SAVE-IT

A Final Report of SAfety VEhicles using adaptive Interface Technology (Phase I: Task 7): Visual Distraction Research

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Table of Contents

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.

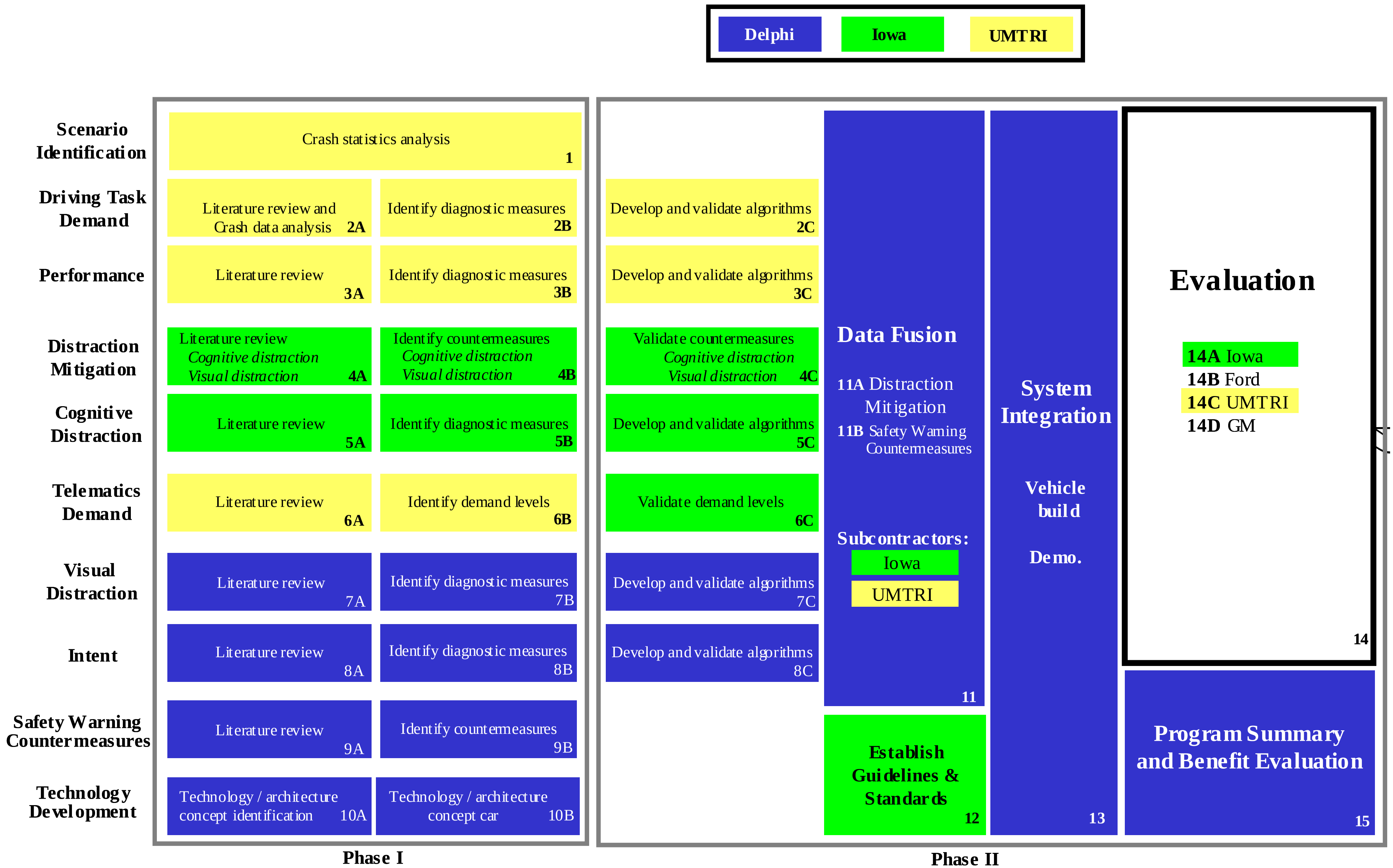

Figure i: SAVE-IT tasks

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

[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.

environments that appear to be predictable may therefore leave drivers less prepared to respond when an unexpected threat does arise.

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.

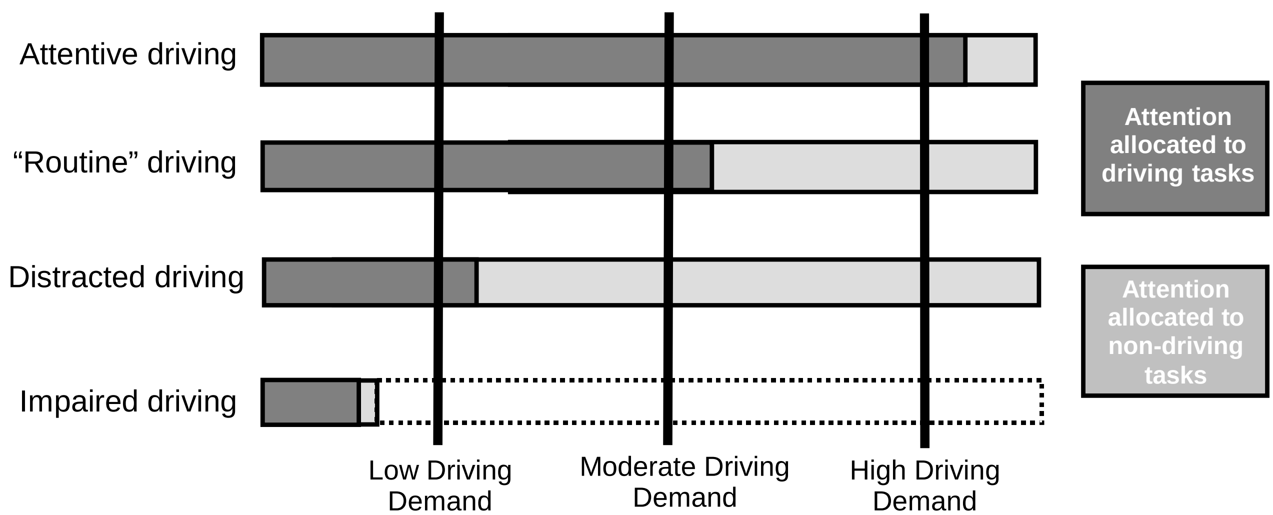

Figure ii. Attention allocation to driving and non-driving tasks

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^{TM} (formerly called GlobalSim^{TM}) from Drive Safety Inc., and the same eye tracking system, FaceLab^{TM} 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 final report for Task 7 that documents the research progress to date (March 2003-March 2004) in Phase I. In this report, the major results from the literature review are summarized to determine the research needs for the present study, the experimental methods and resultant data are described, diagnostic measures and preliminary algorithms are identified, and human factors recommendations are offered.

7.1. INTRODUCTION

Human factors researchers have classified driver distraction in terms of the following four types: visual, cognitive, manual (biomechanical or psychomotor), and auditory. Because the most detrimental component of auditory tasks (e.g., processing synthesized speech) is typically the thought associated with the auditory messages, cognitive distraction and auditory distraction are studied together in Task 5 (Cognitive Distraction). Analogously, because the most detrimental component of visual-manual tasks is typically the off-road glances, visual distraction is a research focus in the SAVE-IT program (Task 7). The major purpose of Task 7 is to identify reliable measures that are indicative of visual distraction and that can be used in a real-time system that uses adaptive interface technologies. It is important to note that in the first phase of the SAVE-IT program, visual distraction and cognitive distraction are studied in separate tasks. This division of labor is required in order to focus our research on two major substantive areas. In the second phase, they will be fused to determine the overall level of distraction.

This is the final report of the first phase research for Task 7 covering one year of research on visual distraction (March 2003-March 2004). Because of its focus on visual distraction, cognitive distraction and auditory distraction are beyond the scope of Task 7. For example, talking on the cell phones, listening to synthesized speeches, and using voice commands will not be covered in Task 7 (but they will be studied in Task 5). The visual-manual components associated with cell phone tasks (e.g., dialing a number and pushing a button), however, are generally covered in the present task. The Phase I research consists of two sub-stages: Literature review (Task 7A) and simulator experiments (Task 7B). A detailed literature review report has been submitted separately (Zhang & Smith, 2004). In this final report, major findings from the literature review are summarized first to set the stage for the experimental work in Task 7B. The bulk of the final report will describe the methods, results, diagnostic measures, and conclusions of two simulator experiments. Final reports for other SAVE-IT tasks should be consulted in order to gain a complete understanding of driver distraction issues and mitigation systems using adaptive interface technologies. For example, the final report for Task 5 will describe the results of the cognitive distraction research.

A variety of eye glance measures have been studied in the literature (see Zhang & Smith, 2004, for a review). Below are the representative measures.

- 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). A related measure, peak glance duration, is defined as the time (in s) of the longest glance.
- Number of glances (glance frequency): It is defined as the total number of glances at a target area during the performance of a task.
- Total glance duration (total eyes-off-road time): It is defined as the cumulative time (in s) elapsed for all glances at a target area during the performance of a task.

- 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., radio tuning). A related measure, Type 2 eyes-off-road exposure, raises the mean glance duration by a power of 1.5.

These measures are not necessarily independent of each other. For example, the mean glance duration and the number of glances are inversely correlated. For a task that requires a total glance duration of 10 s, the number of glances would be 10 if the mean glance duration is 1 s, but 7 if the mean glance duration is 1.4 s.

It is commonly agreed that off-road glances increase the likelihood of crashes. Wierwille and Tijerina (1998) summarized three experiments and obtained results on eye glances that were targeted at various in-vehicle areas. They also examined the 1989 crash data from North Carolina and determined the number of crashes attributable to eye glances at the respective in-vehicle areas. A correlation analysis was performed between the eye glance data and the crash data. The correlation was not very strong for the mean glance duration, the number of glances, and the frequency of use per week when these measures were examined in isolation. When they were combined in terms of Type 1 and Type 2 eyes-off-road exposures, however, a strong correlation was found between the number of crashes and Type 1 or Type 2 eyes-off-road exposures ($r = 0.898$ for Type 1 and $r = 0.941$ for Type 2). Note that the correlation was high for both Type I and Type II exposures, and it was slightly higher for Type II exposure.

Although the connection between visual distraction and automobile crash is commonly acknowledged, its determination is not possible in advance before the occurrence of crashes. Alternatively, driving performance measures such as lane keeping, speed maintenance, car following performance, driver reactions to objects and events are widely-used safety measures. The strong connection between visual glance and SDLP was demonstrated by Zwahlen and DeBald (1986), Popp and Farber (1991) and Tijerina, Kiger, Rockwell, and Tornow (1996). Popp and Farber (1991) found that the SDLP increased when the mean glance duration and the number of glances to an in-vehicle display increased. Tijerina et al.'s (1996) "Heavy Vehicle Driver Workload Assessment" study demonstrated that as the line of text increased from 1 to 2 or 4, both the number of glances to the display and SDLP increased. Zwahlen and DeBald (1986) investigated 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. They found that when subjects closed their eyes or looked away, SDLP was higher than the baseline condition beyond 1 s of the drive.

Larger SDLP for the distraction conditions also implies more lane departures. Several experiments have revealed that the number of lane departures increases with the number of glances and the total glance duration to in-vehicle devices (Blanco, 1999; Dingus, 2000; Green, 1999; Jenness, Lattanzio, O'Toole, & Taylor, 2002; Jenness, Lattanzio, O'Toole, Taylor, & Pax, 2002; Tijerina, 1996; Tijerina, Kiger, Rockwell, & Tornow, 1996). The results with the mean glance duration measure are mixed. Dingus, Hulse, McGehee, Manakkal, and Fleischman (1994) obtained a positive correlation between mean glance duration and lane departure variables. The correlation was not found in Green (1999), Tijerina, Parmer, and Goodman (1999), and Blanco (1999). It appears that the mean glance duration to an in-vehicle display typically does not exceed 2 s (Wierwille, 1993) and that its limited range could weaken its effect on the number of lane departures (e.g., a ceiling effect).

The previous studies have consistently demonstrated that visual distraction slows down brake reaction times to braking lead vehicles. 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 (at 0.93 s) than was for the non-distracted condition (at 0.61 s). Lee, McGehee, Brown, and Reyes (2002) studied the reaction time impact of driver distraction in the context of forward collision warnings. In the distraction condition, subjects were asked to press a button near the rearview mirror and report the number of times the digit 4 appeared on a display above the mirror. In another condition, subjects were not distracted. In either condition, the lead vehicle could brake quickly and imminently, which would require the driver to make an immediate response in order to avoid a crash. The accelerator-release reaction time was 0.4 s longer when subjects were distracted than when they were not distracted. The accelerator-to-brake transition time did not vary with distraction.

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 the reaction time measure in a car following situation. A number keypad task was used to simulate dialing a phone number (visual distraction condition). Subjects were asked to key in a series of three 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 drove an instrumented car on a 30-km roadway and were instructed to follow a lead vehicle and brake as soon as they noticed the lead vehicle decelerating. Compared to the control condition (with eye gaze on the forward road), the brake reaction time was increased by 0.48 s and 0.50 s in the visual and cognitive distraction conditions, respectively. Effects of visual and cognitive distraction appeared similar, and both type of distraction delayed response times considerably.

It is commonly agreed that drivers learn to use peripheral vision in lane keeping. Summala, Nieminen, and Punto's (1996) instructed subjects to direct their foveal vision to an off-road area steadily. Subjects were asked to name digits or perform arithmetic manipulation of digits that were displayed at three eccentricities. Summala et al. (1996) found that subjects were capable of lane keeping with peripheral vision. The lane keeping performance, however, declined with an increasing gaze eccentricity. The distance that drivers were able to drive properly within the lane boundaries decreased as a function of gaze eccentricity.

The effect of gaze eccentricity can also be measured in terms of reaction times. 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 a red light. The reaction time was shortest for detecting objects at the center of the fixation and it increased with an increasing eccentricity. The reaction time for detection of peripheral objects was 14%-25% longer. Similar results were obtained by Faerber and Ripper (1991), Labiale (1993), Mourant, Tsai, Al-Shihabi, and Jaeger (2000), and Summala, Lamble, and Maakso (1998), Lamble, Laakso, and Summala (1999).

It is important to note that in the previous studies, eye glance measures are determined with the analyses of driver face videos. This traditional method has several limitations. One limitation is the massive amount of work involved in the coding of video images. Although videos are useful in determining whether the eye gaze is on the forward road or on a target area, it is difficult to acquire the precise gaze coordinates. Another limitation is that the video analysis can be performed only after the events are over, but not in real time. Recently, automatic eye tracking systems have been developed and researchers have begun to use them in human factors research (Heinzmann & Zelinsky, 1998; Victor, Blomberg, & Zelinsky, 2001). The application of automatic eye tracking systems is key to the SAVE-IT program because such systems are pre-requisites for the direct assessment of visual distraction in real time.

In the previous studies, the eye glance measures are typically computed on a task-by-task basis. The task-based metrics are useful in determining the distraction potential of telematics functions so that product designers can disable complex functions (Deering, 2002; Tijerina, 2001). However, they may not be sufficient for real-time systems such as the SAVE-IT system because given the same device and task, different drivers at different times and days could have different eye glance behaviors and different sequences of interrupting or chunking the task components. It may be difficult, if not impossible, to determine in advance how a task will be performed and how task components will be grouped or chunked. In addition, drivers may perform multiple tasks within a time window, which could increase the level of distraction. In short, the most useful measure for the SAVE-IT system appears to be time-based rather than task-based. Time-based version of eye glance measures will be defined in this report. For example, glance frequency may be defined as the number of glances at a target area (e.g., the radio area) within a time window (e.g., 60-s or 5-s).

7.1.1. Objectives of Simulator Experiments

The major objectives of Task 7 (Visual Distraction) are two-fold. First, reliable eye glance measures that are diagnostic of visual distraction will be identified and validated. Because of the recent advancement in non-obtrusive eye tracking systems such as the faceLab system from Seeing Machines, Inc. (Heinzmann & Zelinsky, 1998; Victor, Blomberg, & Zelinsky, 2001), real-time monitoring of head and eye movements and glances has become feasible. The faceLab system will be used in the simulator experiments. Because time-based rather than task-based glance measures are more useful to the SAVE-IT program, the diagnostic measures will be eye glance variables defined over a time window. Second, the performance impact of the diagnostic eye glance measures will be investigated and regression equations will be developed to delineate the relationship between eye glance measures and performance variables. Performance variables will include those of lane keeping (e.g., standard deviation of lane position or SDLP, lane departures) and reaction times to braking lead vehicles. These two objectives are intertwined because the correlation between performance variables and eye glance measures will be computed in order to identify reliable and diagnostic measures of visual distraction.

To achieve these objectives, two simulator experiments are carried out. Driving simulators are ideally suited for this task because they permit the use of high levels of distraction without an undue level of risk to subjects. They also enable the reaction time measurement that is critical to the SAVE-IT system. The faceLab system from Seeing Machines, Inc. will be used to monitor eye glances in real time. In the first experiment, the lead vehicle may brake periodically at randomly chosen moments (see Lee, Caven, Haake, & Brown, 2001; Lee, McGehee, Brown, & Reyes, 2002). The random nature of the braking events is most realistic and has a high level of face validity. In the second experiment, the lead vehicle braking event is tied with off-road glances. With the close coupling, reaction time and performance effects of off-road glances can be examined for the few moments surrounding the braking event.

Because a major research objective for Task 7 is to determine diagnostic measures for visual distraction exclusively, auditory and cognitive distraction will not be addressed. Therefore, auditory tasks will not be used. Because auditory tasks with high levels of cognitive load could be distracting (Lee et al., 2001; Recarte & Nunus, 2000), they will be investigated in another SAVE-IT task, Task 5.

