In Sections 7.7.2 and 7.7.3, characteristics of driving and non-driving tasks and their effects on visual glance behaviors will be investigated. In particular, complexity of non-driving tasks, display characteristics of in-vehicle device, and characteristics of driving such as road geometry and weather will be examined. In Section 7.7.4, effects of driver age, experience, and route familiarity on visual glance behaviors will be examined.

7.7.1. Visual Glance Behavior During Performance of Conventional and Navigation Tasks

Because eye glance behaviors are of central significance to safety and visual distraction can increase the likelihood of automobile crashes, many studies have been conducted to investigate eye glance duration and glance frequency while performing conventional and navigation tasks. The results from these studies can be regarded as baseline data during routine driving. In the following paragraphs, they are summarized separately for conventional tasks and navigation tasks.

7.7.1.1. Visual Glance Behaviors in Conventional Tasks

Some drivers voluntarily introduce visual workload by insisting on eye contact with passengers during conversations. Other drivers produce eye fixations on highway signs and sample objects of little relevance to their trips. Because of these observations, Rockwell (1988) hypothesized that "spare attentional capacity" exists (e.g., ability to attend to non-driving tasks). Rockwell (1988) investigated eye glance durations across different tasks. For radio tasks, mean glance duration to the radio ranged from 1.27-1.42 s, median glance duration ranged from 1.2-1.3 s, and standard deviations ranged from 0.42-0.50 s. The 5th percentile ranged from 0.80-0.89 s and the 95th percentile ranged from 1.83-2.50 s. For glances on the left mirror, mean glance duration ranged from 1.06-1.22 s, median glance duration ranged from 0.96-1.15 s, and standard deviations ranged from 0.28-0.40 s. The 5th percentile ranged from 0.80-0.94 and the 95th percentile ranged from 1.7-1.80. The glance duration on the rearview mirror was

10% shorter than that on the left mirror, averaging 1.0 s. The glance duration on the speedometer was 20% shorter than that on the left mirror, averaging about 0.8 s.

Rockwell (1988) summarized these results as follow.

> For years researchers studying car following and eye movements have found a 2 second rule, i.e., drivers are loath to go without roadway information for more than 2 second (and right so)…When complex displays require glance durations beyond the 90th percentile, most drivers are clearly facing special visual workload problems. The strategy for most complex targets is to make a series of glances of 1 ¼ second until the task is completed.

In other words, mean glance duration does not vary considerably, but glance frequency reflects the complexity of the information system.

Rockwell's (1988) conclusions were buttressed by recent results. Kurokawa and Wierwille (1990) recorded eye movements on a video camera and analyzed the videos frame-by-frame. They discovered that for simple conventional tasks (e.g., pressing a button), the average number of glances to the instrument panel was 1-2 and the mean glance duration was approximately 1 s (shorter than 1.5 s). For more complex tasks (e.g., dialing a 13-digit number, or pressing AM/FM and then tuning radio), the number of glances to in-vehicle display was between 5 and 7. The results were similar in a driving simulator and on real roads. Similarly, Gellatly and Kleiss (2000) studied the eye glance behavior while subjects performed various in-vehicle tasks (e.g., HVAC or radio). They found that mean glance frequency to in-vehicle display varied with tasks, but mean glance duration remained constant at about 1 s across all tasks.

It is difficult to estimate the size of "spare attentional capacity". Hughes and Cole (1986) and Antin, Dingus, Hulse, and Wierwille (1990) estimated that a third of a driver's visual attention could be allocated to activities unrelated to the driving task. Several studies indicated that approximately 80% of glances were directed on the forward road. For example, Carter and Laya (1998) divided the visual field into 12 zones and studied the proportion of time drivers glanced at each zone. In both the test track and driving simulator, 80% of the glances were on the forward road, and the remaining 20% on the instrument panel, the mirrors, or roadside objects.

Analogously, Hughes and Cole (1988) showed that approximately 85% of fixations were within 6° of the focus of expansion. Cole and Hughes (1987) found similar results. Cole and Hughes (1987) made a color film of a 22-km route and showed sections of this film to 32 subjects. Subjects were divided into four groups and asked to do one of the following activities.

- Watch the film
- Watch the film and some questions will be asked about it at the end
- Report what attracts your attention
- Report all traffic control devices

Half of the subjects in each group were asked to carry out a compensatory tracking task located at the aiming point of the vehicle. The tracking task involved keeping an irregularly moving cursor aligned with a designated point. It was a relatively undemanding visuo-motor task but required subjects to divide their attention between the tracking task and the film-watching task. Cole and Hughes (1987) discovered that 95% of the fixations were within $\pm 8°$ from the focus of expansion, within a circle of 8° radius.

Similarly, Barr, Yang, and Ranney (2003) analyzed the time durations of eye glances to eight regions for both baseline (no distraction) and distraction periods. While not distracted, drivers generally spent over 80% of the time looking at the forward road and a small amount of time looking at the instrument panel, other interior locations, mirrors, windows, and outside surroundings. These results were consistent with other studies. When subjects were distracted (e.g., tuning radio), the amount of time spent looking at the forward roadway decreased, and glance durations to the mirrors, windows, and in-vehicle locations increased.

Tijerina (1996) obtained similar results. Table 7.8 lists the mean glance duration and percentage of total time from nine professional truck drivers in the baseline driving. Note that the eye glances were on the forward road 76.4% of the time and were on or around the forward road nearly 80% of the time.

Table 7.8. Tijerina's (1996) glance results

Target Area	Mean glance duration (s)	Percentage of total time
Left mirror	1.33	5.6%
Right mirror	1.47	3.2%
Instrument panel	0.93	5.0%
Header (up)	0.83	0.8%
Road-ahead	3.85	76.4%
Road-left	1.22	1.2%
Road-right	0.98	2.0%
Left other	1.36	0.6%
Right other	1.28	5.3%
Total		100%

Zwahlen and Schnell (1998) studied eye glances to the turn signals of a lead vehicle and the roadside speed limit signs. Glance durations ranged from 0.25-1.75 s, with a median of 0.5 s. These results were similar to those of Tijerina (1996). In addition, the median distance was at 120-150 m for the first glance and 60 m for the last glance on turn signals and speed limit signs.

Eye glance behaviors are influenced by experimental instructions. Hughes and Cole (1988) demonstrated that instructions (e.g., memory vs. search) had a pronounced effect on the way subjects distributed visual attention. Compared with single-task condition (e.g., no secondary task), subjects glanced more at the central areas with dual tasks. As subjects were instructed to change from undirected observation to directed search, subjects fixated further from the focus of expansion and to the left of the road.

Hada (1994), reported in Green (1999a), performed two experiments to investigate eye glances to speedometer/tachometer cluster, top of the center console, HUD positions. Subjects drove in the area of Ann Arbor, Michigan, while being instructing to look at a display "as long as you feel safe to do so". The median glance duration for all glances combined was 0.68 s. The 95th percentile was 2.2 s, 97.5th percentile 2.5 s, and 99th percentile 3.6 s. On average, subjects looked at the display once every 3 s.

Kimura, Osumi, and Nagai (1990), reported in Green (1999a), performed a study to investigate eye glances to speedometer/tachometer and the center console. Japanese subjects were instructed to look at a display "for as long as possible, until they felt uncomfortable". The median glance duration was 2.0 s and the mode was 1.2 s. These results were larger than Hada's findings, probably attributable to different instructions.

Several conclusions can be drawn about baseline driving. First, mean glance duration rarely exceeds 2 s (the so-called 2-second rule), with only a small percent of glances longer than 2 s. Second, the number of glances varies based on display complexity. Third, for a large amount of time (80%), drivers' glances are directed on the forward roadway, within a circle of 6-8° radius.

7.7.1.2. Visual Glances With Navigation Systems

Because the use of navigation systems entails constant visual input, its effect on visual glance behavior has been examined extensively in the literature. One earlier study is the ETAK study, performed by Wierwille, Dingus, and their colleagues (Wierwille, Antin, Dingus, & Hulse 1988; Dingus, Antin, Hulse, & Wierwille, 1988; Dingus, 1987). These studies were designed to compare the visual attentional demand for navigation system tasks (with ETAK) and "conventional tasks" (e.g., tuning the radio or reading the speedometer). These on-road studies were performed using an instrumented 1985 Cadillac DeVille fitted with an ETAK navigator.

Table 7.9 summarizes the total glance duration, mean glance duration, mean number of glances, and associated standard deviations. Note that the standard deviations were approximately half of the means, indicating that the 95th percentile was approximately twice the mean values.

It is clear from Table 7.9 that for both conventional and navigation tasks, the total glance duration may be short or long. Some navigation tasks, including "roadway name" (determining the name of the next roadway), "roadway distance" (determining the distance to the next roadway), and "cross street" (determining the name of the next cross street), had long total and mean glance durations. The total glance duration can be shortened for these tasks if information was available without the use of zooming-in or -out functions. In order to lower visual demand, therefore, it is recommended to automatically change the zoom such that an optimal amount of usable information is always present.

Table 7.9. Visual glance results from the ETAK study: Mean (SD) (from Dingus, 1987; Dingus, Antin, Hulse, & Wierwille, 1989; Wierwille, Antin, Dingus, & Hulse, 1988)

Task	Total glance duration	Glance duration	Number of glances
Speed	0.78 (0.65)	0.62 (0.48)	1.26 (0.40)
Following traffic	0.98 (0.60)	0.75 (0.36)	1.31 (0.57)
Time	1.04 (0.56)	0.83 (0.38)	1.26 (0.46)
Vent	1.13 (0.99)	0.62 (0.40)	1.83 (1.03)
Destination direction	1.57 (0.94)	1.20 (0.73)	1.31 (0.62)
Remaining fuel	1.58 (0.95)	1.04 (0.50)	1.52 (0.71)
Tone controls	1.59 (1.03)	0.92 (0.41)	1.73 (0.82)
Info lights	1.75 (0.93)	0.83 (0.35)	2.12 (1.16)
Destination distance	1.83 (1.09)	1.06 (0.56)	1.73 (0.93)
Fan	1.95 (1.29)	1.10 (0.48)	1.78 (1.0)
Balance	2.23 (1.50)	0.86 (0.35)	2.59 (1.18)
Sentinel	2.38 (1.71)	1.01 (0.47)	2.51 (1.81)
Defrost	2.86 (1.59)	1.14 (0.61)	2.51 (1.49)
Fuel economy	2.87 (1.09)	1.14 (0.58)	2.48 (0.94)
Correct direction	2.96 (1.86)	1.45 (0.67)	2.04 (1.25)
Fuel range	3.00 (1.43)	1.19 (1.02)	2.54 (0.60)
Temperature	3.50 (1.73)	1.10 (0.52)	3.18 (1.66)
Cassette tape	3.23 (1.55)	0.80 (0.29)	2.06 (1.29)
Heading	3.58 (2.23)	1.30 (0.56)	2.76 (1.81)
Zoom level	4.00 (2.17)	1.40 (0.65)	2.91 (1.65)
Cruise control	4.82 (3.80)	0.82 (0.36)	5.88 (2.81)
Power mirror	5.71 (2.78)	0.86 (0.34)	6.64 (2.56)
Tune radio	7.60 (3.41)	1.10 (0.47)	6.91 (2.39)
Cross street	8.63 (4.86)	1.66 (0.82)	5.21 (3.2)
Roadway distance	8.84 (5.20)	1.53 (0.65)	5.78 (2.85)
Roadway name	10.63 (5.80)	1.63 (0.80)	6.52 (3.15)
Grand Average		1.08 (0.53)	3.12 (1.48)

Note. The 95th percentile is 2.14 s for glance duration and 6.08 for the number of glances.

Table 7.10. Time proportion of glances (from Wierwille, Antin, Dingus, & Hulse, 1988)

Navigation method	On forward road, mirrors, or driving-related instruments	On maps/displays
Memorized route (baseline)	0.898	0
Paper map	0.815	0.068
Navigator	0.602	0.331

Wierwille, Antin, Dingus, and Hulse (1988) revealed that the glance time on driving related locations (e.g., the forward road, mirrors, other driving-related instruments) and on paper map or navigation display varied with experimental conditions. The results are presented in Table 7.10.

These ETAK studies indicated that several of the ETAK functions required a high degree of attention compared to other automotive tasks. Despite that, the ETAK was found to be a usable and useful device. Recommendations from these studies included: automated route selection and zoom capabilities, simplified information displays, and path feature for route planning. Simplified information displays (e.g., using turn-by-turn displays) and automated route selection were adopted in the following TravTek system.

Further, Dingus (1995) reported eye glance results with the navigation system. Eye glances to in-vehicle instruments, mirrors, and roadside signs and landmarks were low-frequency occurrence and largely constant (1%-3% each). Combined, they accounted for 4%-6% of glances. The increase in visual attention by a navigation condition drew attention away from the forward road and its neighboring roadway. There was a wide range of eye glances across different conditions. The percentage of glances ranged from 57%-85% for the forward roadway and 7%-19% for the left or right roadway. Combined, the percentage of glances to the forward, left, and right roadway ranged from 62%-92%. The percentage of glances to paper directions/maps or navigation systems ranged from 7%-33%.

Fairclough and Parkes (1990) tested 20 subjects to compare the eye glance behaviors between the paper map and computer direction conditions. Mean glance duration was 1.8 s for the paper map condition (60% between 1-2 s, and 30% between 2-3 s, and 10% between 3-5 s), and 1.3 s for the computer direction condition (80% between 1-2 s, 18% between 2-3 s, and 2% between 3-5 s). The mean total glance frequency was 234 and 160 for the paper map and computer direction conditions.

Fairclough and Parkes (1990) further revealed that for the paper map condition, subjects spent 1 s looking at the paper map for every 3 s looking at the forward road. For the computer direction condition, they spent 1 s looking at the computer direction for every 7 s looking at the forward road. For the control condition, 92% of glances were on the roadway, 2.3% on the rearview mirror, and 1.5% on the dashboard. For the paper map condition, 67.2% of glances were on the roadway, 1.7% on the rearview mirror, 0.2% on the dashboard, and 22.1% on the paper map. For the computer direction condition, 76.1% of the glances were on the roadway, 2.3% on the rearview mirror, 0.3% on the dashboard, and 12.1% on the computer direction. Clearly, compared with the control condition, there was a "visual cost" (glances away from the roadway) with navigation aids. Compared with the paper map condition, however, there was a clear advantage of using the computer direction in driving.

Fairclough, Ashby, and Parkes (1993) compared the glance behavior for map and navigation condition. They found an increase in visual attention to the map display at the expense of other driving scenes. An increase of eye glances to navigation display may lead to a decrease of eye glances to driving scenes such as rear view mirror, right-side mirror, and the roadway ahead. Consistent with the literature, glance duration appears to be more sensitive to the difficulty of the information uptake from an in-vehicle display, and this difficulty may be grounded in the legibility of the interface, its layout or the amount of information contained.

Brooks, Nowakowski, and Green (1999) installed both a turn-by-turn display and a map display for navigation systems, and studied which display subjects would use more frequently. They discovered that the turn-by-turn display was looked at 3.75 times more often than the map display. The location of the display also affected the glance frequency for each display. When the turn-by-turn display was on the right side of the steering wheel (and the map display on the left side), over 85% of the glances were made to the turn-by-turn display. Conversely, when the turn-by-turn display was on the left side, only 72% of the glances were made to the display. Therefore, the preferred display position would be on the right side of the steering wheel, as drivers are most accustomed to looking in that direction. The turn-by-turn display was used more frequently because it contained many different forms of information that the user could utilize (e.g., distance to turn, countdown bar, turn direction arrow, next road), while the route map display indicated the route and various cross-street names only. Once a glance was made to a particular display, the second glance was more likely to the same display.

Brooks, Nowakowski, and Green (1999) revealed different time courses in eye glance behaviors for the turn-by-turn display and map display. For the turn-by-turn display, a burst of glances usually occurred at the beginning of the segment, averaging 12.2 glances per mile per subject. Thereafter, the glance rate for the turn-by-turn display lowered to a steady rate, averaging 6.8 glances per mile per subject. For the map display, glances to the display were almost uniform throughout each of the segments, averaging 2.0 glances per mile per subject.

To summarize, visual glance behaviors are not markedly different between conventional and navigation tasks. The mean glance duration is shorter than 2 s for both tasks. The total glance duration and the number of in-vehicle glances vary based on the display information, demonstrating an advantage of a simple display such as the turn-by-turn display. Comparing to paper maps, there is a clear advantage of using a computer route guidance system.

7.7.2. Effects of Task Complexity and Display Characteristics on Eye Glance Behaviors

As indicated in the preceding section, display complexity is a major factor of visual glance behaviors. The effects of task complexity and display characteristics on visual glance behaviors are further examined in this section.

Glance duration and frequency to an in-vehicle display are dependent upon the display characteristics such as character size and information density and the complexity of the non-driving tasks. Rockwell (1988) argued that mean glance duration is sensitive to design. Compared to large displays and controls, small displays and controls can produce a 20% increase in mean glance duration. Faerber, Faerber, and Meier-Arendt (1999) demonstrated that more glances to the device were associated with manual tasks than with speech tasks. Whereas manual radio/CD tasks took three 1-s glances, dialing a telephone number required twelve 1-s glances.

Labiale (1996) studied eye glance behavior to in-vehicle text. Fifty-four subjects drove an instrumented vehicle, while reading a text message. Four message lengths were used: 3-4, 6-8, 10-12, and 14-18 information units. Information units were defined as relevant words in a message. For example, a 4-unit message could be "Road construction ahead at Jaspertown." Table 7.11 presents the glance duration and frequency as a function of message length. As the message length increased from 3-4 units to 14-18 units, the increase in glance frequency was over 4-fold, but the increase in mean glance duration was approximately 25%.

Table 7.11. Labiale's (1996) glance results: Mean (SD)

Message length	3-4 units	6-8 units	10-12 units	14-18 units
Glance duration	1.08 s (0.43)	1.18 s (0.58)	1.20 s (0.57)	1.35 s (0.60)
Glance frequency	3.8 (1.6)	6.9 (2.6)	9.6 (2.8)	15.5 (5.5)
Text Recall	100%	97.5%	75.4%	52.4%

Dingus and his colleagues (Blanco, 1999; Blanco, Dingus, & Hankey, 2001; Dingus, 1987) have classified the in-vehicle tasks under categories of low, medium, high, or very high attention demand using the measure of total glance duration. They adopted the following classification system: Attention demand for a particular task is regarded as low if total glance duration is less than 1 s, medium if it is between 1 to 2.5 s, high if it is between 2.5 to 4 s, and very high if it is over 4 s. Blanco (1999) measured the number of glances, peak glance duration, the total glance duration in various tasks. The results are presented in Table 7.12. Using their classification system, it was found that there was no task with low attention demand, one task with medium attention demand, 3 tasks with high attention demand, and the rest (40 tasks) with "very high" attention demand.

Table 7.12. Blanco's (1999) results: Mean (SD)

Display Type	Task Type	Information Density	Total Glance Duration	Number of Glances	Peak Glance Duration
Table	Search	Low	3.60 (0.76)	3.17	1.75
Paragraph	Search	Low	5.79 (1.47)	4.00	2.56
Graph with icon	Search	Low	2.11 (0.94)	1.83	1.67
Table	Search	Medium	4.29 (1.35)	3.08	2.37
Paragraph	Search	Medium	11.11 (1.61)	7.67	2.59
Graph with text	Search	Medium	3.09 (1.01)	2.58	2.02
Graph with icon	Search	Medium	3.21 (1.16)	2.58	1.97
Table	Search	High	5.45 (2.02)	3.67	2.47
Paragraph	Search	High	11.83 (4.15)	8.17	2.31
Graph with text	Search	High	4.33 (1.25)	3.25	2.45
Graph with icon	Search	High	8.11 (4.93)	5.58	2.49

Table	SC	Medium	10.18 (3.81)	7.33	2.48
Paragraph	SC	Medium	16.68 (9.44)	12.67	2.42
Graph with text	SC	Medium	11.66 (4.28)	9.25	2.39
Table	SC	High	13.59 (5.26)	9.92	2.32
Paragraph	SC	High	18.27 (10.80)	13.33	2.30
Graph with text	SC	High	20.65 (9.03)	15.50	2.18
Table	SP	Low	13.79 (6.43)	10.92	1.97
Paragraph	SP	Low	14.70 (7.49)	10.67	2.90
Graph with icon	SP	Low	11.00 (3.36)	8.17	2.77
Table	SP	Medium	10.10 (1.90)	7.92	2.10
Paragraph	SP	Medium	17.99 (5.91)	13.33	2.20
Graph with text	SP	Medium	9.56 (3.24)	6.50	2.93
Graph with icon	SP	Medium	10.31 (4.42)	8.33	2.10
Table	SP	High	16.47 (5.73)	12.58	2.42
Paragraph	SP	High	26.07 (15.26)	19.50	2.58
Graph with text	SP	High	16.46 (8.10)	13.25	2.51
Graph with icon	SP	High	13.85 (4.59)	9.58	3.08
Table	SPC	Medium	10.94 (3.87)	8.00	2.68
Paragraph	SPC	Medium	19.51 (6.82)	13.17	3.34
Graph with text	SPC	Medium	7.82 (1.74)	5.17	2.72
Table	SPC	High	13.67 (5.00)	9.75	2.48
Paragraph	SPC	High	24.89 (14.44)	18.00	2.46
Graph with text	SPC	High	17.93 (7.24)	12.42	2.40
Table	SPI	Low	10.52 (4.07)	9.00	1.96
Paragraph	SPI	Low	16.69 (4.20)	12.67	2.56
Table	SPI	Medium	12.34 (4.84)	9.92	2.79
Paragraph	SPI	Medium	18.17 (5.76)	13.17	2.18
Graph with text	SPI	Medium	10.02 (3.29)	7.42	2.47
Graph with icon	SPI	Medium	11.44 (3.59)	9.25	2.41
Table	SPI	High	14.72 (4.56)	11.83	2.40
Paragraph	SPI	High	22.39 (15.09)	16.92	2.46
Graph with text	SPI	High	18.09 (9.11)	14.92	2.29
Graph with icon	SPI	High	15.99 (6.29)	11.25	2.83
Table	SPIC	High	18.23 (9.31)	14.00	2.61
Paragraph	SPIC	High	21.72 (12.69)	16.58	2.38
Graph with text	SPIC	High	17.39 (7.08)	13.25	2.60

Note. SC = search-compute. SP = search-plan. SPC = search-plan-compute. SPI = search-plan-interpret. SPIC = search-plan-interpret-compute.