7.2. EXPERIMENT 1

7.2.1. Introduction

The major objectives of Experiment 1 were to identify eye glance variables that can reliably predict visual distraction and to determine the reaction time and performance effects of these eye glance variables. Head and eye movements and gaze coordinates were measured with the faceLab system (Version 2.0.1) developed by Seeing Machines, Inc. (Heinzmann & Zelinsky, 1998; Victor, Blomberg, & Zelinsky, 2001). They were used to calculate eye glance variables such as eyes-off-road glance duration and glance frequency. Eye glance variables were compared with performance variables such as lane departures and reaction times to braking lead vehicles.

Visual distraction was introduced by asking subjects to read three rows of unrelated words on a LCD or CRT display. Unrelated words instead of meaningful sentences were used to reduce the cognitive load associated with the visual display. Because the focus of the present task was visual distraction, it was essential to construct tasks that were purely visual and contained little cognitive contents. The use of unrelated words also reflected the in-vehicle environment where labels for buttons and dials were frequently short and unrelated to one another. The number of words on a particular display was manipulated to produce varied levels of visual distraction. The display eccentricity was also manipulated. As the level of visual distraction increased, eyes-off-road glance measures were expected to increase and driving performance was expected to deteriorate. Similar effects were expected for display eccentricity. The correlation between eye glance variables and performance variables was computed in order to identify diagnostic measures of visual distraction.

7.2.2. Method

7.2.2.1. Subjects

Fourteen subjects (seven males and seven females) were recruited from the responders to an advertisement posted in a local newspaper at Kokomo, Indiana. They were required to be in the range of 35-55 years old and possess a valid driver's license. Four subjects wore thin eyeglasses (with low prescription) and ten subjects did not wear eyeglasses. A few individuals wore thick eyeglasses and were rejected because the faceLab system (Version 2.0.1) did not work well with them during the calibration. Subjects had a minimum vision of 20/40 (vision correction with thin eyeglasses permitted) as tested with the Snellen Eye Chart. The actual age for the fourteen subjects ranged between 35-53, averaged 43.86, and had a standard deviation of 5.36. They were paid a $50 Wal-Mart gift card for their participation in the 2.25-h experiment.

7.2.2.2. Apparatus

7.2.2.2.1. Delphi Driving Simulator and Display Monitors

The experiment was performed in the Delphi Driving Simulator at Kokomo, Indiana. It was a fixed-base, one forward channel DriveSafety system. The simulator projected a 1024x768-pixel 50°x40° forward field-of-view image located at the front bumper of the vehicle cab. The vehicle handling system was configured to represent a mid-size front wheel drive sedan, such as a Ford Taurus. Steering feedback was presented with a force-feedback torque motor, to reproduce the feel of the road at the steering wheel, as well as the forces on the front tires during evasive maneuvers. The vehicle cab consisted of the front half of a 1995 Pontiac Bonneville exterior (with doors and roof removed), with a 1996 Buick Park Avenue instrument cluster and dashboard.

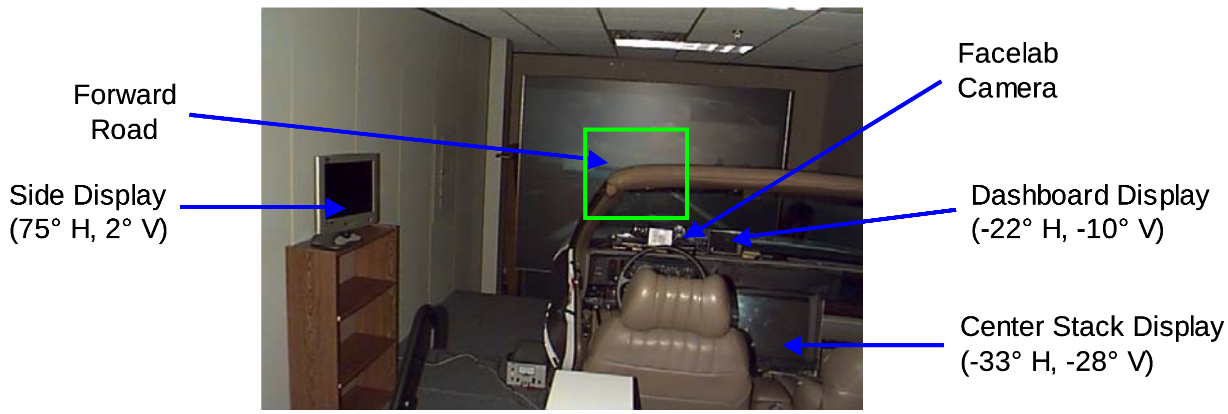

Figure 7.1. Display and camera locations

As illustrated in Figure 7.1, one CRT computer monitor was installed in the center stack of the driving simulator. Three rows of words were displayed on the top portion of the display with an average display eccentricity of 33° (horizontally, to the right of the subject) and 28° (downward). A small LCD monitor was placed above the dashboard with an average display eccentricity of 22° (horizontally, to the right of the subject) and 10° (downward). A 17-in. flat screen LCD monitor was placed on the left side of the vehicle cab with an average display eccentricity of 75° (horizontally, to the left of the subject) and 2° (upward).

7.2.2.2.2. FaceLab Eye Tracking System from Seeing Machines, Inc.

Eye glance variables were measured and recorded with the faceLab eye tracking system (Version 2.0.1) developed by Seeing Machines, Inc. (Heinzmann & Zelinsky, 1998; Victor, Blomberg, & Zelinsky, 2001). The FaceLab system consisted of a stereo head with two Sony cameras for image capturing, and a Dell computer for image processing and gaze coordinate determination. The stereo head was installed above the dashboard and centered horizontally with respect to the subject. The simulator room was dimly illuminated to minimize glares and reflections. A 9x4 infrared LED array with a peak emission of 880 nm was placed between the two cameras to provide a high level of illumination to the subject's face area.

The method of image processing with template matching feature tracking was used by the faceLab system to track both the head and eye movements. An initial calibration was required to mark the salient facial features including the eye corners and mouth corners. Once calibrated, the system operated automatically without subjects' interventions. It generated output measures such as head position and orientation, eye gaze coordinate (e.g., pitch and yaw), attention pitch and yaw angle (combining head orientation and eye gaze coordinate), eye blink, eye closure, and associated confidence levels with a sampling rate of 60 Hz. The reported accuracy for eye gaze coordinates was +/-3° (Victor, Blomberg, & Zelinsky, 2001). Graphic depictions of head orientation and eye gaze were provided by the faceLab system for easy operations by the experimenter.

7.2.2.2.3. Interface Software (IVIS SimConn)

An interface software (IVIS SimConn) was purchased from NEXIQ Technologies, Inc. to continuously feed variables from the faceLab eye tracking system to the driving simulator. The frame numbers from the faceLab system and the simulator were used to synchronize the eye glance data and the performance data that were key for the correlation analyses. The IVIS program was also used to generate the words that were displayed to generate different levels of visual distraction.

7.2.2.2.4. NASA-TLX

The NASA Task Load Index (TLX) was used to measure the workload and perceived task difficulty associated with various experimental conditions (Hart & Staveland, 1988). It was a multi-dimensional rating procedure that provided an overall workload score based on a weighted average of ratings on six sub-scales: Mental demands, physical demands, temporal demands, performance, effort, and frustration. The score on each sub-scale ranged from 0 to 100. The overall workload score varied from 0 to 100, with a higher score indicating a higher level of subjective workload and perceived task difficulty.

7.2.2.3. Experimental Design

There were four independent variables. One variable was road type. One type of roads was rural 2-lane roads with a posted speed limit of 45 MPH, and the other was divided 6-lane highways with a posted speed limit of 65 MPH. The lane width was 12-ft. and lane markers were clearly visible. Subjects were instructed to follow a white-colored car driving in the right lane. The lead vehicle braked slowly without warning at some random moments. For both types of roads, both straight and curved road segments were used.

Road curvature (straight vs. curved segments) at which the braking event took place was a second independent variable.

Another independent variable was the level or amount of visual distraction. Similar to Labiale (1996), a reading task was chosen to simulate visual distraction because reading common words was effortless and involved little cognitive thinking (MacLeod, 1991; Zhang, Zhang, & Kornblum, 1999). In order to control the level of visual distraction, unrelated words (e.g., Freedom, Glossy, Dozen, Honor) were used. The use of related words also minimized the cognitive workload so that a more pure form of visual distraction was examined in the present experiment. The words were written in the sans serif font with mixed upper and lower case letters. They extended a visual angle of 22' for upper cases and 17' for lower cases at the nominal viewing distance. They were written in white and displayed in three rows on a black background. A wide separation existed between the rows to encourage chunking of words on a row-by-row basis. The number of words per row on the center-stack monitor was varied from 2, 3, 4, to 5 in order to control the level of visual distraction. In addition, a baseline condition was included in which subjects did not see or read any words on a display.

Another independent variable was the display eccentricity. Three rows of words with four words in each row were displayed on the dashboard monitor (22° horizontal and 10° downward), center-stack monitor (33° horizontal and 28° downward), or side monitor (75° horizontal and 2° upward). One of these conditions (the center-stack monitor) was the same as one of the visual distraction level (4 words per row) described above. Combining the last two independent variables, the levels of visual distraction and the display eccentricities, seven distraction conditions were generated.

Three of the preceding independent variables were combined to form fourteen experimental blocks (two type of roads by seven distraction conditions). A within-subjects design was used in which each subject experienced each of the 14 conditions. Latin squares were used to balance the order of these conditions across 14 subjects. Within a particular block, subjects encountered two braking events on the straight roads and one braking event on the curved roads. One filler braking event was inserted into some of the experimental blocks to introduce unpredictability of the braking events.

The dependent variables included performance variables such as positions of the accelerator pedal and the brake pedal, steering wheel angles, lane positions, and vehicle speeds. These variables were used to generate performance variables that were commonly investigated in the literature. For example, lane positions were used to produce the standard deviation of lane positions (SDLP) and number and duration of lane departures.

Eye glance variables included head orientations, eye gaze coordinates, and attention coordinates that were based on weighted head orientations and gaze coordinates. Eye closures, blinks and saccades were also recorded. These variables were used to produce eye glance measures that were commonly examined in the literature. For example, attention coordinates were used to determine the eyes-off-road glance duration and glance frequency.

7.2.2.4. Procedure

Upon arrival at the laboratory, subjects were given a brief description of the study and requested to read and sign an informed consent form. They were given the vision test (Snellen Eye Chart) and required to pass the test before proceeding (thin eyeglasses were permitted). The calibration procedure was then completed for the eye tracking system. Five snapshots of the subject's face were taken, one with the subject facing forward, one facing slightly left, one facing slightly right, one facing 90° left, and one facing 90° right. For each snapshot, salient features such as eye corners, mouth corners, eyebrows, and nostrils were selected and marked. Afterward, the faceLab system began to track a subject's head and eye movements automatically.

For the simulator driving, subjects were first given a 5-minute practice block. During the practice block, the first three minutes were normal driving without any vehicle braking events, and one braking event occurred during the last two minutes of the drive. After the practice block, subjects ran 14 experimental blocks. For each experimental block, subjects were informed about the desired speed (45 MPH for rural roads and 65 MPH for highways) and the nature of visual distraction (e.g., display location). When subjects shifted the gear to "D", the lead vehicle began to move forward and gradually reach the desired speed. Subjects were asked to follow the lead vehicle with a close and safe distance. They were instructed to maintain good lane positions and avoid crashes.

In the distraction conditions, subjects were presented with a display of new words every 13 s. When the new words appeared on the display, a beep was sounded to alert the subjects. Subjects were asked to read aloud as many words as possible without sacrificing safety. The manner in which subjects shared their visual attention between the forward driving scene and the visual display was not controlled. For the first 30-45 s of the drive, the subject vehicle and the lead vehicle were not coupled. Approximately 30 s before the lead vehicle began to brake, a software program was activated that automatically accelerated or decelerated the lead vehicle so that the time headway between the lead subject and the subject vehicle was gradually changed to a constant value of 1.8 s. Because it was known from the previous studies that time headways influenced the measurement of reaction times, a constant value was used in order to minimize any confounding. At a randomly chosen moment, the lead vehicle braked slowly for 5 s (at a deceleration rate of $–2\ m/s^2$ for rural roads or $–2.7\ m/s^2$ for highways). When the lead vehicle began to brake, the time headway control program was deactivated so that the subject vehicle gradually closed in with the lead vehicle. This procedure was similar to one that was deployed by Lee, et al. (2001, 2002). A few seconds later, subjects responded to the situation by releasing the accelerator pedal and depressing the brake pedal. The times at which the lead vehicle began to brake and the subjects responded to the braking lead vehicle were recorded in order to calculate the reaction times. After the braking event, the lead vehicle gradually accelerated to the desired speed and subjects again followed the lead vehicle. Within each 5-minute block, subjects experienced three real braking events and zero or one filler braking event. The filler event was used to introduce a level of unpredictability. The real braking events were separated by a minimum of 75 s so that subjects engaged in distraction tasks (except for the baseline conditions) for at least 60 s before each braking event in order to afford data analysis with a time window as large as 60 s.

After each experimental block, subjects were given the NASA-TLX scale and asked to rate the task difficulty and workload for the condition that was just completed. The entire experiment lasted for approximately 2 hours and 15 minutes for each subject.

7.2.2.5. Data Analysis Overview

7.2.2.5.1. Variables

Although the literature often mentioned the concept of forward road or forward view, no standards existed to define the forward road area precisely. One key activity for Task 7 was therefore to define the forward road area with eye gaze coordinates that were obtained with the faceLab system (Version 2.0.1). Because some subjects wore eyeglasses or contact lenses, the gaze pitch and yaw angles were sometimes unreliable. The attention pitch and yaw angles produced by the faceLab system were more reliable because they used the confidence level information and averaged head orientation and eye movement measurements. For Task 7, the attention pitch and yaw angles were used to determine whether or not subjects looked at a forward road area or away from the forward road. Previous studies reported that without visual distraction, drivers spent 80%-90% of time looking at an area of approximately +/-10°. For Task 7, an area of +/-12° (a 24°X24° rectangular area around the focus of expansion) was defined as the forward road area for the following reasons. One reason was that consistent with the literature, approximately 80%-90% of attention coordinates in the baseline (no visual distraction introduced) were within this area. Another reason was that for the high distraction conditions, less than 50% of attention coordinates fell within this area, which was in agreement with the experimenter's observations. This definition worked well for nearly all subjects (with or without eyeglasses) in both Experiments 1 and 2. However, it should be noted that the exact value was not critical in the definition. Small changes in the size, for example, an area of +/-11° or 13° are likely to function similarly. This level of tolerance was important because the faceLab system has a margin of error associated with its eye gaze and attention measurement (with an accuracy of +/-3°).

Figure 7.2 illustrated the sequence of events. The moment that the lead vehicle braked was designated as the zero time point (t = 0). The time interval between the moment that the lead vehicle braked (t = 0) and the moment that the subject completely released the accelerator pedal (when the simulator variable for the accelerator pedal position was zero) was defined as the accelerator release reaction time (ART). The time interval between the moment that the lead vehicle braked (t = 0) and the moment that the subject began to depress the brake pedal (when the simulator variable for the brake pedal position was non-zero) was defined as the brake reaction time (BRT). The difference between ART and BRT was defined as the accelerator-to-brake transition time. These variables were used by Lee et al. (2001, 2002) and Lamble, et al. (1999). Eye glance variables and performance variables were computed within a time window that preceded the zero time point (t = 0). The time window was re-configurable within the range of 3-60 s.

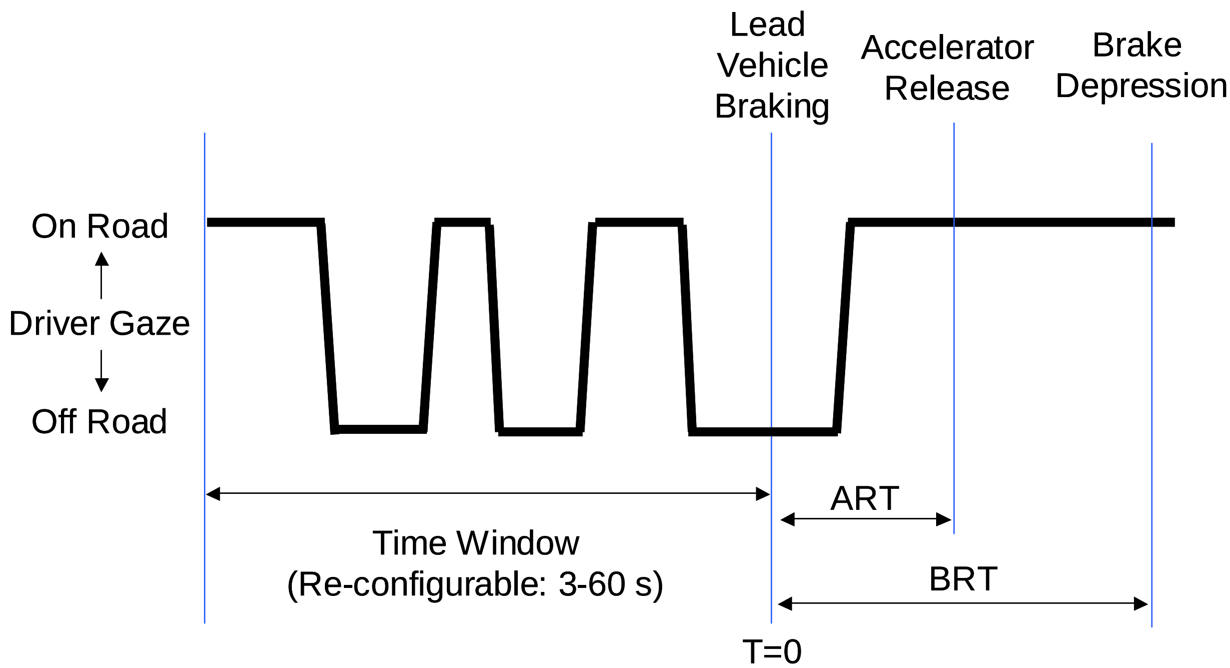

Figure 7.2. Sequence of events and definition of variables

For each reaction time event, one value each was computed for ART, BRT, steering entropy, eye glance variables (e.g., glance frequency), and performance variables (e.g., SDLP). Up to three reaction time events occurred in an experimental block. The values from the same experimental block were averaged to obtain a mean value for each of the 14 subjects and each of the 14 conditions.

The computations were repeated using a re-configurable time window (between 3-60 s). As shown in Figure 7.2, a time window always ended at the zero time point at which the lead vehicle began to brake. Depending on the time window that was used in the analysis, a window began at 3-60 s before the zero time point. Note that the time windows were not sampled continuously from end to end. Because reaction time events were separated by a minimum of 75 s, over 75 s of data were available for a reaction time event. However, data beyond a time window were not included in the analysis. If the time window was 5 s, for example, only 5 s of data were sampled from the database for a reaction time event and remaining data (over 70 s, or 75 - 5 s) were not analyzed. Of course, there was some overlap between the time windows. For example, data from the second half of a 60-s window were exactly identical to data from a 30-s time window, and data from the second half of a 10-s window were exactly identical to data from a 5-s time window.

The following eye glance variables were computed over a re-configurable time window (e.g., 3, 5, 10, 15, 30, and 60 s). The attention pitch and yaw angles produced by the faceLab system were used for the computation of all eye glance variables. Note that all variables were time-based rather than task-based. Separate computations were carried out for different time windows.

- Mean glance duration (s): It was defined as the mean amount of time of all off-road glances (beyond a 24°X24° rectangular forward area) over a time window.
- Peak glance duration (s): It was defined as the time of the longest off-road glance (beyond a 24°X24° rectangular forward area) in a time window.
- Glance frequency (number of glances): It was defined as the total number of off-road glances (beyond a 24°X24° rectangular forward area) in a time window.
- Total glance duration (s): It was defined as the cumulative time elapsed for all off-road glances (beyond a 24°X24° rectangular forward area) over a time window.
- Type 1 eyes-off-road exposure: It was defined as the product of the time-based mean glance duration and glance frequency over a time window.
- Type 2 eyes-off-road exposure: It was defined as (time-based mean glance duration)$^{1.5}$ X (time-based glance frequency) over a time window.
- Attention vector (deg): It was defined as the square root of the sum of the squared attention yaw angle and squared attention pitch angle. This reflected the distance between the focus of expansion and the attention coordinates (a combination of head orientation and eye gaze).
- Attention variability (deg^2): Following the definition of visual inspection window (Recarte & Nunus, 2000), it was defined as 4 X (standard deviation of attention yaw angle) X (standard deviation of attention pitch angle).

The following performance variables were computed over a re-configurable time window (e.g., 3, 5, 10, 15, 30, and 60 s) preceding the zero time point. Again, separate computations were carried out for different time windows.

- Standard deviation of lane position (SDLP, m): The statistical formula for standard deviation was applied to the lane positions produced by the DriveSafety simulator to determine the SDLP in a time window.
- Number of lane departures: A lane departure occurred if any part of the subject vehicle crossed the left or right lane boundary. In the present study, this occurred if the lane position was greater than 1.022 m or less than –1.022 m. The total number of lane departures in a time window was tallied.
- Duration of lane departures (s): The duration of lane departures was defined as the total time that lane departures occurred in a time window.
- Mean and standard deviation of velocity (m/s): The statistical formulas for the mean and standard deviation were applied to the vehicle speed variables produced by the DriveSafety simulator.

The definition of steering entropy was provided by Nakayama, Futami, Nakamura, and Boer (1999) and Boer (2001). First, steering wheel angles from three preceding time steps were used to compute the predicted steering angle. Because the steering angles were produced by the simulator at 60 Hz, each time step was 1/60 ms (16.7 ms). Second, the predicted steering angle was compared with the actual steering angle and their difference was calculated as the prediction error. Third, the prediction errors within a time window were divided into nine bins, and the proportion of prediction errors in each bin, p_i, was calculated. Finally, $-p_i \log_9(p_i)$ was computed for each bin and summed across nine bins to derive the steering entropy measure.

7.2.2.5.2. Analysis of Variance

For NASA-TLX and each variable listed above, a mean value was computed for each of the 14 subjects and each of the 14 blocks (two type of roads by seven distraction conditions). The mean values (14 subjects by 14 blocks or a total of 196 data points) were the input for the repeated-measures analyses of variance (ANOVA). Two ANOVAs (with SAS Proc Mixed procedure, two-tailed) were performed for each of the variables. The first ANOVA employed two repeated-measures variables: road type (rural vs. highway) and levels of visual distraction. The main purpose of this ANOVA was the examination of the effect of visual distraction levels. The second ANOVA employed two repeated-measures variables: road type (rural vs. highway) and display eccentricity (dashboard display, center-stack display, and side display). The main purpose of this ANOVA was the examination of the effect of display eccentricity.

For reaction time variables (ART and BRT), a mean value was computed for each of the 14 subjects, each of the 14 blocks (two type of roads by seven distraction conditions), and the type of road curvature (straight vs. curved roads) at which the braking event occurred. The mean values (14 subjects by 14 blocks by 2 road curvatures or a total of 392 data points) were the input for the repeated-measures analyses of variance (ANOVA). The ANOVAs for ART and BRT were similar to the ANOVAs for the performance variables described above, except that a third variable, road curvature (straight vs. curved roads), was employed. The addition of this variable permitted the examination of its main effect and its interactions with other independent variables.

7.2.2.5.3. Correlation Analyses

For each of the variables listed above (including eye glance, performance, steering entropy, and reaction time variables), a mean value was computed for each of the 14 blocks (two type of roads by seven distraction conditions). Data from 14 subjects were collapsed to increase the reliability of the input data and eliminate the order effect as necessitated by the use of Latin squares design. The 14 mean values per variable were the input data for the correlation analyses. For a pair of variables (e.g., BRT and total glance duration), the Pearson correlation coefficient was computed between the pair of mean values (with SAS Proc Corr procedure). The correlation coefficient could be positive or negative and ranged from –1 to 1. If it was close to 0, the correlation was zero or weak. If it was close to 1 or –1, the correlation was strong. Inferential statistics was used to test whether the Pearson correlation coefficients were statistically different from zero (no correlation). The statistically significant and strong correlations between the eye glance variables and performance or reaction time variables were used as the primary criteria for the identification of diagnostic measures of visual distraction.

7.2.2.5.4. Regression Analyses

The input data for the correlation analyses were also used as the input data for the regression analyses. Pair-wise regressions were only performed after a significant correlation was revealed. Because the major objective of the present experiment was to determine the performance impact of eye glance measures, in the regression analyses, reaction time, steering entropy, and performance variables were considered as the dependent variables and eye glance measures were considered as the independent variables. A linear regression equation was computed between a dependent variable and an independent variable (with SAS Proc Reg procedure).

7.2.3. Results

7.2.3.1. ANOVA Results

7.2.3.1.1. NASA-TLX

The composite NASA-TLX scores were computed for each subject and block (two type of roads by seven distraction conditions). Figure 7.3 displays the means and standard errors for various conditions. The average TLX scores were approximately 20 at the baseline condition (no visual distraction was introduced) and reached approximately 60 with the highest level of visual distraction that was used in the experiment. As the visual distraction level increased, the TLX score increased, $F(4, 52)=48.98$, $p<.01$. There was no main effect for road type and no two-way interaction between road type and visual distraction level. The TLX score also increased as the display eccentricity increased, $F(3, 39)=46.13$, $p<.01$. Similarly, there was no main effect for road type or two-way interaction between road type and display eccentricity.

7.2.3.1.2. Reaction Time Variables

Figure 7.4 displays the accelerator release reaction times (ART) for road type (rural roads vs. highways), levels of visual distraction, display eccentricity, and road curvature (straight vs. curved roads) at which the braking event occurred. Two repeated-measures ANOVAs were conducted. The first ANOVA employed three variables, road type (rural roads vs. highways), levels of visual distraction, and road curvature (straight vs. curved roads). The mean ART was significantly shorter for rural roads (2.14 s) than for highways (2.59 s), $F(1,13)=35.51$, $p<.01$. It was also shorter on straight roads (2.24 s) than on curved roads (2.62 s), $F(1,13)=22.02$, $p<.01$. There was a main effect for visual distraction levels, $F(4,52)=8.36$, $p<.01$. The interaction between road type and road curvature was statistically significant, $F(1,13)=3.55$, $p<.10$. So was the interaction between road type and visual distraction levels, $F(4,52)=2.45$, $p<.10$.

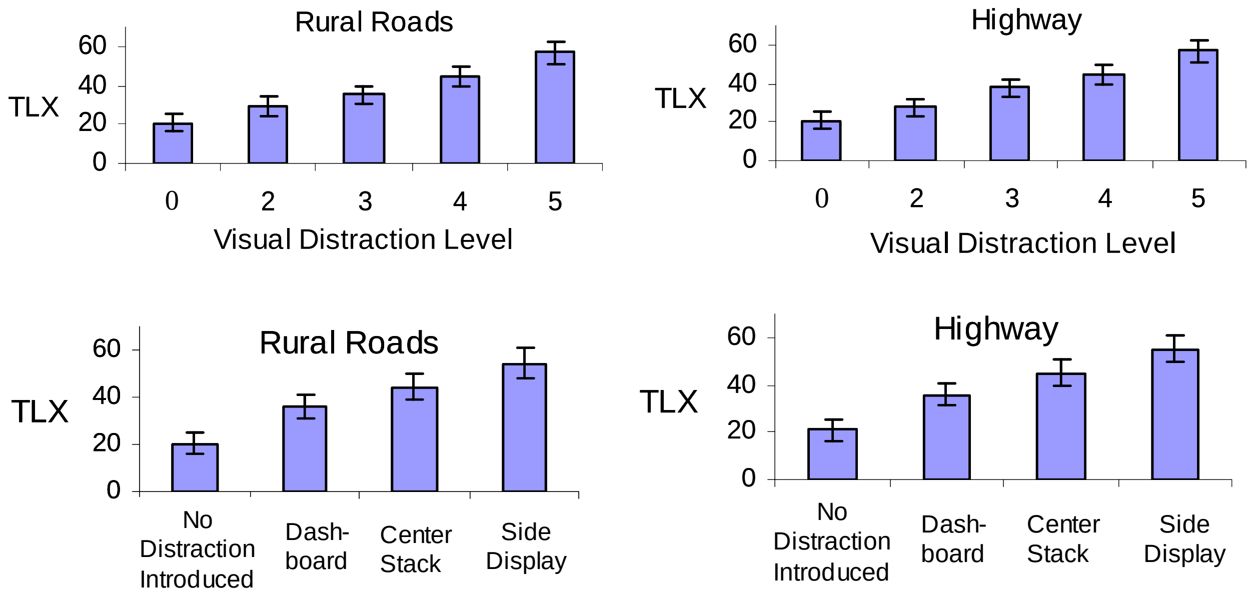

Figure 7.3. Means +/- 1 standard errors (error bars) of composite NASA-TLX scores, N=14. The top half displaying the effect of visual distraction levels (0: no visual distraction introduced; 2-5: 2-5 words per row on the center stack display), and the bottom half displaying the effect of display eccentricity.

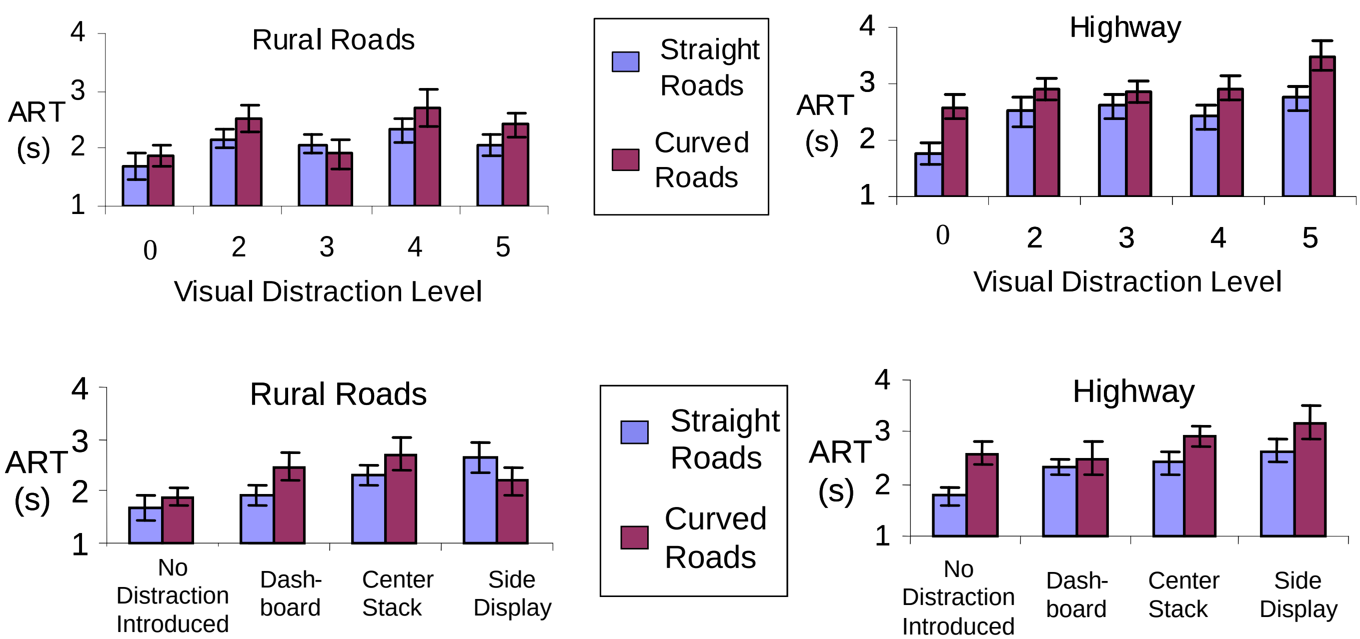

Figure 7.4. Means +/- 1 standard errors (error bars) of accelerator release reaction time (ART) (s), N=14. Visual distraction level: 0 = no visual distraction introduced; 2-5 = 2-5 words per row on the center stack display.

The second ANOVA employed three variables, road type (rural roads vs. highways), display eccentricity, and road curvature (straight vs. curved roads). Again, mean ART was shorter for rural roads (2.18 s) than for highways (2.48 s), F(1,13)=8.82, p<.05, and shorter on straight roads (2.22 s) than on curved roads (2.57 s), F(1,13)=10.11, p<.01. The main effect of display eccentricity was statistically significant, F(3,39)=8.23, p<.01. No interactions were present.

Figure 7.5 displays the brake reaction times (BRT) for road type (rural roads vs. highways), levels of visual distraction, display eccentricity, and road curvature (straight vs. curved roads). Two repeated-measures ANOVAs were conducted. The first ANOVA employed three variables, road type (rural roads vs. highways), levels of visual distraction, and road curvature (straight vs. curved roads). Overall, the mean BRT was shorter for rural roads (2.95 s) than for highways (3.21 s), F(1,13)=14.52, p<.01, and on straight roads (2.97 s) than on curved roads (3.32 s), F(1,13)=20.01, p<.01. As visual distraction level increased, BRT increased too, F(4,52)=5.59, p<.01. The interaction between road type and visual distraction level was statistically significant, F(4,52)=2.31, p<.10.

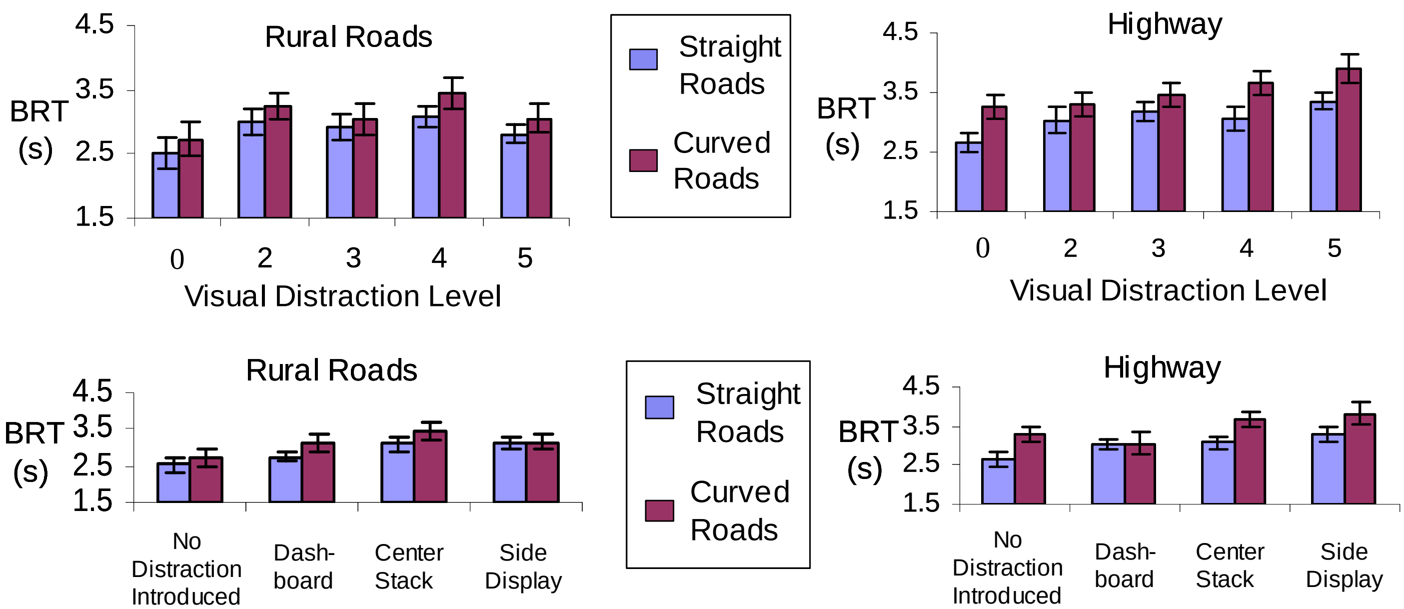

Figure 7.5. Means +/- 1 standard errors (error bars) of brake reaction time (BRT) (s), N=14. Visual distraction level: 0 = no visual distraction introduced; 2-5 = 2-5 words per row on the center stack display.