7.7.3. Effects of Driving Task Demand on Eye Glance Behaviors

Depending on the demand imposed by the driving task, drivers dynamically allocate visual attention. Driving task demand is determined by factors such as road geometry (e.g., straight vs. curved roads), traffic situation (e.g., whether a lead vehicle is present), and weather condition (e.g., presence of crosswind). In this section, these factors and their effects on visual glance behaviors are examined respectively.

7.7.3.1. Road Geometry

Visual glance behaviors appear to vary with road geometry. Although the focus of expansion is the primary source of information typically used by the driver (Gibson, 1950), there are reasons to believe that the primary source may be a function of the vehicle speed and road characteristics. Bartmann, Spijkers, and Hess (1991) found that eye glances to lane features, driving-related features, and non-driving-related features are affected by road type (e.g., urban vs. rural) and travel speed (e.g., 30, 50, or 80 km/h). Jurgensohn, Neculau, and Willumeit (1991) performed a curve negotiation experiment using a fixed-base simulator. For a curved motion, there was no longer a focus of expansion, and accordingly drivers did not look at the focus of expansion. Drivers used roadway boundaries and lane markings in aligning the moving vehicle with the roadway. They looked at approximately 15-40 m ahead of their vehicle. This preview distance was longer for large curvature radii. These results confirmed the hypothesis that the driver's scanning behavior depends on the road geometry.

Similarly, Land and Horwood (1996) investigated the eye glance behaviors during curve negotiation. They demonstrated that the head, eye, and gaze movements were different during the entry, in the curve, and during the exit. During the entry, the eye gaze was directed to the direction of the turn about 2 s before the beginning of the turn. The time course was similar for tight and gentle curves—The eyes switched between the direction of the turn and the vehicle heading. These were likely ranging movements that the visual system used to form an estimate of the road curvature. In the curve, the driver kept looking at the direction of the turn (near the tangent point of the curve). In the 15-m curve, this phase was almost non-existent, because the driver had already begun to fixate at targets beyond the curve. In the 40-m curve, it lasted for 2-3 s. During the exit, drivers' gaze was directed to distant objects beyond the curve.

Similar results were obtained for motorcycle driving. Mortimer and Jorgeson (1975) compared the eye glance behaviors of 2 motorcyclists who first drove a motorcycle and later a car on two-lane rural roads at about 45 MPH, in daytime. They found that most of the drivers' attention was directed within 5° of the forward line of sight, but on curved roads, the drivers' eye fixations shifted in the direction of the curve. They found considerable agreement in eye glances between motorcycle driving and car driving, although the motorcycle drivers attended more to oncoming vehicles.

The mean glance duration is also affected by road geometry. Rockwell (1988) concluded that the mean glance duration was mediated by highway geometry. Osaka (1991) obtained strong evidence suggesting a reduction of fixation duration in curved roads as compared with the straight road condition.

Tsimhoni and Green (2001) instructed subjects to find street names and icons (e.g., "What street are you on?") on a static map display while driving. They argued that visual demand was higher for curved roads and lower for straight roads. As shown in Table 7.13, mean glance duration was shorter on curved roads (with higher visual demand). In addition, Tsimhoni, Smith, and Green (2002) instructed subjects to enter destination address manually using a keyboard while driving. As shown in Table 7.13, mean glance duration to in-vehicle display was 1.4 s for straight roads and 1.1 s for sharp-curved roads, the number of glances was 21.9 for straight roads and 33.1 for sharp-curved roads, and the time between glances was 1 s for straight roads and 1.4 s for sharp-curved roads. As shown in the table, the total glance duration did not change significantly with road curvature.

Although some differences exist between Tsimhoni and Green (2001) and Tsimhoni, Smith, and Green (2002), their patterns were similar. On curved roads, mean glance duration to the in-vehicle display was shorter, the glances back at the road were longer, and more glances to the in-vehicle display were made.

Table 7.13. Road geometry and glances to in-vehicle display

	Tsimhoni & Green (2001)			Tsimhoni, Smith, & Green (2002)		
	Straight	Curved	Difference	Straight	Curved	Difference
Total glance duration	5.0	4.2	-16%	30.1	34.0	+13%
Mean glance duration	2.3	1.4	-39%	1.4	1.1	-21%
Time between glances	1.1	1.8	+64%	1.0	1.4	+40%
Number of glances	2.6	3.5	+35%	21.9	33.1	+51%

In short, eye glance behavior varied based on road geometry and driving task demand. Indeed, "the driving task difficulty was the single most important factor affecting fixation duration" (NHTSA public meeting, 2000, p. 77). Drivers tend to adapt their visual glance behaviors to maintain a certain level of performance.

7.7.3.2. Traffic Situation and Driving Scenarios

Visual glance behaviors vary with traffic situations. A study by Wierwille, Hulse, Fischer, and Dingus (1988), cited in Wierwille (1993a, 1993b), demonstrated that mean glance duration to the forward scene increased from the light traffic condition (1.2 s), to the heavy traffic condition (1.9 s), and to the "possible incident" condition (3.0 s). Conversely, the probability that the eyes were on the navigation display decreased from the light traffic condition (31%), to the heavy traffic condition (26%), to the "possible incident" condition (19%).

Eye glance behaviors vary based on different driving scenarios. Carter and Laya (1998) demonstrated that during the overtaking maneuver, drivers spent more time looking at the left lane and the rearview mirror and less time looking at the dash and instrument panel, in comparison to non-overtaking. Lee, Olsen, and Wierwille (2002) studied the eye glance behaviors prior to lane change maneuvers. They discovered that drivers glanced to the forward scene at least once during the 3 s before a lane change maneuver. This result indicated the importance of visual sampling of the forward road for lane change.

Mourant and Rockwell (1970) demonstrated that eye glance patterns were different depending on whether subjects followed a lead vehicle. Eye fixations were closer in the vehicle-following scenario (75 ft) than when drivers did not follow a lead vehicle (100 ft).

Tijerina (1999a) performed an on-road study to investigate driver eye glance behavior during the vehicle-following scenario. Sixty subjects drove an instrumented car on highways and city roads. For the purpose of data analysis, a vehicle-following epoch began when a lead car was in the same lane, and ended with one of the following events.

- The lead vehicle left the travel lane
- The following vehicle changed lanes
- Another vehicle cut in between
- Vehicles were separated by a distance detectable by the sensor

A total of 2,913 vehicle-following epochs were obtained. Subjects' eye glances were videotaped and a total of 77,000 eye glances were analyzed. Tijerina (1999a) discovered that on average, drivers spent approximately 86.3% of the time per vehicle-following epoch, with the eyes on the forward road (SD of 9.8%). Drivers did look away from the road, and they did so when the range rate was effectively zero. Range or time headway did not appear to influence the timing of the off-road glances. Basically, drivers assumed that the lead vehicle would 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 factor contributing to rear-end crashes. Driver expectations are sometimes violated and the driver has not allotted sufficient distance and time to recover.

Tijerina (1999a) discovered that most of the off-road glances were directed toward objects in the vehicle interior area or rearview mirror. Eye glances on the left mirror and over the left shoulder were more frequent than on the right mirror and over the right shoulder. The longer the vehicle-following epoch, the more frequent the off-road glances.

Consistent with the literature, Tijerina (1999a) demonstrated that mean off-road glance duration was not affected by range, range rate, or travel speed. Most of the off-road glances were short, in support of a well-known strategy that drivers have to keep glance durations below 2 s (Wierwille, 1993a; Rockwell, 1988). Approximately 85% of the off-road glances were less than 1 s, 12.5% between 1-2 s, and only 2.5% over 2 s. The mean off-road glance duration was 0.60 s (SD of 0.46 s). These values were remarkably shorter than those reported by Rockwell (1988). For glances on the left mirror, Tijerina (1999a) found a mean of 0.56 s and a standard deviation of 0.39 s, whereas Rockwell (1988) found a mean of 1.1 s and a standard deviation of 0.3 s. This difference demonstrated the effect of driving scenarios. The off-road glances were considerably shorter (about 0.5 s) in the vehicle-following scenario (Tijerina, 1999a) than when no lead vehicle was present (Rockwell, 1988).

7.7.3.3. Weather Condition

Weather is a major factor influencing the allocation of visual attention. Under poor conditions, the attentional demand imposed by the driving task is high and accordingly, attention to non-driving tasks would be reduced.

This hypothesis has received support in the literature. Kurokawa and Wierwille (1990) discovered an increase of glance duration to the forward road and a decrease of glance duration to an in-vehicle display when random crosswind increased. When no random crosswind was present, mean glance duration was 0.9 s for the forward road and 1.1 s for the in-car display. When the level of random crosswind was moderate, mean glance duration was increased to 1.0 s for the forward road and decreased to 0.87 s for the in-car display. When the random crosswind was strong, mean glance duration was increased to 1.2 s for the forward road and decreased to 0.8 s for the in-car display. When the crosswind was maximum, mean glance duration was increased to 1.3 s for the forward road and decreased to 0.8 s for the in-car display.

7.7.4. Effects of Driver Age, Experience, and Route Familiarity on Eye Glance Behaviors

Individual differences exist in the manner that drivers allocate visual attention to driving and non-driving tasks. They can be attributed to factors including driver age, experience, and drivers' familiarity with the environment. These factors are interrelated. Driver age and experience are correlated because experienced drivers are typically older than novice drivers. Despite the correlation, however, these factors will be examined separately, based on the factor of interest reported by researchers.

7.7.4.1. Driver Age

Although the definition of age categories (e.g., young vs. old drivers) has been inconsistent across different studies, the effect of driver age has been reliably demonstrated. Rockwell (1988) showed mean glance durations for the radio and left mirror as a function of driver age (young than 35 years old vs. older than 45 years old) and gender. The results in Table 7.14 showed that the older drivers and male drivers had slightly longer mean glance durations than did their counterparts.

Table 7.14. Mean glance duration as a function of driver age and gender

	Young	Mature	Total
Male	1.43 (1.09)	1.56 (0.98)	1.50 (1.05)
Female	1.33 (1.07)	1.35 (1.00)	1.34 (1.03)
Total	1.39 (1.08)	1.46 (0.99)	1.42 (1.05)

Note. Mean glance duration results are reported in the format of radio (left mirror).

Hayes, Kurokawa, and Wierwille (1989) studied the driver age effect using three age groups (18-25, 26-48, and 49-72 years old) and concluded that the older subjects (49-72 years old) required significantly more glances to the in-vehicle display, longer total glance duration to the display, and longer glance duration to the display in order to retrieve necessary information for successful completion of the in-vehicle task. The older drivers required significantly more time to move their eyes between the roadway and in-vehicle display. In addition, they required considerably more time to complete the in-vehicle tasks.

Similar results were found in other studies. Snyder and Monty (1986) had 32 younger subjects (18-25 years old) and 32 older subjects (45-70 years old) drive 2-lane and 4-lane highways, state roads, or city/town roads. Subjects were asked to perform the radio tasks (e.g., seek, balance, or pre-select), HVAC tasks (e.g., mode or temperature selection), and no secondary task (baseline). They discovered that the older drivers required more glances to an in-vehicle display than did the younger drivers. In addition, older female drivers required more glances than did older male drivers, although no sex difference was found for the younger drivers.

From the ETAK study, Wierwille, Antin, Dingus, and Hulse (1988) revealed that the older subjects (over 50 years old) took a greater amount of time to complete the tasks, looked at the navigation display and dash instrumentation longer, and made a greater number of errors than did the younger subjects.

Using the TravTek system, Dingus, Hulse, Mollenhauer, Fleischman, McGehee, and Manakkal (1997) studied the driver age effect. In one experiment, 18 visitors to the Orlando area were divided into three age groups (younger: 16-18 years old; middle-aged: 35-45 years old; and older: 65-73 years old). The older participants had the longest mean glance duration to the in-vehicle display for all conditions except the "route map without voice" condition, although the difference was small. A close correlation was demonstrated between eye glances to the in-vehicle display and the number of lane departures. The older drivers had considerably more glances of long duration (over 2.5 s) and consequently, considerably more lane departures than did the younger and middle-aged drivers. On the other hand, the older drivers had lower variances in longitudinal and lateral acceleration than did the younger drivers, suggesting that they drove more cautiously than did the younger drivers.

In Tijerina, Parmer, and Goodman (1998), subjects drove an instrumented car and discovered that the older drivers (over 55 years) took more time to finish a POI entry (118 s) than did younger drivers (younger than 35 years) (66 s). The older drivers took their eyes off the forward road for longer time than did the younger drivers (83 vs. 40 s) and consequently, the older drivers had noticeably more lane departures than did younger drivers (0.8 vs. 0.18 per trial).

Analogously, Tsimhoni, Smith, and Green (2002) instructed subjects to manually enter destination address using a keyboard. The total glance duration was 26 s for the younger subjects (20-29 years old) and 38 s for the older subjects (65-72 years old), nearly a 50% increase. The mean glance duration to the in-vehicle display was 1.4 and 1.1 s, the number of glances was 20.6 and 34.5, and the mean time between glances was 0.9 s and 1.6 s for the younger and older subjects, respectively.

Maltz and Shinar (1999) argued that in comparison to the younger drivers, the older drivers have poorer peripheral vision and smaller useful field of view. Defining fixations as eye gazes of 100 ms or greater within a 1^0 of visual area, they did not find any age difference in mean fixation durations. However, the older drivers focused on a small number of areas rather than glanced at visual areas more evenly. Overall, the older drivers had poorer sustained attention.

In a study by Mourant, Tsai, Al-Shihabi, and Jaeger (2000), ten younger drivers (23-46 years old) and ten older drivers (58-76 years old) drove a 1985 Dodge Caravan. Subjects were asked to report digits shown on an in-vehicle display located at 18° below the horizon and 32° to the right of the focus of expansion, or digits superimposed on the driving scene. The digits may be presented at inter-stimuli intervals of 2.4, 1.8, 1.2, and 0.6 s. The percent correct of digits reported was consistently higher for the younger drivers than for the older drivers, especially at shorter inter-stimuli intervals. The lane position error was greater for the older subjects than for the younger subjects. So was the time spent outside of the lane boundaries.

These studies clearly illustrated the driver age effect in visual glance behavior and associated driving performance. Older drivers required considerably longer total glance duration and greater number of glances to the in-vehicle display, and consequently resulted in longer task completion time and greater number of lane departures. These results suggested that an in-vehicle advanced transportation information system is a two-edged sword for older drivers because with advancing age, drivers experienced diminished perceptual and cognitive abilities that made it difficult to use in-vehicle displays.

7.7.4.2. Driver Experience

Although driver experience is often related to driver age, it has been studied independently. Major findings with respect to driver experience are summarized in the following paragraphs.

Mourant and Rockwell (1970) discovered that novice drivers had the tendency to search a smaller area of visual scene and that this area was closer to the car. They made fewer fixations on the mirrors. This discovery supports the hypothesis that novice drivers have "perceptual narrowing", a shrinking of peripheral visual field. The novice drivers made longer fixations and more pursuit tracking eye movements than did the experience drivers. The novice drivers fixated at lane control markers more frequently, whereas the experienced drivers typically fixated at the vanishing point of the horizon at the greater distance from the vehicle.

Land and Horwood (1995) revealed that the experienced drivers extracted information about road layout from two main sources: a far location approximately 16 m ahead (4° below the horizon), and a near location approximately 9 m ahead (7° below the horizon). The far point provided information on the curvature of the road allowing a smooth drive, whereas the near point provided information on the driver's position relative to immediate lane markers, allowing lane maintenance. When subjects viewed the road, they had the tendency to fixate at the far location, with very few fixations at the near location, suggesting that the information for lane maintenance was acquired through peripheral vision.

Mourant and Rockwell's (1970) results suggested an experience effect for lane keeping behavior. This effect is obtained by Summala, Nieminen, and Punto (1996). They discovered that experienced drivers were able to utilize para-foveal or peripheral vision to maintain lane position, whereas novice drivers were more dependent on foveal visual sampling to control the lateral vehicle position.

Summala, Lamble, and Laakso (1998) found that driving experience did not have an effect on reaction time. This suggests that detection of closing-headway situations with peripheral vision does not improve with driving experience as lane-keeping performance does. This could be due to differential practice effect. Because lane keeping is continuous and always functional, and detection of lead vehicle braking occurs only in a vehicle-following scenario and is infrequent, drivers tend to receive more practice on lane keeping performance than on detecting the braking of a lead vehicle. In addition, less learning could occur for responses to closures or brake lights because of a natural stimulus-response mapping between the closures or brake lights and the braking responses.

Crundall and Underwood (1998) found that on average, experienced drivers had shorter fixation durations than did novice drivers. Fixation duration was also dependent on the road type. On rural roads, experienced drivers had longer fixation durations than novice drivers. On suburban and "dual carriageway" roads, experienced drivers had shorter fixation duration than novice drivers.

Nieminen and Summala (1994) asked 26 experienced drivers (with over 150 km driving) and 23 novice drivers (with less than 5 Km driving) to drive an instrumented car on a 126-km route including city streets and rural roads. Little group difference was found in terms of eye glances at in-vehicle tasks and the forward road, or in terms of lane keeping performance. The only difference was in the speed control. All groups slowed down at the beginning of a secondary task, and while experienced drivers were able to restore their speed level, the novices' speed decreased evenly through the first twenty seconds.

In contrast, Lansdown, Parkes, Fowkes, and Comte (1999) and Carter and Laya (1998) found a significant effect of experience. Lansdown, Parkes, Fowkes, and Comte (1999) studied experienced drivers (over 8 years of driving experience) and novice drivers (with 10 hr of tuition, not passed the UK driving test). The results are presented in Table 7.15.

The novice drivers deviated out of the lane boundaries significantly more often than did the experienced drivers. They glanced at the in-vehicle entertainment system (e.g., radio/cassette functions) more frequently and for longer durations than did the experienced drivers. They spent a significantly greater percentage of time away from the forward view than did the experienced drivers. These results support the hypothesis that increased distraction from the forward view results in decreased lane keeping performance. Novice drivers spent significantly more total time glancing to the instrument panel than the experienced drivers. Similarly, Carter and Laya (1998) found experienced drivers spent more time on the focus of expansion and less time on the dash, compared to inexperienced drivers.

Table 7.15. Glance duration, frequency, and percentage for experienced and novice drivers: Mean (SD) (from Lansdown, Parkes, Fowkes, & Comte, 1999)

	Experienced drivers	Novice drivers
Glance duration (s)	0.66 (0.14)	0.79 (0.16)
Glance frequency	2.01 (0.50)	2.23 (0.61)
Time away from forward view	6.40% (2.30%)	11.8% (3.1%)
Glance time to instrument panel	4% (1.6%)	8.7% (2.8%)

7.7.4.3 Route Familiarity

In addition to driver age and experience, drivers' familiarity with the driving route may play an important role in determining visual sampling strategies. This is evident in Mourant and Rockwell (1970). They analyzed the eye glance behaviors of eight drivers, while driving on the same route repeatedly. During the first exposure, the drivers sampled a wide area in the forward scene. After they gained knowledge of their route (e.g., during the third exposure), visual sampling was confined to a smaller area. As the route became more familiar, drivers increased glances to the right edge marker and the horizon. While following a car, drivers glanced more frequently at lane markers.

7.8 DESIGN GUIDELINES AND PROTOCOLS

Because of the large body of human factors literature in the area of visual distraction, it is natural and also useful to extract major findings from the literature and establish design guidelines and protocols that can be used by product designers and engineers so that the amount of visual distraction can be minimized. A necessary step would be the development of protocols (including measures and methods) to evaluate performance impact of different design alternatives. The following questions are frequently asked.

- What is an acceptable and what is an unacceptable level of visual distraction?
- What is safe and what is not safe?
- What are red-line (severe) and yellow-line (cautionary) thresholds?

Before proceeding, it is important to point out that the determination of thresholds is extremely difficult. It may be a sociopolitical decision because the threshold values should be accepted by the general public (Hancock, & Ranney, 1999; Hancock, Simmons, Hashemi, Howarth, & Ranney, 1999; Tijerina, 1999b). Establishing standards and guidelines is time-consuming and often controversial (Green, 2000, 2002).

An early attempt was made by Zwahlen, Adams, and DeBald (1988). As depicted in Figure 7.4, they proposed a maximum of 4 glances, with a maximum of 2 s per glance. It should be noted that four 2-s glances fall into the "unacceptable region". They believed that four intermittent glances within a short period of time (e.g., 4 s) were unacceptable because the amount of road and traffic information available in visual working memory was below the threshold value. Further, SDLP and lane departures reached an unacceptable level after 2-4 s of visual occlusion.