A second ANOVA was performed for BRT using three variables, road type (rural roads vs. highways), display eccentricity, and road curvature (straight vs. curved roads). Again, mean BRT was shorter for rural roads (2.95 s) than for highways (3.17 s), F(1,13)=6.57, p<.05, and on straight roads (2.95 s) than on curved roads (3.28 s), F(1,13)=12.38, p<.01. As display eccentricity increased, the BRT increased, F(3,39)=7.89, p<.01.

The accelerator-to-brake transition time from the accelerator pedal to the brake pedal was calculated as the difference between ART and BRT. As visual distraction level increased, the least square mean for the transition time was reduced from 0.915 s at the baseline condition to 0.714 s, 0.773 s, 0.678 s, and 0.617 s for increasing levels of visual distraction. The reduction was statistically significant, F(4,52)=3.91, p<.01. Similarly, as display eccentricity increased, the least square mean for the transition time was reduced from 0.91 s at the baseline condition to 0.676 s, 0.678 s, and 0.739 s for the dashboard display, center stack display, and side display. This reduction was statistically significant, F(3,39)=3.50, p<.01.

7.2.3.1.3. Performance Variables

Figure 7.6 presents the SDLP for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. SDLP was approximately 0.22 m for baseline conditions, and increased up to 0.40 m when subjects were distracted. The ANOVA with road type and levels of visual distraction as variables demonstrated a main effect for road type, F(1,13)=3.56, p<.10, and levels of visual distraction, F(4,52)=15.77, p<.01. A second ANOVA with road type and display eccentricity as variables demonstrated a main effect for road type, F(1,13)=8.39, p<.05, and display eccentricity, F(3,39)=26.83, p<.01, and a significant interaction between them, F(3,28)=4.31, p<.05. The SDLP results using other time windows (30-s, 15-s, 10-s, 5-s, and 3-s) were similar.

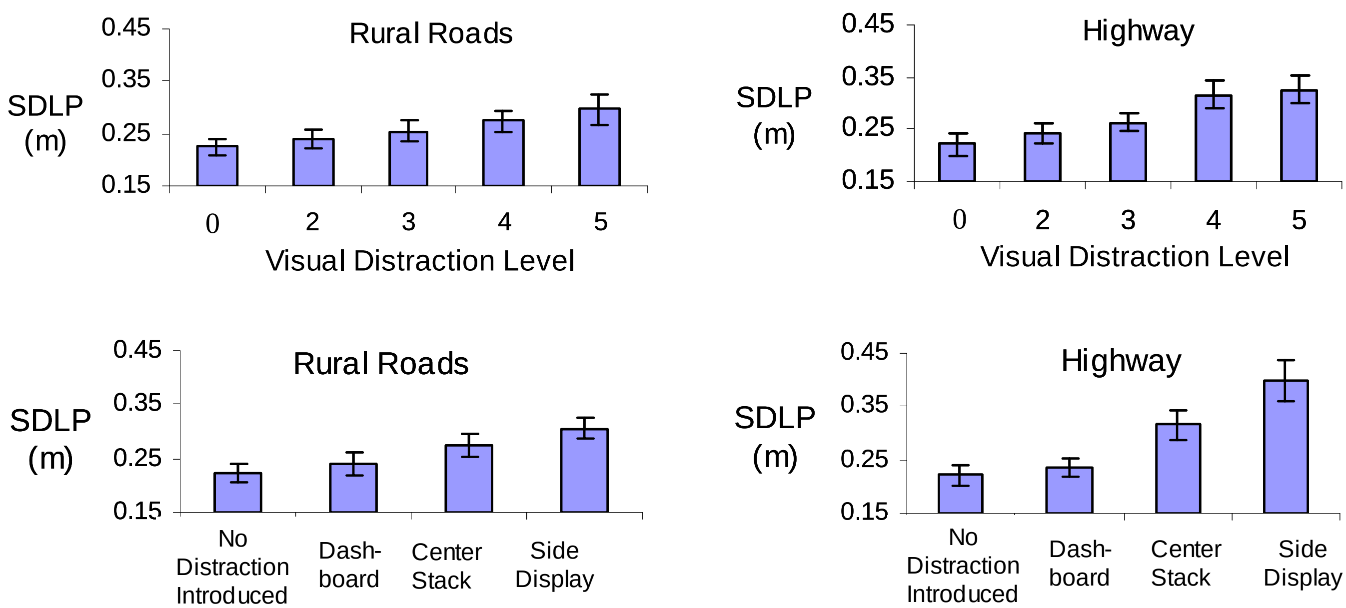

Figure 7.6. Means +/- 1 standard errors (error bars) of SDLP (m), N=14.
Visual distraction level: 0 = no visual distraction introduced;
2-5 = 2-5 words per row on the center stack display.

Figure 7.7 displays the number of lane departures for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. The number of lane departures was approximately 0.3 per minute at the baseline, and increased up to 3 per minute when subjects were visually distracted. The number of lane departures increased with an increasing level of visual distraction, $F(4,52)=10.05$, $p<0.01$, and increasing display eccentricity, $F(3,39)=11.66$, $p<0.01$. There was no main effect for road type. Similar results were obtained with other time windows (30 s, 15-s, 10-s, 5-s, and 3-s).

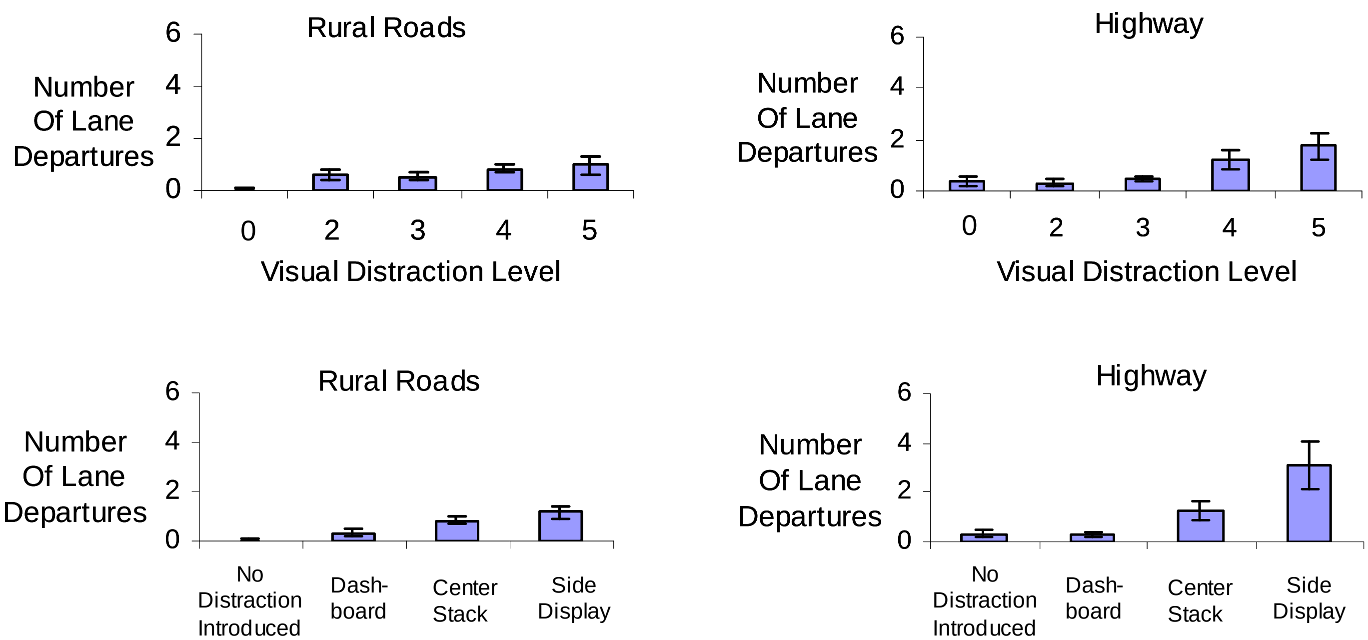

Figure 7.7. Means +/- 1 standard errors (error bars) for the number of lane departures, N=14. Visual distraction level: 0 = no visual distraction introduced; 2-5 = 2-5 words per row on the center stack display.

Figure 7.8 displays the duration of lane departures for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. The duration of lane departures was usually less than 1 s for the baseline conditions, and increased up to 8 s when subjects were visually distracted. The duration of lane departures increased with an increasing level of visual distraction, $F(4,52)=8.43$, $p<0.01$, and with increasing display eccentricity, $F(3,39)=12.93$, $p<0.01$. There was no main effect for road type. Similar results were obtained for the duration of lane departures with other time windows (30 s, 15-s, 10-s, 5-s, and 3-s).

Table 7.1 presents the mean velocity as a function of visual distraction level and road type. As the visual distraction level increased, the mean velocity increased slightly. There was a main effect for road type, $F(1,13) = 854.77$, $p<.01$, and for visual distraction, $F(4,52) = 2.17$, $p<.10$. Table 7.2 presents the mean velocity as a function of display eccentricity and road type. There was a significant effect for road type, $F(1,13) = 611.45$, $p<.01$. There is no main effect for display eccentricity, $F(3,39) = 0.54$, $p>.10$.

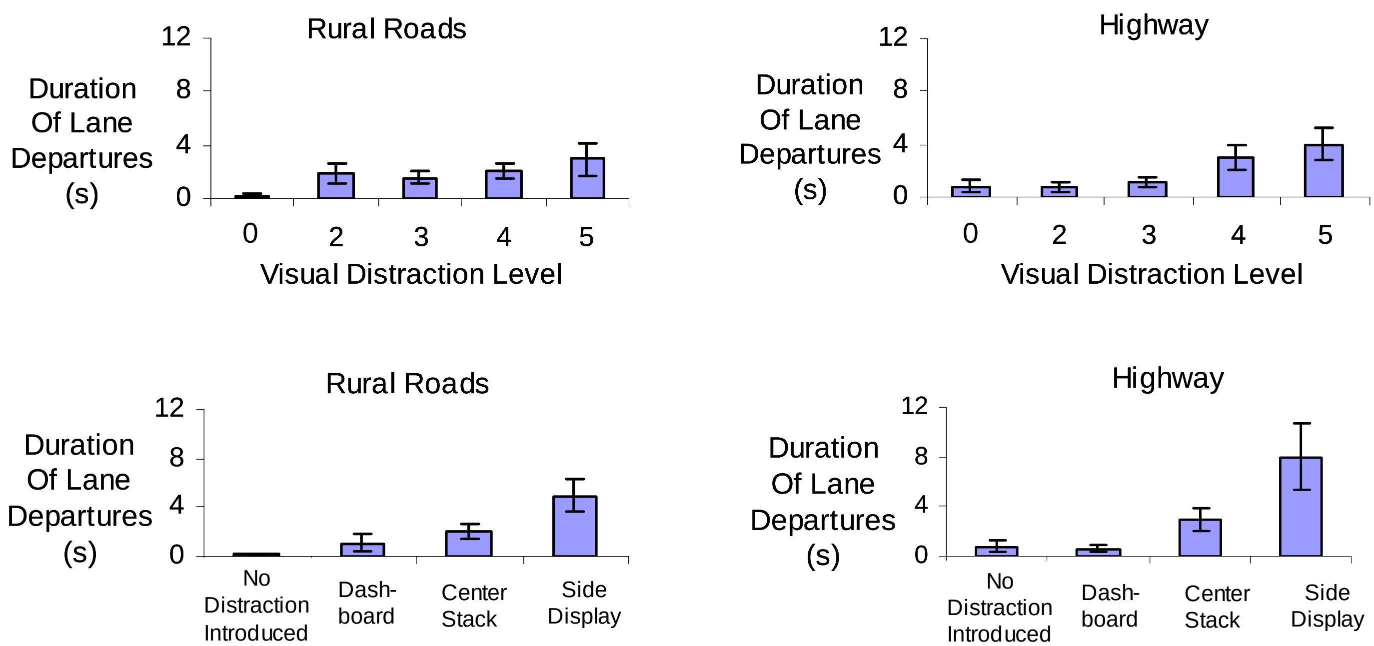

Figure 7.8. Means +/- 1 standard errors (error bars) for the duration of lane departures, N=14. Visual distraction level: 0 = no visual distraction introduced; 2-5 = 2-5 words per row on the center stack display.

Table 7.1. Means (and standard errors)

		Visual Distraction Level				
		0	2	3	4	5
Velocity	Rural Roads	19.63 (0.88)	19.82 (0.35)	19.27 (0.35)	19.71 (0.36)	20.01 (0.48)
	Highways	26.92 (0.55)	27.13 (0.39)	26.79 (0.34)	27.82 (0.38)	28.29 (0.26)
Standard Deviation of Velocity	Rural Roads	2.07 (0.39)	1.9 (0.2)	1.97 (0.13)	2.06 (0.2)	1.81 (0.17)
	Highways	1.91 (0.21)	2.19 (0.24)	2.39 (0.2)	1.93 (0.21)	2.98 (0.28)

Note: For visual distraction level, 0 = no visual distraction introduced, and 2-5 = 2-5 words per row on the center stack display.

Table 7.1 presents the standard deviation of velocity as a function of visual distraction level and road type. The standard deviation of velocity was greater for highways than for rural roads, $F(1, 13) = 6.65$, $p<.05$. As the visual distraction level increased, there were slight but insignificant variations in the standard deviation of velocity, $F(4,52) = 1.52$, p>.10. Table 7.2 presents the standard deviation of velocity as a function of display eccentricity and road type. There were small but insignificant variations in standard deviation of velocity for different display eccentricities. There was no main effect for type of roads, $F(1, 13) = 0.69$, $p>.10$, or for display eccentricity, $F(3,39) = 0.03$, $p>.10$.

Table 7.2. Means (and standard errors)

		Display Eccentricity			
		No Distraction Introduced	Dashboard Display	Center-stack Display	Side Display
Velocity	Rural Roads	19.63 (0.88)	19.7 (0.34)	19.71 (0.36)	19.37 (0.55)
	Highways	26.92 (0.55)	27.54 (0.28)	27.82 (0.38)	28.2 (0.37)
Standard Deviation of Velocity	Rural Roads	2.07 (0.39)	1.84 (0.22)	2.06 (0.2)	1.70 (0.14)
	Highways	1.91 (0.21)	2.13 (0.16)	1.93 (0.21)	2.15 (0.22)

7.2.3.1.4. Steering Entropy

Figure 7.9 presents the steering entropy for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. Steering entropy increased by 4-7% when the level of visual distraction was increased, $F(4,52)=24.38$, $p<.01$, and when display eccentricity was increased, $F(3,39)=53.81$, $p<.01$. It did not vary with road type. Similar results were obtained with other time windows (30 s, 15-s, 10-s, 5-s, and 3-s). It remains to be tested whether the small steering entropy effect can be obtained from on-road testing in which the steering angles are frequently noisy.

7.2.3.1.5. Eye Glance Variables

Figure 7.10 presents mean off-road glance duration for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. The mean glance durations were in the range of 1-2.5 s and did not vary with the level of visual distraction or display eccentricity. Similar results were obtained with other time windows (30 s, 15-s, 10-s, 5-s, and 3-s).

Figure 7.11 presents eyes-off-road glance frequency for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. As the level of visual distraction increased, glance frequency increased approximately from 10 to 30, $F(4,52)=48.09$, $p<.01$. Similarly, as the display eccentricity increased, glance frequency increased approximately from 10 to 30, $F(3,39)=31.6$, $p<.01$. There was no significant effect for the road type (rural roads vs. highways). The glance frequency results using other time windows (30 s, 15-s, 10-s, 5-s, and 3-s) were similar.