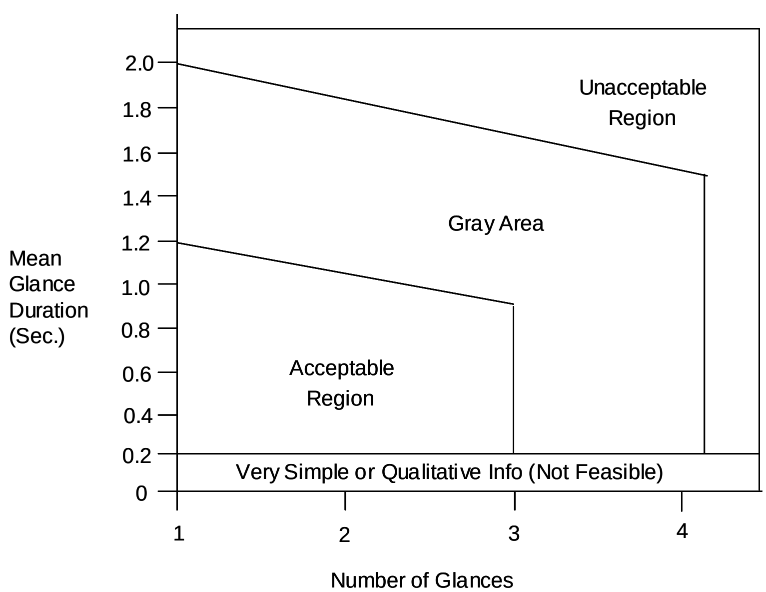

Figure 7.4. Zwahlen, Adams, and DeBald's (1988) recommendation.

Zwahlen, Adams, and DeBald's (1988) recommendation may represent the conservative extreme of the continuum. It has been argued that "you can go higher in terms of number of glances in certain circumstances and still be relatively safe" (Dingus' statement at NHTSA public meeting, 2000, p. 82). Blanco, Dingus, and Hankey (2001) defined the "red-line" threshold as the point at which driving would be substantially degraded, based on a priori criteria, and defined the "yellow-line" threshold as the point at which driving performance is significantly different from that obtained from a set of baseline driving measures (e.g., $p<0.05$). Blanco (1999) proposed a red-line threshold of 9 or more glances for glance frequency to in-vehicle displays, and a red-line of 2.5 s for peak glance duration. A threshold of 2.5 s was proposed because Bhise, Forbes, and Farber (1986) suggested that any glances longer than 2.5 s were inherently dangerous.

Several national or professional organizations have attempted to establish formal design guidelines and protocols. A significant amount of research has been conducted on the development of driver distraction and workload metrics and methods. In the following paragraphs, the formal guidelines and protocols are reviewed.

7.8.1. The European Statement of Principles on Human Machine Interface

The European principles of human machine interface pertained to both portable and permanently installed systems. They reinforced the notion that the driver's primary task is vehicle control, and the driver's interactions with in-vehicle systems should not impair the driver's ability to control the vehicle safely and respond to unexpected occurrences promptly. Many of the principles suggested methods to present information in order to minimize visual distraction. At present, the proposed guidelines are general in nature, some of which are presented below.

- The system should be designed to support the driver and should not give rise to potentially hazardous behavior by the driver or other road users.
- The system should be designed in such a way so that the allocation of driver attention to the system displays or controls remain compatible with the attentional demand of the driving situation.
- The system should be designed so as not to distract or visually entertain the driver.
- Visual displays should be positioned as close as practicable to the driver's normal line of sight.
- The system should not require long and uninterruptible sequences of interactions.
- Visual information not related to driving that is likely to distract the driver significantly (e.g., TV, video and automatically scrolling images and text) should be disabled or should only be presented in such a way that the driver cannot see it while the vehicle is in motion.
- Visually displayed information should be such that the driver can assimilate it with a few glances that are brief enough not to adversely affect driving.

With respect to the final principle listed above, human factors professionals in Europe have discussed the allowable glance frequency and glance duration. Hoedemaeker, de Ridder, and Janssen (2002) contended the following.

> European experts, working on the further specification and expansion of the principles, are considering the proposition that four glances off the road for not longer than two seconds each for any glance should be considered as a practical limit. Thus, five glances off the road would always be considered unacceptable, however brief they are. (p. 9)

7.8.2. The JAMA (2000) Guidelines

The JAMA guidelines apply to both OEM- or dealer-installed in-vehicle displays that are visible to drivers. They are intended to minimize the amount of visual distraction (e.g., glance duration and gaze eccentricity). It is stipulated that visual images on the display screen shall be simple and easily understood in a short time. The display of travel time shall be easily recognized at a glance and obtained without requiring complex calculation by the driver. Minor roads should not be displayed on the navigation map screen. Televised picture, video images, addresses and telephone numbers, descriptive information for hotels and restaurants shall not be displayed on the screen while a vehicle is in motion.

A maximum of 31 characters (mixed Chinese characters and alphabetic characters) is permitted for the presentation of traffic information. According to Green (1999b), that is equivalent of 128.5 alphabetic characters, or approximately eighteen 7-character words. With the reading speed of 2-3 words per second, that is translated into 9 s reading time.

The JAMA guidelines further stipulate that the display should be mounted in a position with a no greater than 30° downward viewing angle. The downward angle is the angle between two lines that project on the vehicle's Y plane. The first line should be drawn from the Japan Industrial Standard eye-point parallel to the X-axis, and the second line should be drawn from the center of the display to the Japan Industrial Standard eye-point.

7.8.3. The IVIS Demand (In-Vehicle Information System Design Evaluation and Model of Attention Demand)

Hankey, Dingus, Hanowski, Wierwille, Monk, and Moyer (2000) adopted a behavioral model that was comprised of five types of driver resources: visual demand, auditory demand, supplemental information processing (SIP) demand (e.g., cognitive processing to determine the correct response and decision), manual demand, and speech demand. They developed an In-Vehicle Information System (IVIS) Demand program to assist human factors designers and engineers to evaluate the workload and demands placed on the driver by IVIS designs. It can be used to compare two or more candidate IVIS designs, evaluate an upgrade for a current design, or evaluate a given design or task against a set of benchmark criteria.

Currently, there are approximately 200 tasks built into the task library, which may be selected for input into the program. It included visual, manual, SIP, auditory, and speech tasks and combination tasks. For example, the visual tasks included checking mirrors to determine if an object exists, and checking speedometer, odometer, or warning lights. Visual-manual combination tasks included adjusting mirrors and temperature, tuning radio, and inserting cassette or CD. Visual-SIP combination tasks included finding a hotel from a display that varies in information complexity (e.g., low, medium, or high-density) and display type (e.g., paragraph, icon, table, or text). It has not included tasks requiring the use of a keypad or keyboard. Nor has it included advanced-technology functions such as wireless email, wireless Internet, and route guidance. However, the task library is expandable to incorporate new findings.

The IVIS Demand program uses nominal values, which are applicable to all age groups of drivers, moderate traffic density and roadway complexity. The nominal values may be changed to better reflect the task condition and user characteristics. Once the input values are specified for a particular task or design, output values are presented for various measures in a summary table, or in a "figure of demand" model. Output measures include visual resource measures (e.g., mean glance duration, mean number of glances, mean eye transition time, and total glance duration), auditory resource measures (e.g., mean message duration), manual resource measures, speech resource measures, SIP resource measures, and overall measures (e.g., time to complete task, expected percentage of drivers unable to complete the task). These output measures can serve as the design criteria to evaluate multiple tasks and devices.

7.8.4. Human Factors Design Guidelines for Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO)

Under the sponsorship of Federal Highway Administration, Campbell, Carney, and Kantowitz (1997) drafted detailed guidelines that can be used by human factors professionals during the conceptualization, development, design, and evaluation of in-vehicle devices. Recommendations were put forward for the design of displays, controls, warnings, presentation of routing and navigation information, and presentation of signage information. For design of visual displays, guidelines were proposed for symbol contrast, color, font, height, width-to-height ratio, and spacing.

They proposed to tailor the information presentation to fit drivers' preferences and driving requirements, particularly for information requiring immediate compliance. Based on the results from Labiale (1996) that were described earlier in this report, they proposed to restrict the number of information units to four in order to minimize the eyes-off-road time.

7.8.5. SAE J2364 (the 15-Second Rule)

In 1999, J2364, the so-called 15-second rule, was approved as a Recommended Practice by the Safety and Human Factors Committee of the Society of Automotive

Engineers (SAE). It was rejected by the SAE ITS Division for lack of consensus, and was returned to the Safety and Human Factors Committee to build a greater consensus. SAE J2364 applies to both OEM and aftermarket route-guidance and navigation system functions for passenger vehicles. It applies to only visual-manual interfaces, but not voice-based interfaces.

SAE J2364 is a performance standard, not a design standard (Society of Automotive Engineers, 2000). It recommends a 15-s threshold as the maximum time for completion of navigation-related tasks involving visual displays and manual controls (Green, 1999b, 2002). For evaluation purpose, it recommends the use of operational systems fitted to the vehicle, buck, or mock-up in the design intent location, using 5-10 subjects of 45-65 years old. Subjects will be provided with a clear explanation of the system operation and the task of interest, and afforded five practice trials prior to actual testing. It recommends individual testing in a static single-task situation (e.g., when the vehicle is in park). Tasks will be timed from start to finish without interruption, including error times, except for computationally interrupted tasks.

For every subject, a mean task completion time will be calculated from three test trials to determine whether the 15-s threshold has been exceeded. If five out of five subjects complete a task within 15 s, the function/task passes. If eight out of ten subjects complete the task within 15 s, the function/task passes. If at any point, three subjects exceed the 15-s threshold, the function/task fails. A practical result of the 15-second rule is that most destination entry tasks will not pass the rule and therefore will not be allowed in moving vehicles.

The logical basis of J2364 is as follows. Lane departure is a safety-relevant performance measure, and it is positively correlated with the number of eye glances to in-vehicle device. In turn, the number of eye glances is positively and highly correlated with the task completion time, either dynamic (in a moving vehicle) or static (in a parked vehicle). Because measurement of eye glances was difficult and time-consuming, task completion time was chosen as the safety and usability measure for J2364. The 15-s threshold was chosen because the literature suggested that one minute was too long, three seconds were too short, and the approximate threshold was in the range of 9-12 s (Green, 1999b).

The validity of the 15-second rule was assessed by Tijerina, Johnston, Parmer, Winterbottom, and Goodman (2000). Ten 55-69 years old subjects (five male and five female) drove the 7.5-mile test track at TRC, while using one of four commercially available route guidance systems. For comparison purpose, the following five additional tasks were included.