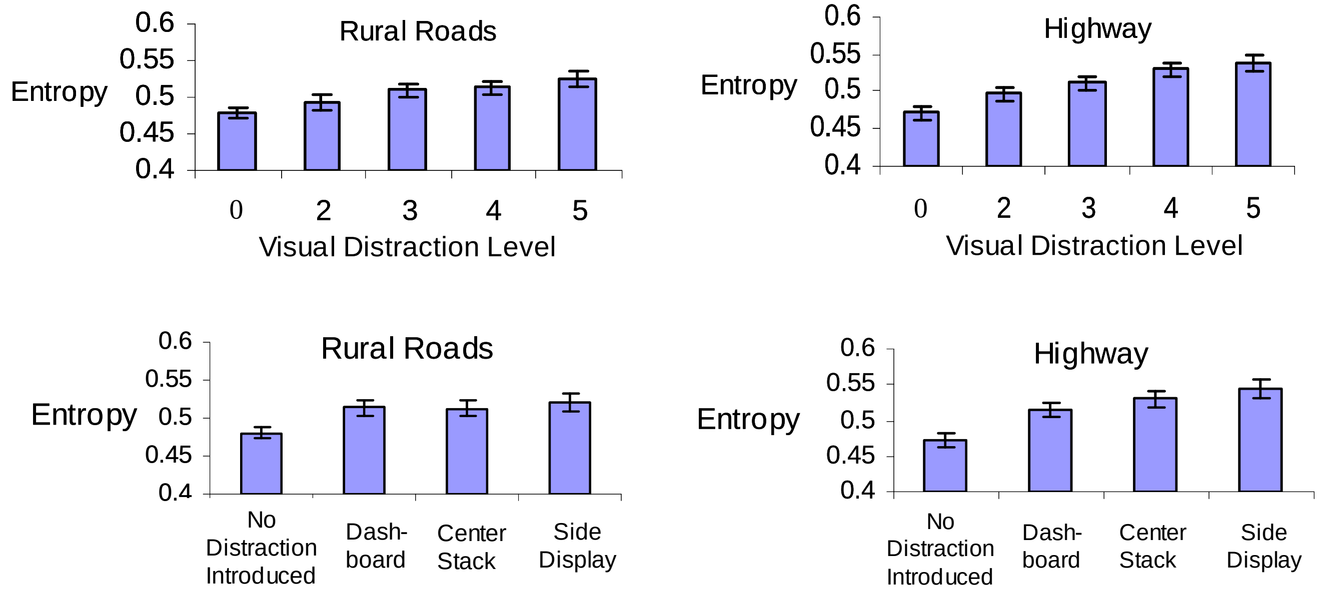

Figure 7.9. Means +/- 1 standard errors (error bars) of steering entropy, N=14.
Visual distraction level: 0 = no visual distraction introduced;
2-5 = 2-5 words per row on the center stack display.

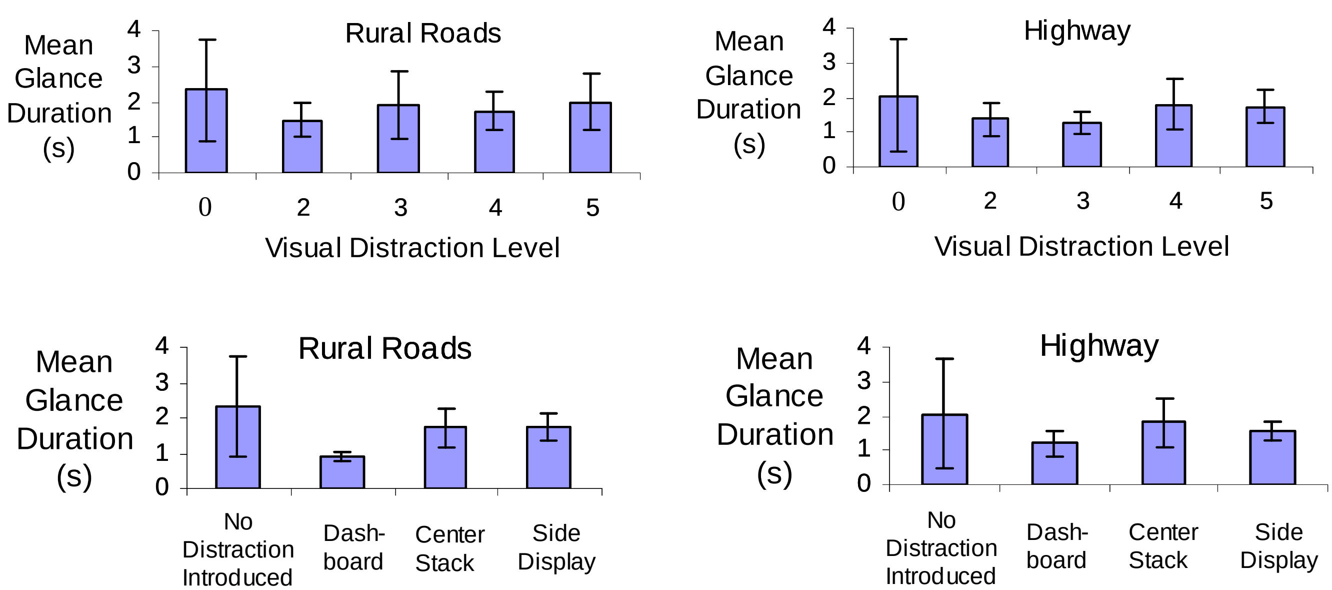

Figure 7.10. Means +/- 1 standard errors (error bars) of mean glance duration, N=14.
Visual distraction level: 0 = no visual distraction introduced;
2-5 = 2-5 words per row on the center stack display.

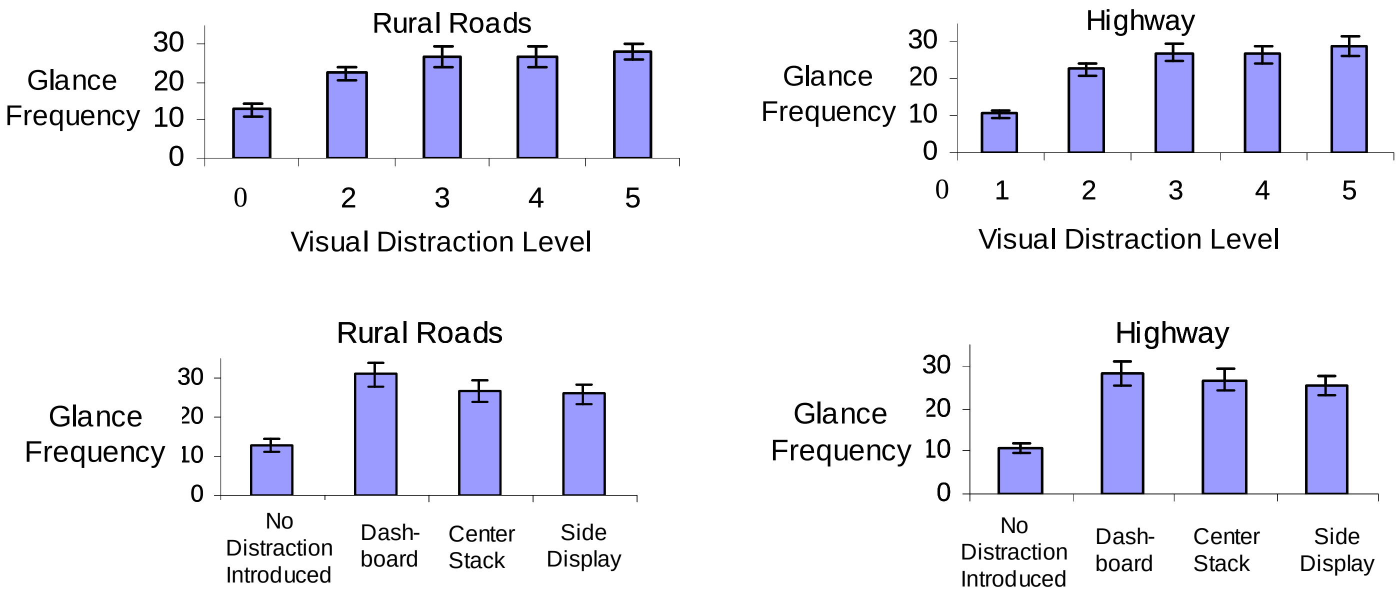

Figure 7.11. Means +/- 1 standard errors (error bars) of glance frequency, N=14.
Visual distraction level: 0 = no visual distraction introduced;
2-5 = 2-5 words per row on the center stack display.

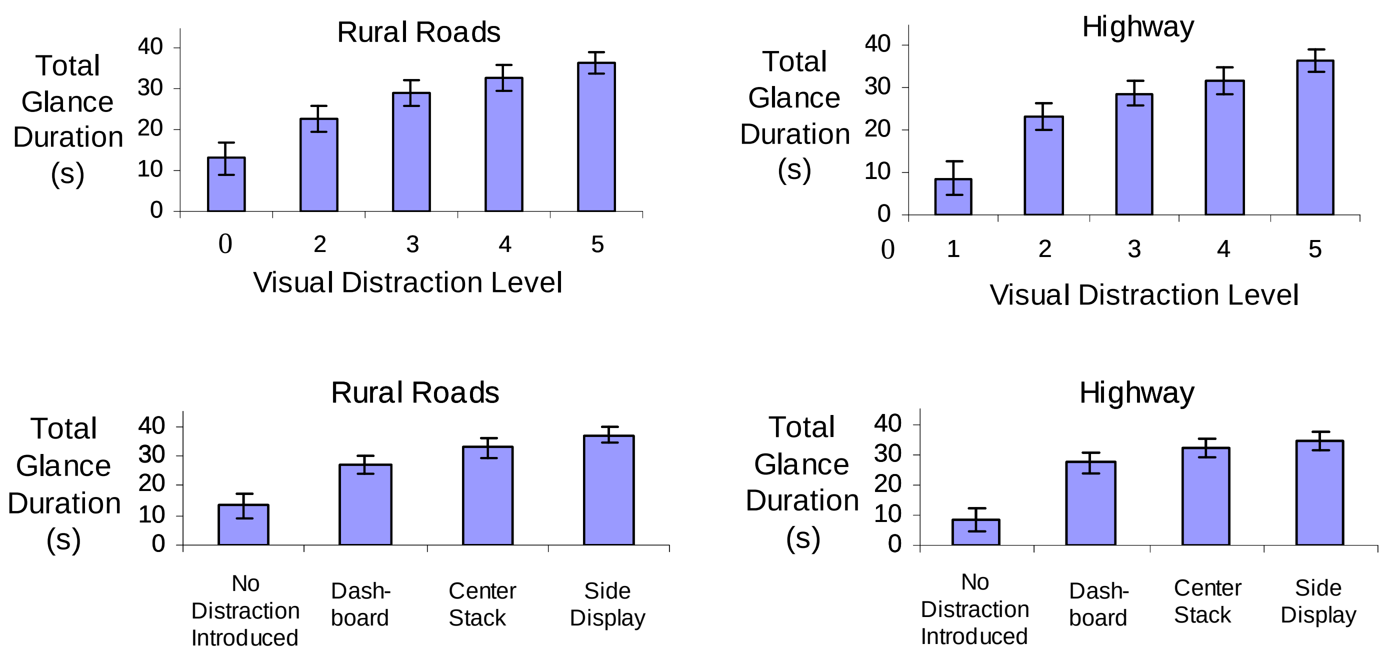

Figure 7.12. Means +/- 1 standard errors (error bars) of total glance duration, N=14.
Visual distraction level: 0 = no visual distraction introduced;
2-5 = 2-5 words per row on the center stack display.

Figure 7.12 presents total off-road glance duration for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. The total glance duration was approximately 10 s at the baseline and increased up to 37 s when subjects were visually distracted. Total glance duration increased with the level of visual distraction, $F(4,52)=83.20$, $p<.01$, and with display eccentricity, $F(3,39)=44.42$, $p<.01$. There was no main effect for road type (rural roads vs. highways). The total glance duration results using other time windows (30 s, 15-s, 10-s, 5-s, and 3-s) were similar.

Figure 7.13 presents attention variability for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. Attention variability was approximately 150 deg^2 for the baseline condition and increased up to 450 deg^2 when subjects were visually distracted. There was a main effect for the levels of visual distraction, $F(4,52)=14.75$, $p<.01$. As display eccentricity increased, attention variability increased, $F(3,39)=21.74$, $p<.01$. There was no main effect on attention variability for road type (rural roads vs. highways). Similar results were obtained with other time windows (30 s, 15-s, 10-s, 5-s, and 3-s).

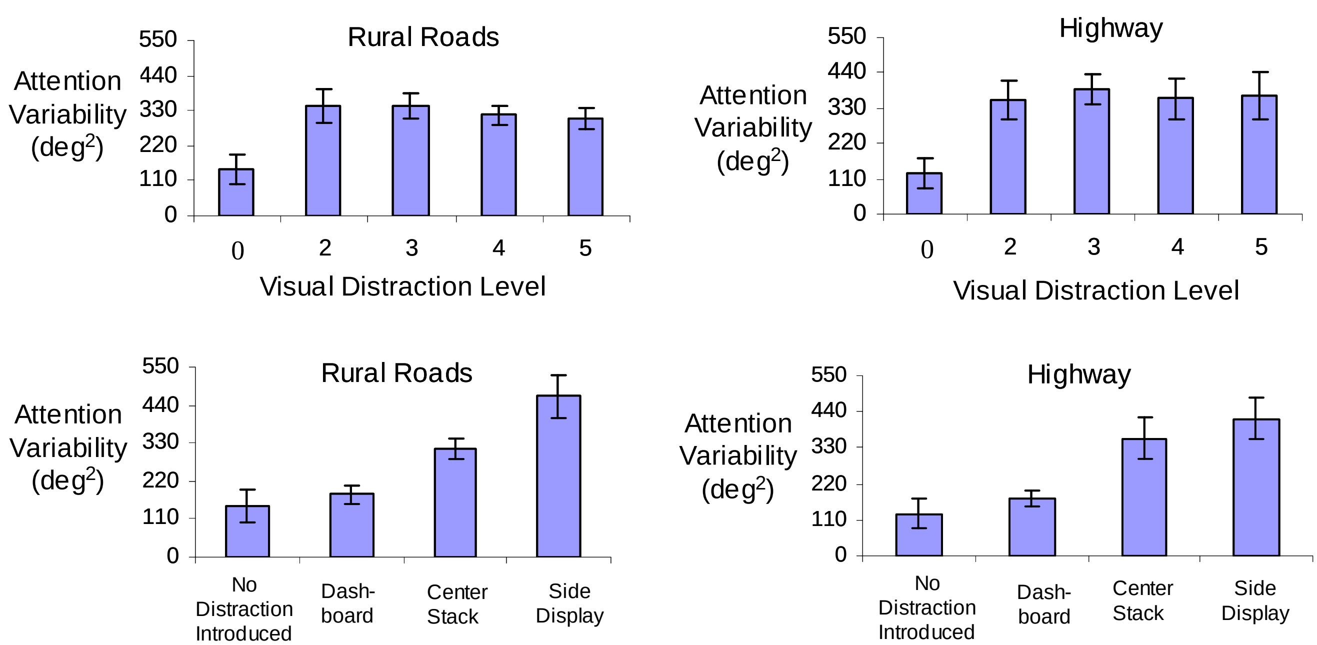

Figure 7.13. Means +/- 1 standard errors (error bars) of attention variability, N=14. Visual distraction level: 0 = no visual distraction introduced; 2-5 = 2-5 words per row on the center stack display.

Figure 7.14 presents attention vector for 14 blocks (two type of roads by seven distraction conditions) using a 60-s time window. Attention vector was approximately 10° for the baseline condition and increased up to 25° when subjects were distracted. There was a main effect for levels of visual distraction, $F(4,52)=38.30$, $p<.01$, and display eccentricity, F(3,39)=43.70, p<.01. There was no main effect on attention vector for road type (rural roads vs. highways). Similar results were obtained with other time windows (30 s, 15-s, 10-s, 5-s, and 3-s).

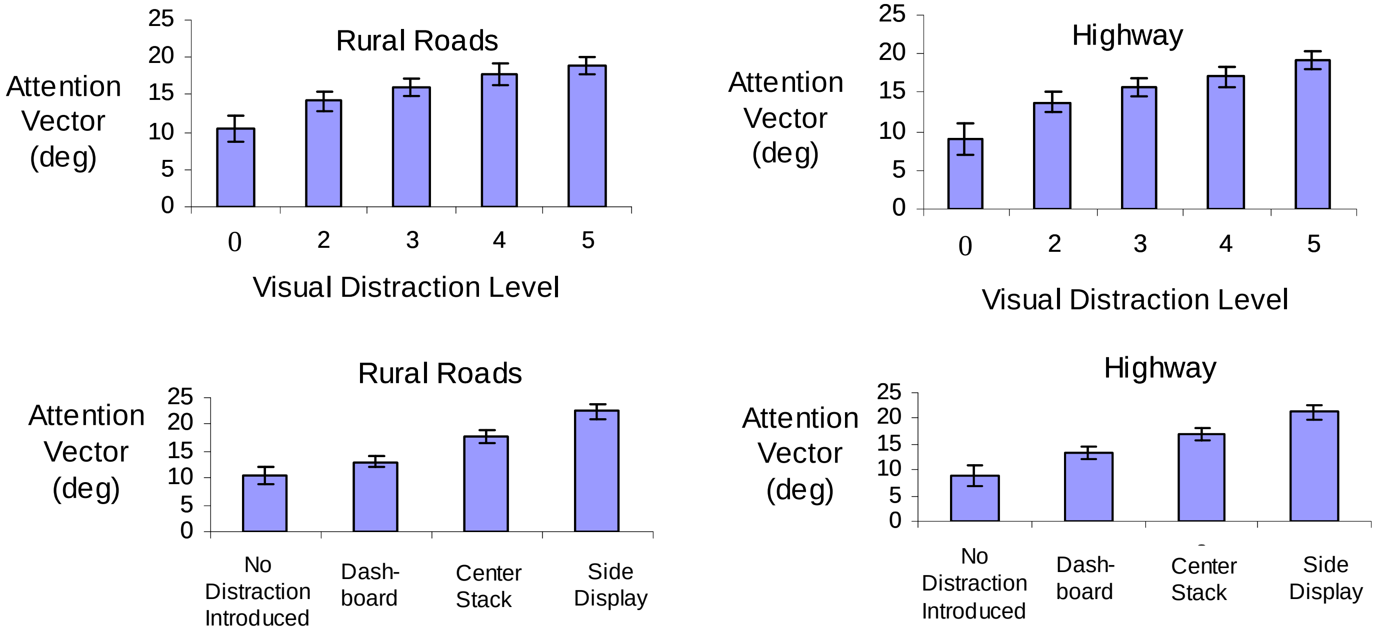

Figure 7.14. Means +/- 1 standard errors (error bars) of attention vector, N=14.
Visual distraction level: 0 = no visual distraction introduced;
2-5 = 2-5 words per row on the center stack display.

7.2.3.2. Correlation Results

Table 7.3 presents the Pearson correlation coefficients among performance variables, eye glance variables, reaction times, steering entropy, and NASA-TLX. All variables except the NASA-TLX score were computed over a 60-s time window. The performance, reaction time, and entropy variables in Table 7.3 were strongly correlated with one another. ART and BRT were highly correlated with SDLP, number and duration of lane departures, steering entropy, and TLX scores. Many eye glance variables, including eye-off-road glance frequency, total off-road glance duration, attention variability, and attention vector were correlated with each other. They were also correlated with the TLX scores. The mean off-road glance duration was negatively correlated with off-road glance frequency, and unrelated to other eye glance variables.

Perhaps the most important results were the strong association among several eye glance variables and performance and reaction time variables. The mean off-road glance duration was correlated with ART, but unrelated to other performance variables. The off-road glance frequency was correlated with both ART and BRT in addition to steering entropy. Total off-road glance duration, attention variability, and attention vector were all highly correlated with ART, BRT, steering entropy, SDLP, number and duration of lane departures. The correlation results clearly demonstrated that the total off-road glance duration, attention variability, and attention vector were reliable and diagnostic measures of visual distraction.

Table 7.3. Pearson correlation coefficients with a 60-s time window (N=14)

	BRT	Steering Entropy	SDLP	# of Lane Departures	Lane Departure Duration	Mean Glance Duration	Glance Frequency	Total Glance Duraton	Attention Variability	Attention Vector	TLX
ART	0.959***	0.682***	0.65**	0.63**	0.55**	-0.5*	0.516*	0.604**	0.657**	0.586**	0.60**
BRT		0.719***	0.734***	0.728***	0.653**	-0.393	0.501*	0.645**	0.725***	0.666***	0.649**
Steering Entropy			0.853***	0.77***	0.746***	-0.369	0.806***	0.916***	0.60**	0.836***	0.908***
SDLP				0.97***	0.95***	-0.042	0.412	0.727***	0.667***	0.845***	0.841***
# of Lane Departures					0.965***	-0.044	0.303	0.61**	0.593**	0.76***	0.754***
Lane Departure Duration						-0.036	0.309	0.652**	0.662***	0.839***	0.792***
Mean Glance Duration							-0.674***	-0.348	-0.202	-0.132	-0.172
Glance Frequency								0.861***	0.46*	0.615**	0.693***
Total Glance Duration									0.721***	0.92***	0.935***
Attention Variability										0.838***	0.649**
Attention Vector											0.933***

Note. *: p<0.10; **: p<0.05; ***: p<0.01.

The correlation analyses were also performed using other time windows (3, 5, 10, 15, and 30 s). Table 7.4 presents the Pearson correlation coefficients among performance variables, eye glance variables, and NASA-TLX, for these time windows. It was clear from Table 7.4 that although there were some variations in the correlation coefficients that could be attributed to changes in the size of the time window, the general pattern remained the same across the time windows. The only exception was the mean glance duration. As shown in Tables 7.3 and 7.4, with larger time windows (with 60-s and 30-s), the correlation between mean glance duration and other variables was always negative and usually insignificant. With smaller time windows, however, the correlation became positive and statistically significant. The positive correlation did not make sense and was likely an artifact attributable to small time windows.

Table 7.4. Pearson correlation coefficients (N=14). When applicable, each cell contained one coefficient for each time window in the order of 30, 15, 10, 5, and 3-s windows (*: p<0.10; **: p<0.05; ***: p<0.01.)

	BRT	Steering Entropy	SDLP	# of Lane Departures	Lane Departure Duration	Mean Glance Duration	Glance Frequency	Total Glance Duraton	Attention Variability	Attention Vector	TLX
ART	0.959***	0.51* 0.57** 0.549** 0.508* 0.568**	0.561** 0.529* 0.555** 0.641** 0.605**	0.626** 0.561** 0.604** 0.606** 0.628**	0.572** 0.533** 0.589** 0.626** 0.615**	-0.021 0.101 0.407 0.563** 0.465*	0.507* 0.532* 0.474* 0.335 0.517*	0.598** 0.572** 0.559** 0.638** 0.624**	0.63** 0.577** 0.653** 0.716*** 0.673***	0.58** 0.566** 0.572** 0.618** 0.582**	0.60**
BRT		0.669*** 0.70*** 0.67*** 0.631** 0.675***	0.709*** 0.663*** 0.674*** 0.757*** 0.736***	0.757*** 0.692*** 0.708*** 0.712*** 0.721***	0.711*** 0.66** 0.703*** 0.731*** 0.704***	-0.011 0.12 0.49* 0.663*** 0.597**	0.502* 0.521* 0.452 0.305 0.499*	0.637** 0.608** 0.61** 0.679*** 0.661**	0.702*** 0.634** 0.70*** 0.781*** 0.764***	0.659** 0.637** 0.65** 0.697*** 0.665***	0.649**
Steering Entropy			0.879*** 0.903*** 0.945*** 0.927*** 0.902***	0.835*** 0.868*** 0.912*** 0.874*** 0.853***	0.829*** 0.849*** 0.868*** 0.851*** 0.806***	-0.137 0.041 0.33 0.491* 0.568**	0.69** 0.647** 0.605** 0.487* 0.518*	0.74*** 0.643** 0.636** 0.609** 0.645**	0.52* 0.426 0.493* 0.653** 0.749***	0.723*** 0.644** 0.659** 0.647** 0.674***	0.703*** 0.641** 0.651** 0.623** 0.647**
SDLP				0.967*** 0.954*** 0.96*** 0.942*** 0.909***	0.95*** 0.954*** 0.957*** 0.943*** 0.873***	0.044 0.086 0.358 0.605** 0.569**	0.38 0.366 0.394 0.335 0.431	0.585** 0.472* 0.539** 0.615** 0.567**	0.529* 0.40 0.477* 0.692*** 0.718***	0.708*** 0.598** 0.637** 0.709*** 0.651**	0.634** 0.554** 0.607** 0.684*** 0.656**
# of Lane Departures					0.985*** 0.984*** 0.964*** 0.966*** 0.926***	0.059 0.166 0.301 0.605** 0.463*	0.359 0.337 0.35 0.284 0.441	0.588** 0.507* 0.513* 0.521* 0.495*	0.507* 0.461* 0.46* 0.661** 0.666***	0.711*** 0.647** 0.62** 0.648** 0.631**	0.668*** 0.611** 0.627** 0.61** 0.615**
Lane Departure Duration						0.074 0.158 0.384 0.546** 0.599**	0.339 0.309 0.274 0.204 0.328	0.592** 0.48* 0.501* 0.53* 0.523*	0.555** 0.489* 0.554** 0.706*** 0.703***	0.743*** 0.643** 0.653** 0.695*** 0.71***	0.665*** 0.579** 0.605** 0.61** 0.64**
Mean Glance Duration							-0.305 0.007 0.388 0.243 0.309	0.115 0.474* 0.801*** 0.798*** 0.788***	0.167 0.376 0.657** 0.746*** 0.752***	0.283 0.587** 0.867*** 0.883*** 0.889***	0.212 0.481* 0.786*** 0.792*** 0.776***
Glance Frequency								0.838*** 0.841*** 0.818*** 0.733*** 0.755***	0.428 0.424 0.447 0.447 0.585**	0.595** 0.627** 0.627** 0.527* 0.618**	0.684*** 0.709*** 0.674*** 0.645** 0.708***
Total Glance Duration									0.639** 0.637** 0.683*** 0.836*** 0.847***	0.922*** 0.928*** 0.933*** 0.927*** 0.917***	0.951*** 0.941*** 0.936*** 0.944*** 0.926***
Attention Variability										0.737*** 0.741*** 0.781*** 0.879*** 0.893***	0.534** 0.523* 0.599** 0.767*** 0.777***
Attention Vector											0.936*** 0.93*** 0.943*** 0.944*** 0.928***

Tables 7.3 and 7.4 reveal a few correlations that were higher than 0.90. The correlation between ART and BRT was 0.959, reflecting the close association between these two braking events. All but one of the pair-wise correlations among SDLP, number of lane departures, and duration of lane departures for all time windows exceeded 0.90, reflecting the strong associations among these lane keeping performance variables. The strong associations were reliable across a range of time windows. With 60-s time window, all but one of the pair-wise correlations among TLX, total glance duration, attention vector, and steering entropy exceeded 0.90, suggesting that all these variables represented driver workload and visual distraction. Using smaller time windows (30-3 s), all pair-wise correlations among TLX, total glance duration, and attention vector exceeded 0.90, indicating that the strong associations among these workload and visual distraction measures were reliable across a range of time windows. As shown in Table 7.4, however, steering entropy was less strongly correlated with TLX, total glance duration, and attention vector for a time window of 30-3 s. The reduced correlations indicated that a time window longer than 30 s was preferred for most reliable determination of steering entropy.

Regardless of the time window, total glance duration, attention variability, and attention vector were correlated with reaction time variable variables, performance variables (e.g., SDLP, number and duration of lane departures), and steering entropy. A comparison of Tables 7.3 and 7.4 demonstrated that the correlations did not vary with different time windows. In other words, if the correlation coefficients were plotted as a function of time windows, the plot would be almost flat. The high correlations between the eye glance variables and performance or reaction time variables over a wide range of time windows provided the strong evidence for using these eye glance variables as diagnostic measures of visual distraction.

Type I and Type II eyes-off-road exposures have been proposed as measures of visual distraction. For time-based measures, Type I and Type II exposures were defined as the product of (mean glance duration)^n and glance frequency, where n was 1 for Type I and 1.5 for Type II. Other values could also be used (e.g., 0.5 or 2). The correlations between Type I or Type II exposure and performance variables were presented in Table 7.5 for a range of time windows (60-s, 30-s, 15-s, 10-s, 5-s, and 3-s). It was clear from Table 7.5 that the correlations for Type I exposure were higher than those for Type II. It appeared that the simple linear function of mean glance duration and glance frequency (Type I exposure) was a better measure.

Table 7.5 also demonstrated that the correlations between Type I eyes-off-road exposure and performance variables did not vary with different time windows. The invariance of the correlations provided strong evidence for using Type I exposure as a reliable and diagnostic measure of visual distraction.

Table 7.5. Correlation coefficients between eye glance and performance variables (N=14) for 60, 30, 15, 10, 5, and 3-s time windows (*: p<0.10; **: p<0.05; ***: p<0.01).

	(Mean Glance Duration)$^{0.5}$ * (Glance Frequency)	(Mean Glance Duration) * (Glance Frequency)	(Mean Glance Duration)$^{1.5}$ * (Glance Frequency)	(Mean Glance Duration)^{2} * (Glance Frequency)
ART	0.591** 0.586** 0.578** 0.531* 0.565** 0.639**	0.597** 0.577** 0.54** 0.516* 0.614** 0.612**	0.429 0.468* 0.411 0.466* 0.571** 0.517*	-0.516* -0.086 0.0 0.329 0.41 0.353
BRT	0.608** 0.61** 0.599** 0.562** 0.577** 0.669***	0.639** 0.619** 0.578** 0.571** 0.654** 0.676***	0.518* 0.518* 0.453 0.531* 0.642** 0.621**	-0.441 -0.089 0.003 0.39 0.512* 0.496*
Steering Entropy	0.902*** 0.757*** 0.676*** 0.669*** 0.597** 0.612**	0.917*** 0.742*** 0.634** 0.632** 0.587** 0.601**	0.784*** 0.591** 0.476* 0.512* 0.51* 0.553**	-0.367 -0.203 -0.065 0.226 0.328 0.454
SDLP	0.62** 0.536** 0.458* 0.522* 0.549** 0.554**	0.733*** 0.594** 0.476* 0.54** 0.611** 0.57**	0.757*** 0.543** 0.396 0.477* 0.60** 0.551**	-0.058 -0.02 -0.007 0.264 0.479* 0.478*
# of Lane Departures	0.502* 0.525* 0.467* 0.488* 0.461* 0.507*	0.614** 0.59** 0.503* 0.512* 0.506* 0.509*	0.641** 0.546** 0.443 0.446 0.476* 0.482*	-0.057 0.0 0.073 0.216 0.336 0.404
Lane Departure Duration	0.53* 0.52* 0.439 0.446 0.436 0.51*	0.657** 0.593** 0.474* 0.492* 0.516* 0.571**	0.691*** 0.554** 0.414 0.456 0.523* 0.588**	-0.056 0.0 0.05 0.278 0.423 0.537**
TLX	0.858*** 0.876*** 0.888*** 0.884*** 0.597** 0.918***	0.939*** 0.956*** 0.952*** 0.952*** 0.587** 0.944***	0.919*** 0.929*** 0.916*** 0.941*** 0.51* 0.885***	-0.167 0.181 0.448 0.757*** 0.328 0.713***

7.2.3.3. Regression Results

Because eye glance variables such as total glance duration, attention variability, attention vector, and Type I eyes-off-road exposure were highly correlated with variables such as ART, BRT, SDLP, and steering entropy, linear regression equations were determined between them. The dependent variables included ART, BRT, SDLP, and steering entropy, and the independent variables were the eye glance variables. The regression equations shown below used a 60-s time window.

With ART (in s) as the dependent variable, the regression equations were as follow.

ART = 1.692 + 0.025 X (Total Glance Duration)
ART = 1.549 + 0.0356 X (Attention Vector)
ART = 1.715 + 0.0022 X (Attention Variability)
ART = 1.676 + 0.016 X (Type I Exposure)

With BRT (in s) as the dependent variable, the regression equations were as follow.

BRT = 2.564 + 0.019 X (Total Glance Duration)
BRT = 2.414 + 0.043 X (Attention Vector)
BRT = 2.564 + 0.00172 X (Attention Variability)
BRT = 2.55 + 0.019 X (Type I Exposure)

With SDLP as the dependent variable, the regression equations were as follow.

SDLP = 0.1544 + 0.0043 X (Total Glance Duration)
SDLP = 0.1016 + 0.011 X (Attention Vector)
SDLP = 0.1762 + 0.000315 X (Attention Variability)
SDLP = 0.1492 + 0.0044 X (Type I Exposure)

With steering entropy (Nakayama, et al. 1999; Boer, 2001) as the dependent variable, the regression equations were as follow.

Entropy = 0.4499 + 0.0022 X (Total Glance Duration)
Entropy = 0.4417 + 0.0044 X (Attention Vector)
Entropy = 0.4757 + 0.000117 X (Attention Variability)
Entropy = 0.4477 + 0.0023 X (Type I Exposure)

Using the total glance duration as the independent variable, for every 25%-50% increase in total glance duration (15-30 s over a 60-s window), ART, BRT, SDLP, and steering entropy would increase significantly. Table 7.6 presents the increases based on the preceding regression equations.

Table 7.6. Increase of ART, SDLP, and steering entropy as a function of total off-road glance duration.

If "total glance duration" is increased by	Corresponding Increase in			
	ART (s)	BRT (s)	SDLP (m)	Steering Entropy
25% (15 s over a 60-s window)	0.375	0.285	0.065	0.033
50% (30 s over a 60-s window)	0.75	0.57	0.129	0.066

7.2.4. Discussion

The present experiment represented a novel approach to the study of visual distraction. It used a non-intrusive eye tracking system to measure eye glance behaviors automatically. It also synchronized the eye glance behaviors with driving performance behaviors measured in a driving simulator. For the first time, it identified several eye glance variables including total glance duration, Type I eyes-off-road exposure, attention variability, and attention vector that appeared to reliably detect the level or amount of visual distraction. The fact that multiple variables may be reliable and diagnostic measures of visual distraction is encouraging and affords the product designers and engineers the ability to choose among the multiple choices. These eye glance variables are positively correlated with many performance and safety variables, including accelerator release reaction time (ART), brake reaction time (BRT), standard deviation of lane position (SDLP), number and duration of lane departures, and steering entropy.

The eye glance variables that are identified in the present experiment are time-based rather than task-based and therefore are more appropriate for real-time systems such as the SAVE-IT system. It appears that the size of the time window can be flexible. The correlations between eye glance variables and performance or reaction time variables appear to be reliable and invariant across a variety of time windows ranging from 3-60 s. Within this wide range of time windows, the correlation coefficients do not seem to vary and are consistently shown to be reliable and strong. This finding is encouraging because with this finding, relatively long or short time windows may be used for different applications and different situations.

The relationships between the eye glance variables and performance variables are represented in terms of linear regression equations. It is shown that time-based measures such as total glance duration can impact reaction time and performance measures to a large extent. For example, a 25% increase in total glance duration could slow down reaction times by 375 ms, a meaningful degradation that could significantly impact traffic safety. Similar degradations could also occur for lane keeping performance.

Consistent with the literature (Green, 1999; Wierwille, 1993), the mean glance duration does not seem to vary significantly with visual distraction conditions. As a matter of fact, the mean glance duration seems to be numerically larger and more variable in the baseline condition than the visual distraction conditions. These differences are not statistically significant, however. Therefore, the mean glance duration is not a diagnostic measure of visual distraction. The glance frequency variable varies with visual distraction conditions, but its correlations with performance or reaction time measures are not as reliable and strong as other eye glance measures such as total glance duration. Therefore, the glance frequency measure is not the first choice for the detection of visual distraction.

In the literature, it has been demonstrated that both Type I and Type II eyes-off-road exposures are related to crashes (Wierwille & Tijerina, 1998). Wierwille and Tijerina (1998) also demonstrated that Type II eyes-off-road exposure does a better job than Type I eyes-off-road exposure in predicting the number of crashes. The present experiment showed different results. In the present experiment, Type I eyes-off-road exposure is clearly a better measure than Type II eyes-off-road exposure. It is more reliably correlated with reaction time and performance variables. The difference between the present experiment and the earlier study could be the use of different dependent variables (driving performance and reaction time variables in the present study vs. number of crashes in the earlier study) and the research methods (e.g., use of an automatic eye tracking system in the present study vs. estimation of eye glance behaviors in the earlier study).