- Manually tuning a radio for AM with the "SEEK" button
- Manually tuning a radio for FM
- Manually dialing an unfamiliar 10-digit phone number
- Manually dialing a familiar 7-digit phone number
- Performing an HVAC task

Tijerina, Johnston, Parmer, Winterbottom, and Goodman (2000) did not obtain very high correlation coefficients among different measures. R^2 was 0.39 between static and dynamic task completion times, 0.27 between static task completion time and the number of lane departures, and 0.43 between dynamic task completion time and the number of lane departures. Using the signal detection method, they discovered that the 15-second rule did not perform significantly better than the chance level. Because of these problems, Tijerina, Johnston, Parmer, Winterbottom, and Goodman (2000) argued that measuring eye glances, especially the number of glances and the percentage of time spent looking at a particular area (e.g., the forward road), was more useful.

Tijerina, Johnston, Parmer, Winterbottom, and Goodman (2000) pointed out another problem, the problem of "chunking" or partitioning of a task. As discussed previously, multiple glances are typically required for most in-vehicle tasks. The chunking of a task, and consequently, the number of glances and glance duration, depends on driving task demand (e.g., road characteristics, traffic, weather condition), system location and design, individual difference, and drivers' willingness to divert visual attention from the roadway. Tijerina, Johnston, Parmer, Winterbottom, and Goodman (2000) contended that "two systems with identical task completion times may exhibit very different time-based demands and consequently very different task chunking." (p. 61) The 15-second rule is problematic because "it implies that a driver can safely look away from the driving scene for 15 seconds" (Tijerina, Johnston, Parmer, Winterbottom, & Goodman, 2000, pp. 62-63). In short, chunking poses a serious challenge for design guidelines such as the 15-second rule.

7.8.6. The Statement of Principles by the Alliance of Automobile Manufacturers

The Driver Focus-Telematics Working Group (2002) of the Alliance of Automobile Manufacturers drafted a statement of principles for light-vehicle HMI designs including both OEM and aftermarket products. The statement covers new information and entertainment technology and devices with visual or manual-visual interfaces, and features and functions that are used by drivers when the vehicle is in motion. It does not apply to head-up displays, voice-activated devices, haptic displays and cues, purely cognitive distraction, or driver assistance systems (e.g., forward collision warning systems). Nor does it cover the information format and the allowable amount of information on a display. Currently, compliance is voluntary.

The statement is comprised of 24 principles. Some of these principles are similar to the EU and JAMA principles described previously. Below are sample principles that deal with visual distraction directly.

- Systems providing non-safety-related dynamic visual information should be capable of a means by which that information is not provided to the driver.
- Visual information not related to driving that is likely to distract the driver significantly (e.g., video and continuously moving images and automatically-scrolling text) should be disabled while the vehicle is in motion or should be only

presented in such a way that the driver cannot see it while the vehicle is in motion.

- The instructions should distinguish clearly between those aspects of the system that are intended for use by the driver while driving, and those aspects (e.g. specific functions, menus, etc.) that are not intended to be used while driving.
- The system should not require uninterruptible sequences of manual/visual interactions. The driver should be able to resume an operator-interrupted sequence of manual/visual interactions with the system at the point of interruption or at another logical point in the sequence.
- Visual displays that carry information relevant to the driving task and visually-intensive information should be positioned as close as practicable to the driver's forward line of sight. For example, the downward angle should be no greater than 30° at the geometric center of display.
- Systems with visual displays should be designed such that the driver can complete the desired task with sequential glances that are brief enough not to adversely affect driving.

Regarding the final principle listed above, it is recommended that single glance duration should not exceed 2 s and total glance duration should not exceed 20 s. These recommended values were based on the 85th percentile of driving performance effects associated with manually tuning the radio. As a reference, over the many years of on-road testing, Rockwell (1988) obtained 1,250 glances and 180 glances (15% of 1,250 glances) were longer than 1.9 s. In other words, 85% of the glances were shorter than 1.9 s, which was rounded to 2 s. As described previously, Dingus (1987) found that the mean number of glances away from the road scene for the radio-tuning task was 6.91 glances with a standard deviation of 2.39 glances. Assuming a normal distribution, the 85th percentile for the number of glances to complete a manual radio-tuning task was 9.40 glances (6.91+1.04*2.39), which was rounded to 10 glances. Putting these two numbers together, the Alliance of Automobile Manufacturers came up with 2 s by 10 glances, or 20-s total glance duration.

Questions have been raised about the statement put forth by the Alliance of Automobile Manufacturers. Although radio tuning is often used as the baseline reference task, there is no universally accepted script for radio tuning tasks. For example, radio tuning may be accomplished with pressing a pre-set button, or pressing the "SEEK" button repeatedly until a desired station is located. Although 2 s and 10 glances are the 85th percentiles of glance duration and frequency, the mean values are considerably smaller. In addition, radio tuning may not have the same level of time urgency as other tasks such as calling someone to inform of a late arrival or accessing the navigation system for directions.

7.8.7. The CAMP Driver Workload Metrics Project

The CAMP driver workload metrics project (Deering, 2002; Tijerina, 2001) is a NHTSA-sponsored project currently underway. Its objective is to develop performance metrics and test procedures for visual, manual, and cognitive aspects of driver workload to facilitate product design of telematics systems. It involves several OEMs, including Ford, GM, Nissan Technical Center North American, Inc., and Toyota Technical Center Inc. The research will investigate driving performance measures of driver workload taken under test track or on-road driving conditions, as well as "surrogate metrics" which include models, simulations or procedures that have been recently developed or proposed.

Driving performance measures include:

- Measures of visual allocation such as glance duration, number of glances, and glance sequence
- Vehicle control measures such as lane keeping, car following, and speed control
- Object/event detection such as situational awareness, perceptual processes, and way finding

"Surrogate metrics" include:

- Count of task steps
- IVIS DEMAND model
- GOMS model
- Modified multiple resources model
- Static single task method using task completion time
- Visual occlusion metrics
- Peripheral detection task metrics
- Rated situational awareness
- Rated workload
- Steering entropy

The objective of this project is to develop practical, repeatable, and meaningful driver workload performance metrics and test procedures that can be used to assess which in-vehicle tasks a driver might reasonably be allowed to access and perform while driving. These metrics and procedures will use surrogate measures.

The workload metrics should be meaningful and be correlated with other safety-relevant measures of driver distraction, such as eyes-off-road time. In the proposed approach, a set of in-vehicle tasks that span a wide range of driver demands will be used, and the correlation between driving performance and surrogate measures will be determined. For example, task completion time as a surrogate measure will be correlated with measures such as eyes-off-road time and brake RT, and the reliability and validity of this correlation will be assessed. For each performance measure, a threshold will be established to distinguish between acceptable and unacceptable values. The same will be established for surrogate measures. Classification performance can be assessed, in terms of true positive, false positive, true negative, false negative, for the workload metrics and procedures.

Although the CAMP project shares similarities with the SAVE-IT program, it is important to point out the major differences. First, one major objective of the SAVE-IT program is to demonstrate a "proof of concept" for a real-time, adaptive driver assistance system, whereas the CAMP project does not intend to measure driver distraction and workload in real time, nor does it intend to adaptively change the user interface. The focus of the SAVE-IT program is on the development of adaptive interface technology to measure and mitigate driver distraction, whereas the focus of the CAMP project is on the development of metrics and protocols for product design. Second, the SAVE-IT program intends to identify and validate eye glance measures that will be directly assessed in actual driving, whereas the CAMP project is not. Instead, the CAMP project uses the glance measures as a research tool to validate the surrogate measures (e.g., task completion time). Third, the SAVE-IT program will investigate adaptive safety warning systems such as forward collision warning systems, whereas the CAMP project will not.

7.9 A BRIEF REVIEW OF THEORY AND METHOD

Because the focus of the report is on the research findings on visual distraction, the review on the theoretical and methodological developments will be selective and brief. They will be reviewed in the following two sub-sections.

7.9.1. A Brief Review of Theory

A good theory of driving is urgently needed because the best measures of driver distraction should be theory-driven (Llaneras, 2000). Senders, Kristofferson, Levison, Dietrich, and Ward (1967) developed an early theoretical model. It is proposed that drivers must sample the forward view and between the samples there is an uncertainty buildup with time. Eventually, an uncertainty threshold is reached and the driver must then look at the forward scene. This minimum threshold can be demonstrated by using the visual occlusion method.

This time-sharing strategy is borne out in many studies. Rockwell (1988) obtained results in strong support of the strategy. When drivers performed in-vehicle tasks (e.g., radio tuning), the duration of glances to in-vehicle device was relatively consistent, and more glances were made for complex tasks. Bhise, Forbes, and Farber (1986) obtained similar results.

Wierwille (1993a, 1999b) has proposed a more detailed theory. Drivers generally adopt a time-sharing strategy to perform the primary task of driving and a secondary (non-driving) task. For safe driving, drivers must not look away from the forward view excessively. In order to accomplish in-vehicle tasks, however, drivers must occasionally look away from the forward view. Because foveal fixation is required for perception of details and drivers have only one foveal visual resource, time-sharing is the only logical choice. This is a simple, but powerful realization. Although humans have two eyes, the eyes do not operate independently. Humans cannot direct the foveal resource to different areas simultaneously. Humans have only one foveal resource, and that must be shared temporarily and moved around to gather detailed information. Although human behaviors result from massively parallel processing in the brain and can be explained by parallel distributed processing models (McClelland & Rumelhart, 1981; Zhang, Zhang, & Kornblum, 1999), at least to the first approximation, a driver can be considered as a limited-capacity single-channel information processor (Pashler,1998; Tijerina, 1999a).

The visual time-sharing process is depicted in Figure 7.5. If a driver can extract information within 1.5 s, the information is extracted and the driver will return the gaze to the forward road. If a driver cannot extract information within 1.5 s, the driver will return the gaze to the forward road first. The driver then continues glancing into the vehicle for 1.5 s and back to the road until the task is completed. When the driver looks away from the forward road, time pressure and forward scene uncertainty build up, and eventually the driver will be compelled to return glances to the forward road. A similar proposition was made by Zwahlen, Adams, and DeBald (1988) and Sheridan (1991). Sheridan (1991) contended that information intensity is a function of how recently a particular source of information has been observed. It is a well-known phenomenon in the study of human memory that information tends to fade and become stale as the time passes.

Figure 7.5 is no doubt too normative and deterministic. Drivers do not measure elapsed time with a stopwatch, chunk information optimally all the time, and follow the logic flow precisely as outlined in Figure 7.5. The model parameters, for example, the upper bound, may vary with the driving task and individual driver.