Although total glance duration, Type I eyes-off-road exposure, attention variability, and attention vector can be considered as reliable measures of visual distraction, attention variability and attention vector require a more advanced eye tracking system that can generate precise eye gaze and attention coordinates. Systems with the highest levels of precision may be cost-prohibitive. In addition, such high levels of precision may not always be attainable under realistic driving conditions. For example, eyeglasses and sunglasses could degrade the accuracy of eye tracking systems. Unfavorable lighting and vibration conditions and untypical head movements could also degrade the accuracy. On the other hand, the total glance duration and Type I eyes-off-road exposure do not require highly accurate determination of eye gaze coordinates. These measures are based on whether or not the driver's gaze is on the forward road. As demonstrated in the present experiment, these measures are equally, and in several occasions more highly and reliably, correlated with performance and reaction time variables. For reasons of performance, practicality, and cost, time-based total glance duration and Type I eyes-off-road exposure appear to be the first choices that can be used to detect the amount of visual distraction. If high levels of precision can be achieved, attention variability and attention vector are good choices too.

Consistent with the literature (Lee, McGehee, Brown, & Reyes, 2002), both the accelerator release reaction time and brake reaction time are sensitive measures of distraction. Unlike Lee, McGehee, Brown, and Reyes (2002), the accelerator-to-brake transition time varied with the amount of visual distraction. The transition time was longer at the baseline condition than for high levels of visual distraction. It appears that when subjects are attentive to the driving task, they respond to the braking lead vehicles faster in terms of releasing the accelerator pedal but take longer time to decide whether and when to depress the brake pedal. The shorter decision time associated with the distraction conditions could be due to a compensatory mechanism. Because visually distracted drivers usually respond later than the non-distracted drivers, by the time they release the accelerator pedal, the time headway is typically shorter and the situation is more severe. Thus, they decide to apply the brake immediately. On the other hand, for the non-distracted drivers, the situation is less severe when they release the accelerator pedal. Therefore, they do not need to apply the brake immediately.

Because the accelerator-to-brake transition time is in an opposite direction of the accelerator release reaction time, their composite, the brake reaction time, is not as sensitive as the accelerator release reaction time with respect to detection of visual distraction. In general, the accelerator release reaction time may be more reflective of a driver's awareness (or perception) of the driving environment, and the brake reaction time may be more reflective of a driver's reaction (or action) to environmental threats. Because driver distraction is a reflection of a driver's awareness and perception of the driving environment, the accelerator release reaction time is arguably a better variable.

Consistent with the literature, reaction times are longer for the curved roads than for the straight roads. Reaction times are usually longer for highways than for rural roads, possibly reflecting the impact of vehicle speed (65 mph for highways and 45 mph for rural roads). Other performance measures, including lane departures and SDLP, and steering entropy are also sensitive measures of visual distraction.

7.3. EXPERIMENT 2

7.3.1. Introduction

Experiment 1 presented the initial evidence for using eye glance measures such as total glance duration, attention variability, attention vector, and Type I eyes-off-road exposure for detection of visual distraction. The present experiment was performed to provide converging evidence to further substantiate these findings. If similar results could be obtained with different subjects, the findings would be strengthened considerably. To achieve the objective, Experiment 2 used similar conditions and designs.

Another major objective of Experiment 2 was to couple the braking events closely with eyes-off-road glances. Unlike Experiment 1 in which the lead vehicle braking occurred at a randomly chosen moment, in Experiment 2, most braking events occurred while subjects were induced to read aloud the words on a display. With the coupling of off-road eye glances and lead vehicle braking events, the effects of eye glance behaviors on driving performance for the few seconds surrounding the braking events can be investigated in more detail.

7.3.2. Method

7.3.2.1. Subjects

Fourteen novel subjects (seven males and seven females) were recruited, screened, and compensated in the same manner as in Experiment 1. Three subjects wore thin eyeglasses (with low prescription) and eleven subjects did not wear eyeglasses. The actual age range was 35-54, the average age was 45.43, and the standard deviation was 6.25.

7.3.2.2. Apparatus

The same DriveSafety simulator, faceLab eye tracking system (Version 2.0.1), and visual displays were used. Data from the simulator and eye tracking system were synchronized with the same interface software (IVIS SimConn). The NASA-TLX scale was again used to measure subjective rating of workload (Hart & Staveland, 1988).

7.3.2.3. Experimental Design

The independent variables were similar to those in Experiment 1. Three independent variables were employed. One variable was road type (rural roads vs. highways), which was the same as that in Experiment 1. For both type of roads, both straight and curved road segments were used. Unlike Experiment 1, however, the real braking events always occurred on straight roads. To introduce a level of unpredictability, one filler braking event could occur in some blocks, on either straight or curved roads.

A second independent variable was the level of visual distraction. Similar to Experiment 1, subjects were asked to read unrelated words displayed on a black background. Unrelated words were used to control the amount of visual distraction and minimize the cognitive load so that the effects were not contaminated by cognitive distraction. The display layout and format were the same as in Experiment 1. The number of words per row on the center-stack monitor was slightly different from Experiment 1. Because Experiment 1 showed that it was difficult for subjects to read five words per row every 13 s, that condition was removed. Instead, a new condition was added in which only one word appeared on a particular row.

A third independent variable was the display eccentricity. The dashboard monitor and the center-stack monitor were placed at the same locations and displayed the same number of words as in Experiment 1. Because in Experiment 1 subjects found it difficult to read words on the side monitor due to its large eccentricity (75° horizontal and 2° upward), the side monitor was moved forward slightly to reduce the display eccentricity (60° horizontally to the left of the subject, and 2° upward).

As in Experiment 1, three independent variables were combined to form the 14 blocks (two type of roads by seven distraction conditions). Again, Latin squares were used to balance the order of these blocks in a within-subjects design. Within each block, subjects encountered two real braking events on the straight roads and zero or one filler braking event.

The dependent variables were the same as those in Experiment 1, including reaction times, performance variables, and eye glance variables.

7.3.2.4. Procedure

The experimental procedure was the same as that in Experiment 1 except that the lead vehicle braking was tied to the display of a new page of words. As in Experiment 1, subjects were instructed to start reading a page of words when a beep was sounded. One and a half seconds later, the lead vehicle could brake slowly for 5 s (at a deceleration rate of $-2\ m/s^2$ for rural roads, or $-2.7\ m/s^2$ for highways). Similar to Experiment 1, the braking event was infrequent and occurred no more frequently than once every 75 s.

7.3.2.5. Data Analysis Overview

The eye glance, performance, reaction time, and steering entropy variables were the same as in Experiment 1. Like Experiment 1, the data analyses included the ANOVA, correlation analyses, and regression analyses. Because the lead vehicle braking was tied with eyes-off-road glances, eye glance data for the few seconds surrounding the lead vehicle braking event were analyzed in more detail.

7.3.3. Results

7.3.3.1. ANOVA Results

7.3.3.1.1. NASA-TLX

Figure 7.15 presents the means and standard errors for composite NASA-TLX scores. Similar to Experiment 1, the TLX scores were approximately 20 at the baseline conditions and increased to approximately 60 at the high distraction conditions. As the visual distraction level increased, the TLX score increased significantly, $F(4, 52)=32.57$, $p<.01$. There was neither a main effect for road type nor an interaction between road type and visual distraction level. The TLX score also increased as the display eccentricity increased, $F(3, 39)=50.68$, $p<.01$. The main effect for road type was not significant. Nor was the interaction between road type and display eccentricity.

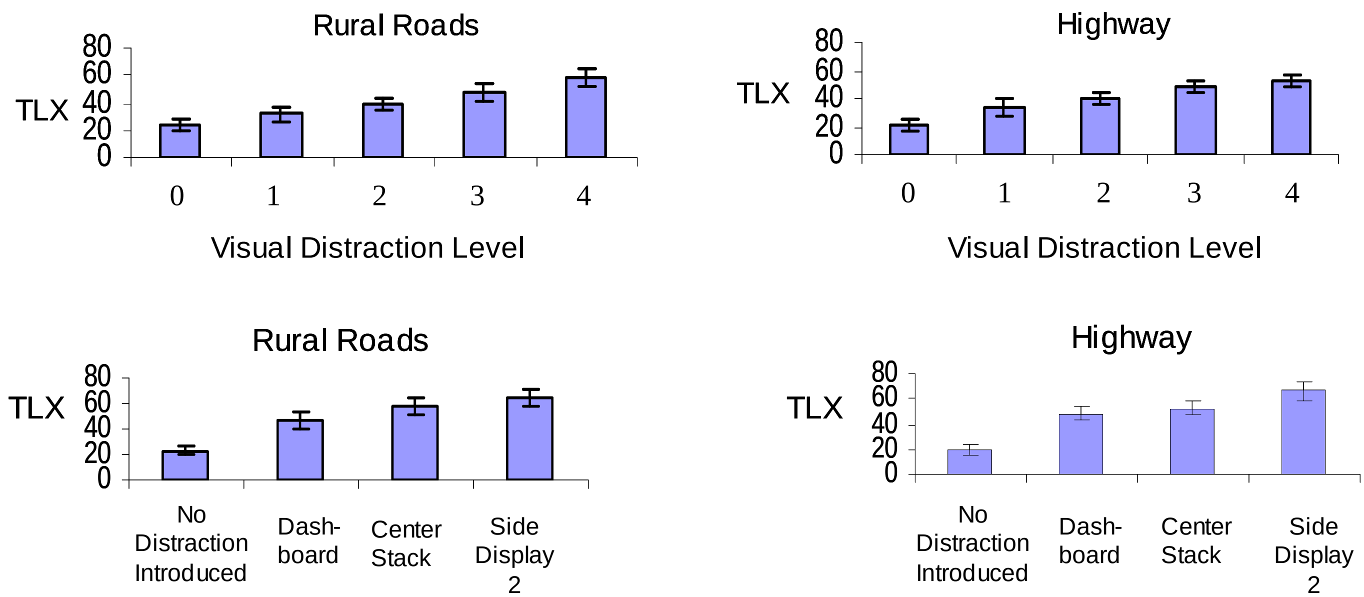

Figure 7.15. Means +/- 1 standard errors (error bars) of NASA-TLX scores, N=14. The top half displaying the effect of visual distraction levels (0: no visual distraction introduced; 1-4: 1-4 words per row on the center stack display), and the bottom half displaying the effect of display eccentricity.

7.3.3.1.2. Reaction Time Results

Figure 7.16 displays the accelerator release reaction times (ART). A repeated-measures ANOVA with road type (rural roads vs. highways) and levels of visual distraction as variables demonstrated main effects for road type, $F(1,13)=34.36$, $p<.01$, and levels of visual distraction, $F(4,52)=6.54$, $p<.01$. A second repeated-measures

ANOVA with road type (rural roads vs. highways) and display eccentricity as variables demonstrated main effects for road type (rural roads vs. highways), F(1,13)=17.43, p<.01, and display eccentricity, F(3,39)=5.69, p<.01. The results were similar to those in Experiment 1. One difference was that the mean ART was slightly longer for the side display than for the center stack display in Experiment 1, but in Experiment 2, it was slightly shorter for the side display than for the center stack display (the difference was not statistically significant).

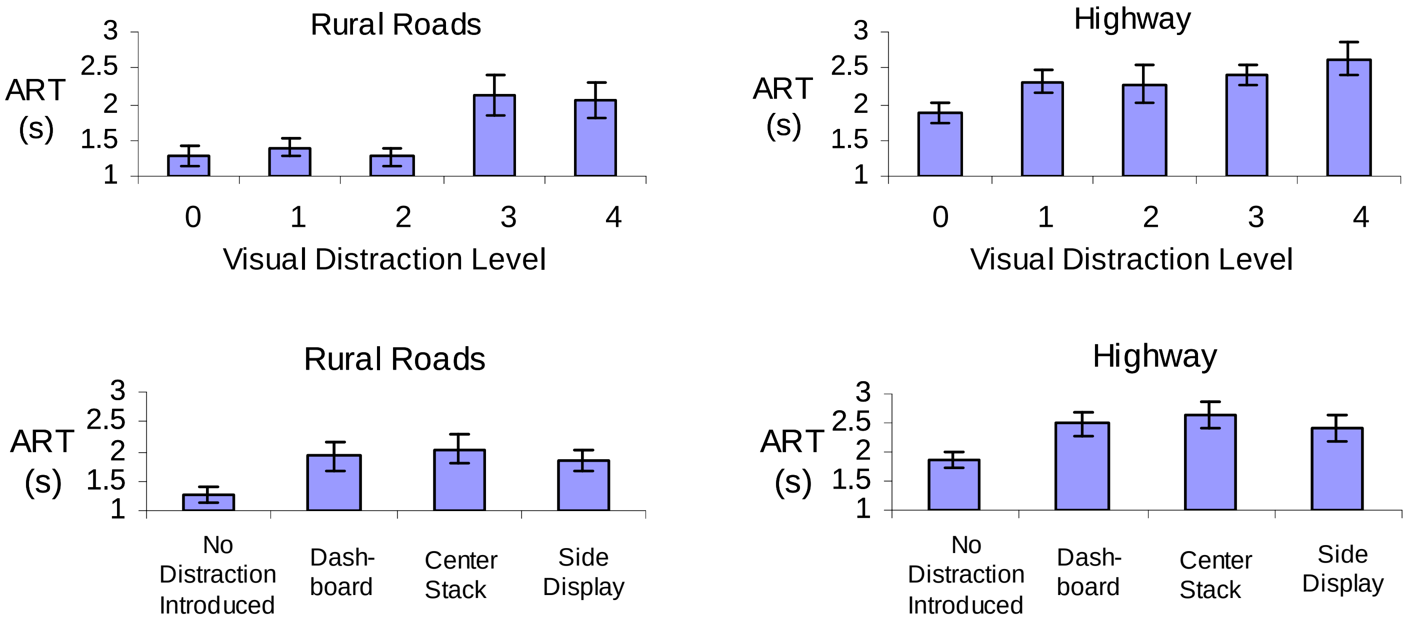

Figure 7.16. Means +/- 1 standard errors (error bars) of accelerator release reaction time (ART) (s), N=14. Visual distraction level: 0 = no visual distraction introduced; 1-4 = 1-4 words per row on the center stack display.

Figure 7.17 presents the BRT results. A repeated-measures ANOVA with road type (rural roads vs. highways) and levels of visual distraction as variables demonstrated main effects for road type, F(1, 13) = 12.36, p < .01, and levels of visual distraction, F(4, 52) = 4.54, p < .01. Another repeated-measures ANOVA with road type (rural roads vs. highways) and display eccentricity as variables demonstrated main effects for road type, F(1, 13) = 9.49, p < .01, and display eccentricity, F(3, 39) = 3.93, p < .05. Surprisingly, on rural roads, the mean BRT was considerably shorter for the side display (2.55 s) than for the center display (3.29 s). The difference between these two conditions, 0.74 s, was statistically significant, F(1, 13) = 5.0, p < .05.

The accelerator-to-brake transition time was computed as the difference between ART and BRT. At the baseline condition, the least square mean transition time was 1.251 s. As visual distraction level increased from levels 1-4, the least square mean transition time decreased to 1.083 s, 1.027 s, 0.844 s, and 0.985 s. The reduction was statistically significant, F(4, 52) = 3.20, p<.01. Compared with the baseline condition (1.251 s), the least square mean transition time was shorter at various display eccentricities, 0.844 s for the dashboard display, 0.986 s for the center stack display, and 0.863 s for the side display. The difference was statistically significant, F(3, 39) = 4.67, p<.01.

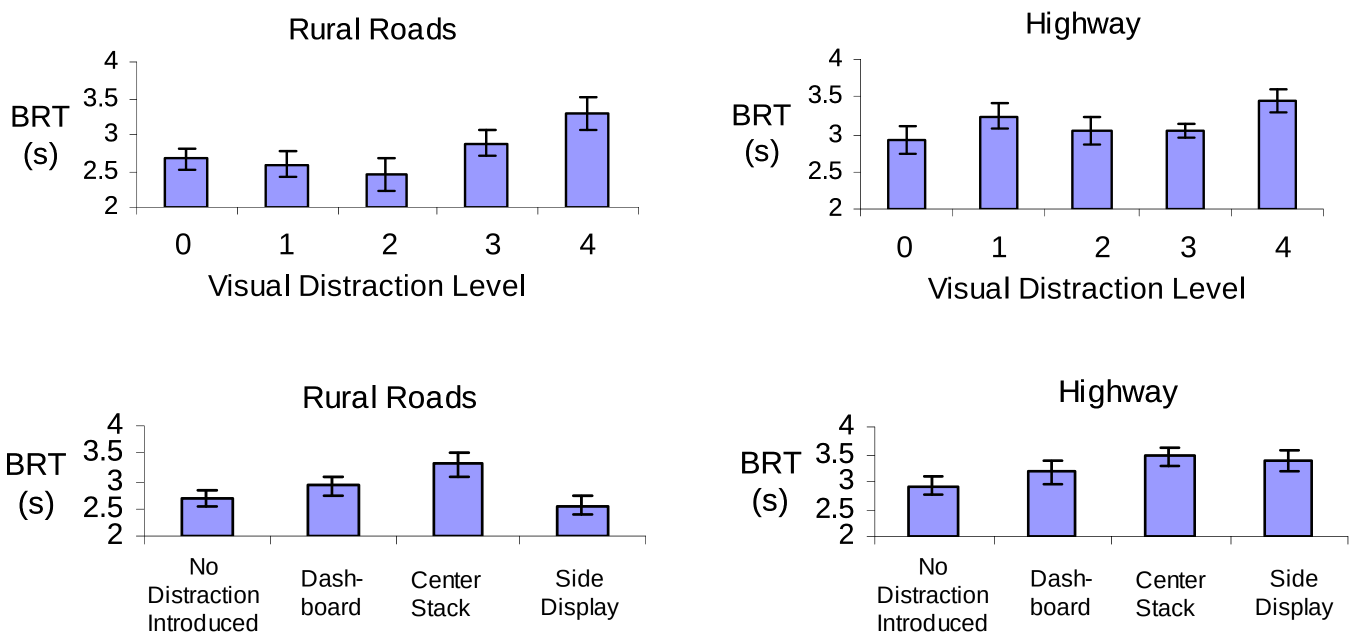

Figure 7.17. Means +/- 1 standard errors (error bars) of brake reaction time (BRT) (s), N=14. Visual distraction level: 0 = no visual distraction introduced; 1-4 = 1-4 words per row on the center stack display.