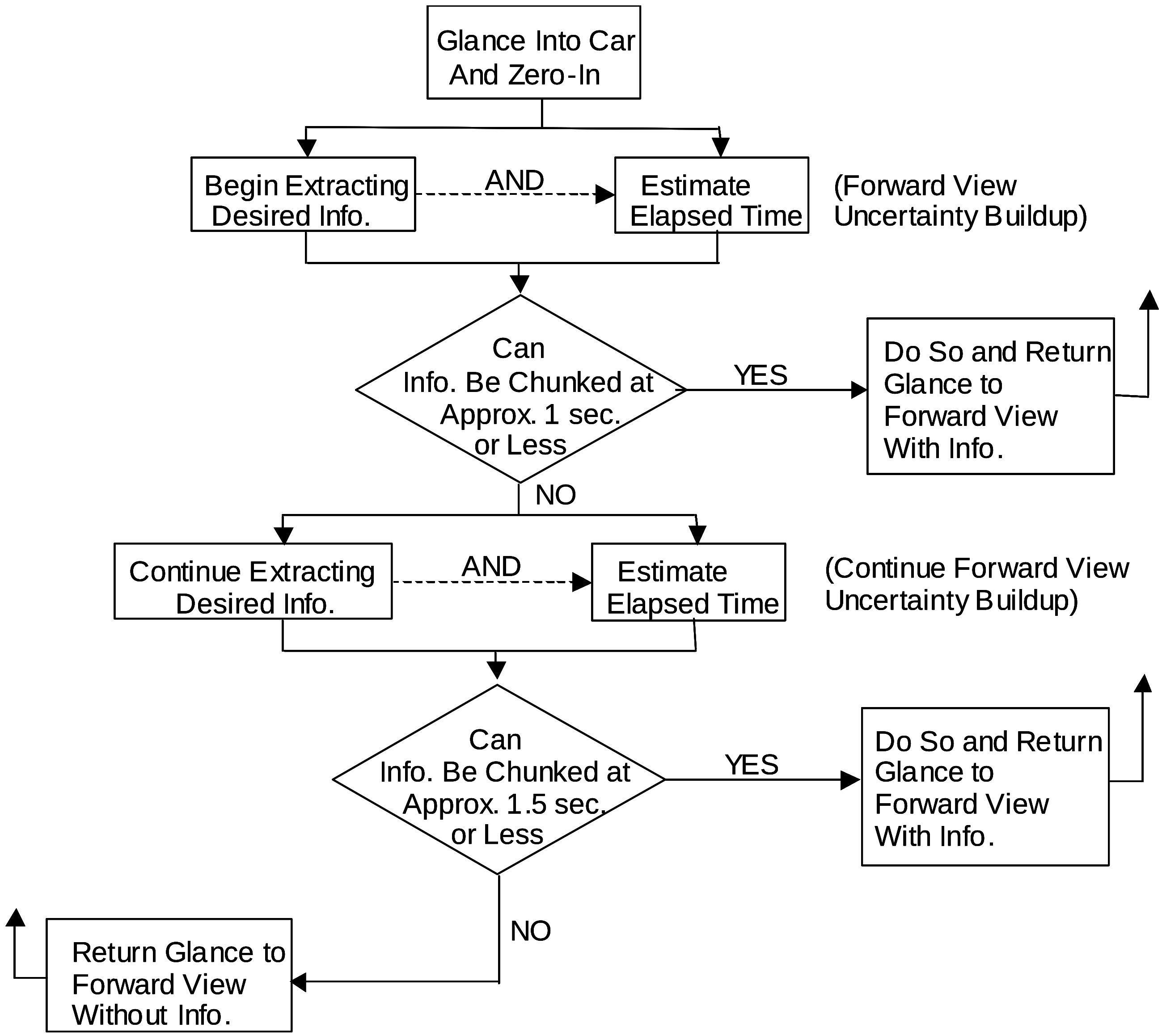

Figure 7.5. Wierwille's visual sampling (time sharing) theory (from Wierwille, 1993a)

To decompose the time involved in a lead vehicle braking operation, Morita, Mashiko, and Okada (2000) proposed a time model as presented in Figure 7.6. It is worth noting that the commonly defined "brake reaction time" is the same as "event response time" in Figure 7.6, the sum of "noticing time" and "brake response time". Because event occurrence is unpredictable, "noticing time", "brake response time", and "event response time" are probabilistic. They assumed that as long as the driver is viewing the display screen, the driver does not notice situations ahead and does not notice such situations until he returns the line of sight to the forward road.

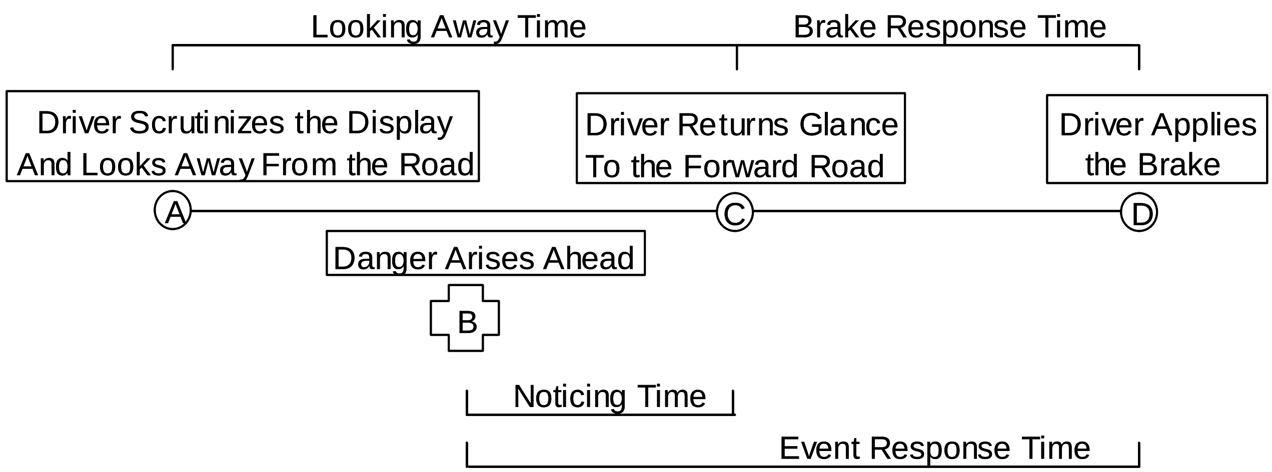

Figure 7.6. Time decomposition of a braking operation
(Morita, Mashiko, & Okada, 2000)

Morita, Mashiko, and Okada (2000) did an experiment and some simulations and revealed that the average time between the moment when a dangerous event occurs and the moment when the driver notices the event ("noticing time", or gaze reaction time) is half of the average "looking away time". In particular, the average "looking away time" from the experiment was 3.7 s, and the average "noticing time" was 1.70 s. The "looking away time" (3.7 s) was considerably longer than that typically reported (2 s). To our knowledge, this analysis is the first explicit inclusion of "noticing time" (gaze reaction time) in the calculation of total "event response time" (the so-called brake reaction time).

7.9.2. A Brief Review of Method

It is clear from the preceding discussion that eye glance behaviors are pivotal to the safety of driving. For many years, the standard method of eye glance measurement has been the video recording of drivers' head and eye features and subsequent frame-by-frame image analysis of the video tapes by human raters. Regularly, two or more trained raters are employed to code the video images in order to increase the coding reliability. This method is simple and appears to have high face validity. It has been widely used in many of the human factors studies reviewed in this report.

This method has several drawbacks. First, the frame-by-frame video analysis can be performed only after the events, but not in real time. Second, it can be very time-consuming and the coding accuracy may decline when the raters become fatigued. The ratio of analysis time to video data capture could be very high. Third, a precise determination of gaze coordinate (e.g., in terms of pitch and yaw) and glance duration is difficult with this method, although glance frequency to a target area (e.g., the forward road) is more easily determined.

It is commonly assumed that it is difficult to measure eye glance behaviors reliably, accurately, and non-obtrusively. "Eye tracking is difficult, particularly eye tracking where the driver doesn't have to wear any devices at all" (NHTSA public meeting, 2000, p. 304). This assumption has been challenged by the recent progress in computer vision, especially the development of automatic eye tracking systems. In recent years, significant advancements have been made to measure eye glance behaviors using non-obtrusive, automatic eye tracking systems. The ISCAN system from ISCAN, Inc. (www.iscaninc.com; under the brand name "VisionTrak", www.polhemus.com), and the FaceLab system from the Seeing Machines, Inc. (www.seeingmachines.com) are two examples of promising eye tracking systems suitable for human factors research. This report will review the FaceLab system, because it is more relevant to, and will be used in, the SAVE-IT program.

The FaceLab system is a commercial product for face and eye gaze tracking and measurement (Heinzmann & Zelinsky, 1998; Matsumoto, Ogasawara, & Zelinsky, 2000; Matsumoto & Zelinsky, 2000; Victor, 2000), marketed by Seeing Machines, Inc. (www.seeingmachines.com). It grew out of a co-operative Research and Development project between the Australian National University and Volvo Technological Development.

The FaceLab system consists of a stereo head with two Sony cameras for image capturing, and a Dell computer for image processing and gaze coordinate determination. It uses the "image processing using template matching feature tracking" method to track both the head and eye movements. An initial calibration is required to mark the salient facial features such as the eye corners and mouth corners. Once calibrated, the system operates automatically without subjects' intervention. It generates output measures such as head position and orientation, eye gaze coordinates (e.g., pitch and yaw), blink, eye closures, and associated confidence levels. Graphic depiction of head orientation and eye gaze is provided.

Victor, Blomberg, and Zelinsky (2001) validated the FaceLab system for the measurement of eye gaze coordinates. They instructed subjects to drive a simulator and perform two repetitions of six tasks (e.g., mirror, text on IP left, text on IP right, fan, radio, and mobile phone). They compared visual glance measures by video transcription and FaceLab system. Pearson product-moment correlations revealed near perfect correlations between video transcription and faceLab system on dependent variables such as total glance duration (r=0.995) and glance frequency (r=0.997), and a strong correlation for glance duration (r=0.732). These high correlation values demonstrated that the FaceLab system can reliably and accurately measure eye glance behaviors.

It is encouraging to witness the development of non-obtrusive eye tracking systems that generate gaze coordinates automatically and in real time. Indeed, the FaceLab system is a very good research tool. Despite these advancements, however, robust and accurate eye tracking remains difficult under certain circumstances. The tracking accuracy may be degraded under conditions of poor illumination or when subjects wear high-prescription eyeglasses. Presently, the FaceLab system runs at 60 Hz and has a reported accuracy of $\pm 3°$. Faster sampling rate and improved accuracy may be desired to measure fast eye movements (e.g., saccade velocity).

7.10 CONCLUSION

In this report, we have reviewed and summarized major research findings on visual distraction in the literature. As indicated previously, the review has been focused on the mean statistic rather than the variance or distribution statistic. Most human factors researchers believe that a driver has but one visual resource that cannot be allocated to different locations simultaneously. Because of this, a driver must employ a time-sharing strategy to manage multiple tasks: a primary task of driving and a secondary (non-driving) task. For safe driving, a driver must devote a vast majority of visual resource (e.g., two thirds) to the forward roadway, a circular area of approximately $\pm 8°$ around the focus of expansion. When it becomes necessary to look at an in-vehicle device or a roadside object, a driver typically looks away from the forward roadway for 1-1.5 s. Afterwards, the driver will return to look at the forward road to gather more information regarding the driving scene. If information about the in-vehicle device or the roadside object is not fully obtained in a single glance, the driver will look at the device or object again for another 1-1.5 s. This process will continue until the driver gathers enough information about the device or object. There seems to be an upper bound for the duration of the off-road glances and most drivers are reluctant to look away from the forward road for longer than 2 s (the 2-second rule).

Despite the finding that the mean glance duration and peak glance duration are typically shorter than 2 s, some off-road glances are longer than others. The mean glance duration varies directly with display complexity and zoom requirement for navigation systems. It may be considerably longer for a complex display or a display with small objects and characters. Other measures of visual distraction, including the number of off-road glances, total off-road glance duration, Type 1 or Type 2 eyes-off-road exposure, do not seem to be bounded. They vary directly with task type (e.g., manual vs. speech task), message length (e.g., short vs. long), and information density (e.g., low vs. high). The number of off-road glances, for example, can be numerous for long and high-density visual messages.

In addition, visual scanning behaviors vary based on the driving task demand as represented in terms of road geometry, weather, traffic, and driving scenarios. When driving on curved roads, the mean glance duration to an in-vehicle display is shorter, the glances back at the forward road are longer, and the number of glances to the in-vehicle display is greater than when driving on straight roads. When driving on straight roads, drivers tend to look at the focus of expansion. During a curve negotiation, however, they tend to look at the direction of the turn. With the presence of random crosswind or heavy traffic, the glance duration to the forward road is increased and the glance duration to an in-vehicle display is reduced accordingly. When following a lead vehicle, the mean glance duration to an in-vehicle display is markedly shorter than when a driver does not follow a lead vehicle.

Visual glance behaviors are also affected by driver age, experience, and their familiarity with the route. In contrast to younger drivers, older drivers require considerably longer total glance duration and greater number of glances to the in-vehicle display. In comparison with experienced drivers, novice drivers have a greater number of off-road glances, longer off-road glance duration, and longer total glance duration. Furthermore, novice drivers have a narrower visual field ("perceptual narrowing") than do experienced drivers. As a driver becomes more familiar with a driving route, visual sampling will become confined to a smaller area, mainly focused on the right edge marker and the horizon.

There has been a massive amount of human factors research demonstrating that visual distraction, as measured in terms of the number of off-road glances, mean and total off-road glance duration, degrades driving performance as measured in terms of SDLP, number of lane departures, task completion time, or reaction time. In particular, SDLP is enlarged as the duration or the number of off-road glances increases. The number of lane departures multiplies when the number of glances or the total glance duration to in-vehicle device increases. A strong correlation is found between the number of lane departures and the mean glance duration in some experiments, although the correlation is small or insignificant in other experiments. The inconsistent results may be due to a ceiling effect, because the mean glance duration is typically shorter than 2 s. When drivers look away from the forward road more frequently (e.g., when the number of off-road glances or the total off-road glance duration is increased), they tend to drive more slowly and lengthen the task completion time accordingly. Human factors studies consistently demonstrate that the brake reaction time is longer for visually distracted drivers than for non-distracted drivers.

Experienced drivers typically look at the vanishing point of the road and appear to be able to use the peripheral vision for lane keeping. Despite that, the lane keeping performance is degraded as gaze eccentricity increases. So is the detection of objects such as signs and icons and the detection of traffic events such as lead vehicle braking or decelerating. The reaction time for detecting peripheral objects is noticeably slower than that for detecting foveal objects.

Analyses of crash databases clearly indicate that visual distraction, as represented in terms of the number of off-road glances, mean glance duration, frequency of device use/week, Type 1 or Type 2 eyes-off-road exposure, increases the likelihood of crashes. Based on this and other human factors findings, it is evident that the amount of visual distraction should be minimized to achieve safe driving. To address this and related issues, many design guidelines have been proposed, for example, the European statement of principles, the JAMA guideline, the IVIS demand, Human Factors Design Guidelines for Advanced Traveler Information Systems (ATIS) and Commercial Vehicle Operations (CVO), the 15-second rule (SAE J2364), and the Statement of Principles by the Alliance of Automobile Manufacturers. In addition, the CAMP Driver Workload Metrics Project is developing practical and repeatable surrogate measures that can be used by designer and engineers. A common theme of these guidelines is that good HMI designs are critical in the reduction of visual distraction. Despite these efforts, it remains a challenging task to reach a consensus on the establishment of thresholds for measures of visual distraction such as mean and total glance duration, number of glances, and task completion time. Based on the 2-second rule, most researchers would recommend a 2-s threshold for mean glance duration (e.g., see Alliance Statement, and Zwahlen, Adams, and DeBald's recommendation). The recommended number of off-road glances ranges between 4 and 10.

It is worth noting that most of the studies reviewed in this report did not measure, or did not intend to measure, visual distraction in real time. The research has focused on a demonstration of visual glance behaviors on driving performance as well as on the effects of driving and non-driving task demands and task complexity on visual glance behaviors. However, there are compelling reasons for an equal emphasis on measuring and mitigating visual distraction in real time. Tijerina, Johnston, Parmer, Winterbottom, and Goodman (2000) have built a strong case for the real-time measurement. They argued that the chunking of a task (which determines the number and the duration of off-road glances) represents a driver's willingness to look away from the forward roadway under a particular set of circumstances. Because chunking cannot be determined in advance, the exact nature of visual sampling and the exact amount of visual distraction cannot be determined without a real-time measurement system. It seems imperative that the amount of visual distraction be determined individually under realistic driving conditions.

For determination of momentary workload and distraction, Hoedemaeker, de Ridder, and Janssen (2002) examined relevant European projects and pointed out the problems with two previous methods. The first is an intrusive method, including the use of physiological measures, secondary task performance, subjective judgments and rating scales. These measures are inappropriate for adaptive interface technology because they are intrusive or require drivers to perform additional activities. A second method is to use performance measures such as drivers' interactions with pedals and controls and associated vehicular parameters (e.g., speed and lane keeping performance). The performance measures are practical and can be obtained "for free." At present, however, it is not clear how they are related to momentary workload and whether they are diagnostic of visual distraction.

Realizing these difficulties, Hoedemaeker, de Ridder, and Janssen (2002) reached the following conclusion.

> There are a multitude of measures available to monitor driver state over an extended time (minutes and longer) period. However, pinpointing a driver's momentary workload in a moving vehicle, so as to judge whether he may momentarily be overloaded, requires very specific methodology. (p. 5)

In agreement with Hoedemaeker, de Ridder, and Janssen's (2002) conclusion, we believe that it is important to monitor momentary driver state, and that driver state monitoring with intrusive means is not appropriate for SAVE-IT applications. Until very recently, it has not been possible to monitor driver state non-obtrusively and in real time. Fortunately, as discussed in the preceding section, non-obtrusive tools such as automatic eye tracking systems are emerging and suitable for human factors research and development. Future research should utilize non-obtrusive eye tracking systems such as Seeing Machines Inc.'s FaceLab to identify measures that are diagnostic of visual distraction.

It is conceivable that new measures are needed. The measures of visual distraction reviewed in this report are task- or device-based. The peak glance duration, mean glance duration, and the number of off-road glances are defined for a particular task or device, for instance, the radio-tuning task. These task-based measures are suitable for product design. However, they may be inappropriate for real-time adaptive interface systems such as SAVE-IT systems. For example, if a driver looks away from the forward road for half of the time (30 s) within a 1-min period, we can probably argue that the driver is highly distracted, regardless of whether the off-road glances are on the same task/device, or on several different tasks/devices. In a real-time system, the diagnostic measures of visual distraction and their units of measurement should be time-based rather than task-based. These measures may be a combination of off-road glance duration and glance frequency over a period of time. They may be assessed with non-obtrusive, automatic eye tracking systems such as the FaceLab™ system developed by Seeing Machines, Inc.

In the present program (Task 7B), two simulator experiments will be performed to identify eye glance measures that are diagnostic of visual distraction and that can be used in real-time, adaptive interface technology systems and to determine performance effects of visual distraction. The literature review points out three most important factors influencing visual distraction: display complexity (or amount of information), gaze eccentricity, and driving task. These factors will be manipulated in the experiments. They will likely result in different eye glance behaviors and associated performance differences. Eye glance variables such as off-road glance duration and glance frequency will be measured in real time with the FaceLab™ system. Effects of visual distraction will be measured in terms of performance measures such as standard deviation of lane position, speed variance, steering entropy, and especially RT to lead vehicle braking. The performance variables will then be related to real-time eye glance measures in terms of regression equations such as RT = f(glance duration, glance frequency, etc.). In one experiment, the visual distraction "trend" will be determined—a regression equation expressing the relationship between RT and visual glance behavior over a time interval, in terms of RT = f(eye glance measures over a time interval). Glance measures may include glance duration and frequency, and they will be averaged over a certain time interval. In another experiment, the momentary visual distraction potential will be determined—a regression equation expressing the relationship between RT and gaze coordinate at a particular moment, in terms of RT = f(momentary gaze coordinate). Ultimately, algorithms will be developed to operationally define the level of visual distraction using eye glance variables obtained in real time from the FaceLab™ system.

This task, along with other SAVE-IT tasks, Tasks 3 (Performance) (Green, 2003) and 5 (Cognitive Distraction) (Lee, 2003b), is performed to assess the state of the driver (distraction level). The driver state information will be an important input to both SAVE-

IT countermeasure sub-systems ("Distraction Mitigation" and "Safety Warning Countermeasures" sub-systems) (Lee, 2003a; Smith & Zhang, 2004). For the "Distraction Mitigation" sub-system, the information about the driver state (distraction level) will be compared with the information about driving task demand to determine whether distraction warnings should be issued or non-driving tasks should be blocked or screened out. The allowable level of distraction should be commensurate with the demand imposed by the driving environment. The specific strategies and methods used to mitigate the distraction will be studied in another SAVE-IT task, Task 4 (Distraction Mitigation) (Lee, 2003a). Furthermore, the information about the driver state, defined in terms of RT, is a key input to "Safety Warning Countermeasures" sub-systems such as the FCW system to adaptively adjust the timing of the warnings. The warning onset may be earlier for a distracted driver than for an attentive driver to simultaneously maximize the effectiveness of collision warnings systems and minimize false alarms and nuisance alerts. The specific manners that the distraction information is used to adapt the safety warning systems will be studied in another SAVE-IT task, Task 9 (Safety Warning Countermeasures) (Smith & Zhang, 2004).

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