7.3.3.1.3. Performance Results

Because the performance results from Experiment 2 were similar to those in Experiment 1, results were presented in Tables rather than figures. Table 7.7 presents the means and standard errors for SDLP as a function of visual distraction level. As visual distraction level increased, the SDLP increased significantly, F(4, 52) = 9.21, p<0.01. Table 7.8 presents the means and standard errors for SDLP as a function of display eccentricity. As display eccentricity increased, the SDLP increased significantly, F(3, 39) = 25.64, p<0.01.

Table 7.7 presents the means and standard errors for the number of lane departures as a function of visual distraction level. The number of lane departures did not increase with visual distraction level, F(4, 52) = 0.49, p > 0.10. Table 7.8 presents the means and standard errors for the number of lane departures as a function of display eccentricity. As display eccentricity increased, the number of lane departures increased significantly, F(3, 39) = 8.85, p<0.01.

Table 7.7 presents the means and standard errors for the duration of lane departures as a function of visual distraction level. The duration of lane departures did not increase with visual distraction level, F(4, 52) = 0.49, p > .10. Table 7.8 presents the means and standard errors for the duration of lane departures as a function of display eccentricity. A repeated-measures ANOVA with road type and display eccentricity as factors revealed main effects for road type, F(1, 13) = 4.94, p<.05, and for display eccentricity, F(3, 39) = 6.19, p<.01.

Table 7.7. Means (and standard errors)

		Visual Distraction Level				
		0	1	2	3	4
SDLP (m)	Rural Roads	0.249 (0.016)	0.249 (0.02)	0.289 (0.029)	0.259 (0.019)	0.323 (0.022)
	Highways	0.229 (0.021)	0.246 (0.018)	0.28 (0.023)	0.264 (0.021)	0.315 (0.015)
Number of lane departures	Rural Roads	0.286 (0.18)	0.464 (0.15)	0.714 (0.26)	0.321 (0.099)	1.25 (0.377)
	Highways	0.571 (0.40)	0.75 (0.47)	0.571 (0.272)	0.571 (0.27)	0.821 (0.24)
Duration of lane departures (s)	Rural Roads	1.75 (1.29)	1.142 (0.35)	2.026 (0.7)	1.077 (0.45)	2.753 (0.87)
	Highways	1.474 (0.82)	1.903 (1.21)	1.583 (0.75)	1.983 (0.92)	1.856 (0.72)
Velocity (m/s)	Rural Roads	19.12 (0.63)	19.33 (0.66)	19.47 (0.42)	19.02 (0.62)	21.47 (0.84)
	Highways	28.41 (0.32)	28.04 (0.38)	28.03 (0.36)	26.62 (0.62)	28.44 (0.32)
Standard Deviation of Velocity (m/s)	Rural Roads	2.06 (0.26)	1.77 (0.19)	2.08 (0.24)	1.95 (0.16)	2.31 (0.23)
	Highways	1.41 (0.18)	1.4 (0.15)	1.55 (0.19)	1.57 (0.18)	1.68 (0.18)
Steering Entropy	Rural Roads	0.489 (0.0073)	0.498 (0.0084)	0.498 (0.011)	0.512 (0.011)	0.53 (0.01)
	Highways	0.497 (0.0069)	0.501 (0.0093)	0.521 (0.0084)	0.512 (0.0134)	0.536 (0.0098)

Table 7.7 presents the velocity as a function of visual distraction level and road type. There was a main effect for road type, F(1,13) = 686.19, p<.01, and for visual distraction level, F(4, 52) = 4.70, p<.01. However, there was no clear trend and mean velocity could increase or decrease as visual distraction level was increased. Table 7.8 presents the velocity as a function of display eccentricity and road type. There was a main effect for road type, F(1,13) = 449.84, p<.01, and for display eccentricity, F(3, 39) = 5.36, p<.01. The interaction between road type and display eccentricity was significant, F(3,

39) = 5.38, p<.01, indicating an increase of mean velocity for rural roads and a decrease for highways as display eccentricity increased.

Table 7.7 presents the standard deviation of velocity as a function of visual distraction level and road type. The standard deviation of velocity was smaller for highways than for rural roads, $F(1,13) = 23.55$, $p<.01$. There was no main effect for visual distraction, $F(4, 52) = 1.58$, $p>.10$. Table 7.8 presents the standard deviation of velocity as a function of display eccentricity and road type. As display eccentricity increased, the standard deviation of velocity increased significantly, $F(3, 39) = 6.03$, $p<.01$. So was its interaction with road type, $F(3, 39) = 4.84$, $p<.01$.

Table 7.8. Means (and standard errors)

		Display Eccentricity			
		No Distraction Introduced	Dashboard Display	Center-stack Display	Side Display
SDLP (m)	Rural Roads	0.249 (0.016)	0.276 (0.018)	0.323 (0.022)	0.375 (0.024)
	Highways	0.229 (0.021)	0.267 (0.021)	0.315 (0.015)	0.351 (0.028)
Number of lane departures	Rural Roads	0.286 (0.18)	0.393 (0.16)	1.25 (0.377)	1.964 (0.42)
	Highways	0.571 (0.40)	0.429 (0.25)	0.821 (0.24)	1.214 (0.34)
Duration of lane departures (s)	Rural Roads	1.75 (1.29)	1.641 (0.8)	2.753 (0.87)	5.918 (1.34)
	Highways	1.474 (0.82)	0.964 (0.54)	1.856 (0.72)	2.829 (0.86)
Velocity (m/s)	Rural Roads	19.12 (0.63)	20.42 (0.67)	21.47 (0.84)	20.32 (0.39)
	Highways	28.41 (0.32)	27.48 (0.51)	28.44 (0.32)	25.79 (0.51)
Standard Deviation of Velocity (m/s)	Rural Roads	2.06 (0.26)	2.16 (0.27)	2.31 (0.23)	2.23 (0.21)
	Highways	1.41 (0.18)	2.07 (0.16)	1.68 (0.18)	2.85 (0.26)
Steering Entropy	Rural Roads	0.489 (0.0073)	0.533 (0.013)	0.53 (0.01)	0.544 (0.0074)
	Highways	0.497 (0.0069)	0.544 (0.011)	0.536 (0.0098)	0.542 (0.01)

7.3.3.1.4. Steering Entropy Results

Table 7.7 presents the means and standard errors for steering entropy as a function of visual distraction level. Steering entropy increased by approximately 5% as visual distraction level increased. A repeated-measures ANOVA with road type and visual distraction level as factors revealed main effects for road type, $F(1, 13) = 7.13$, $p<.05$, and for visual distraction level, $F(4, 52) = 18.82$, $p < .01$. Table 7.8 presents the means and standard errors for steering entropy as a function of display eccentricity. As display eccentricity increased, steering entropy increased significantly, $F(3, 39) = 44.34$, $p<.01$. It remains to be seen whether the small effect of steering entropy can be obtained in real driving in which steering angles are more noisy.

7.3.3.1.5. Eye Glance Results

Figure 7.18 presents the means and standard errors for eyes-off-road glance frequency with a 60-s time window. As visual distraction level increased, the glance frequency increased approximately from 10 to 30, $F(4, 49) = 27.40$, $p<.01$. Compared with the baseline condition, all three display eccentricities increased the glance frequency, $F(3, 36) = 19.40$, $p<.01$.

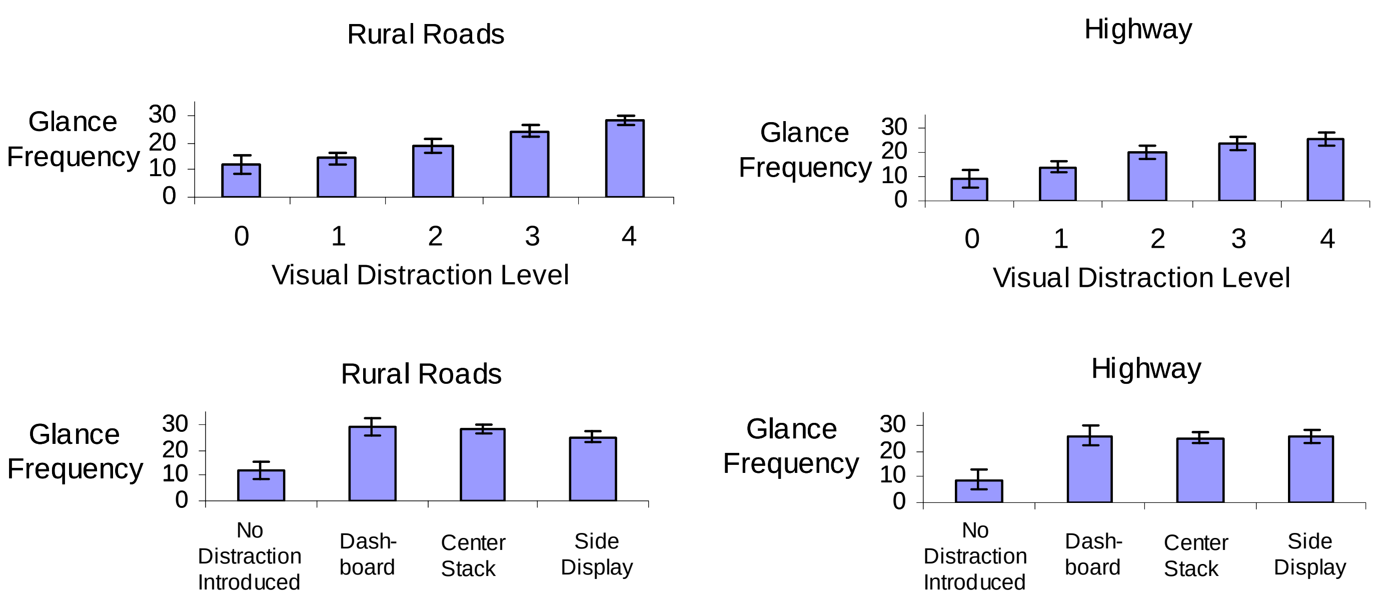

Figure 7.18. Means +/- 1 standard errors (error bars) of glance frequency, N=14.
Visual distraction level: 0 = no visual distraction introduced;
1-4 = 1-4 words per row on the center stack display.

Figure 7.19 presents the means and standard errors of total off-road glance duration with a 60-s time window. When visual distraction level increased, the total glance duration increased approximately from 10 s to 30 s, $F(4, 52) = 38.45$, $p<.01$. Total glance duration was greater for the three display eccentricities than for the baseline condition, F(3, 39) = 32.60, p<.01.

Table 7.9 presents the means and standard errors for attention variability as a function of visual distraction level. As visual distraction level increased, attention variability increased significantly, F(4, 52) = 21.99, p<.01. Table 7.10 presents the means and standard errors for attention variability as a function of display eccentricity. As display eccentricity increased, attention variability increased significantly, F(3, 39) = 41.96, p<.01.

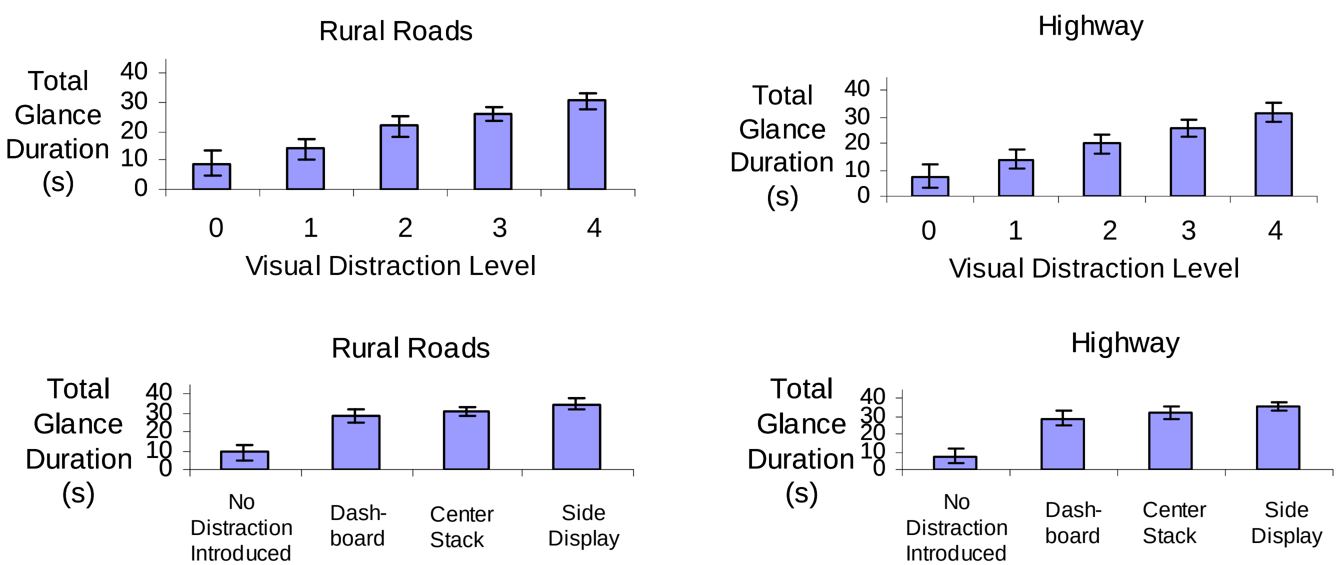

Figure 7.19. Means +/- 1 standard errors (error bars) of total glance duration, N=14.
Visual distraction level: 0 = no visual distraction introduced;
1-4 = 1-4 words per row on the center stack display.

Table 7.9. Means (and standard errors)

		Visual Distraction Level				
		0	1	2	3	4
Attention Variability (deg^2)	Rural Roads	65.0 (19.04)	141.36 (24.62)	185.18 (32.83)	220.97 (39.4)	205.21 (31.19)
	Highways	47.28 (11.82)	139.87 (15.43)	187.15 (27.25)	193.71 (27.58)	212.1 (32.83)
Attention Vector (deg)	Rural Roads	8.19 (1.66)	10.20 (1.20)	13.47 (1.83)	14.73 (1.09)	15.87 (1.03)
	Highways	7.56 (1.66)	10.26 (1.32)	12.49 (1.09)	15.13 (1.49)	17.71 (1.83)

Table 7.9 presents the means and standard errors for attention vector as a function of visual distraction level. As visual distraction level increased, attention vector increased significantly, $F(4, 52) = 26.27$, $p<.01$. Table 7.10 presents the means and standard errors for attention vector as a function of display eccentricity. As display eccentricity increased, attention vector increased significantly, $F(3, 39) = 31.67$, $p<.01$.

Table 7.10. Means (and standard errors)

		Display Eccentricity			
		No Distraction Introduced	Dashboard Display	Center-stack Display	Side Display
Attention Variability (deg^2)	Rural Roads	65.0 (19.04)	180.58 (36.12)	205.21 (31.19)	352.63 (36.12)
	Highways	47.28 (11.82)	153.33 (32.83)	212.10 (32.83)	354.6 (41.04)
Attention Vector (deg)	Rural Roads	8.19 (1.66)	15.41 (1.72)	15.87 (1.03)	21.03 (1.32)
	Highways	7.56 (1.66)	14.96 (1.26)	17.71 (1.83)	20.80 (1.20)

7.3.3.2. Correlation Results

Table 7.11 presents the results of correlation analyses with a 60-s time window. The ART and BRT results were highly correlated with each other. The ART and BRT variables were correlated with the steering entropy variable, but not with SDLP, number and duration of lane departures. There were high correlations among SDLP, number and duration of lane departures. The total glance duration was correlated with ART and other performance variables. Attention variability or attention vector was correlated with performance variables, but not ART or BRT. Glance frequency was correlated with ART, SDLP, and steering entropy. The NASA-TLX scores were correlated with all variables except BRT and mean glance duration. Similar patterns were shown with other time windows (e.g., 30, 15, 10, 5, and 3-s).

Table 7.11 clearly demonstrates a strong association (with correlation coefficients exceeding 0.80) between ART and BRT, among the lane keeping performance variables (including SDLP, number of lane departures, and duration of lane departures), among eye glance variables (including total glance duration, glance frequency, attention vector, and attention variability). Steering entropy was strongly correlated with glance frequency, total glance duration, attention vector, and TLX (with correlation coefficient exceeding 0.80). The TLX score was strongly correlated with steering entropy, SDLP, glance frequency, total glance duration, attention variability, and attention vector (with correlation coefficient exceeding 0.80).

Table 7.11. Pearson correlation coefficients with a 60-s time window (N=14)

	BRT	Steering Entropy	SDLP	# of Lane Departures	Lane Departure Duration	Mean Glance Duration	Glance Frequency	Total Glance Duration	Attention Variability	Attention Vector	TLX
ART	0.868***	0.624**	0.21	0.121	-0.051	-0.059	0.493*	0.506*	0.324	0.454	0.488*
BRT		0.477*	0.156	0.062	-0.173	-0.034	0.38	0.362	0.151	0.292	0.366
Steering Entropy			0.738***	0.531*	0.43	-0.049	0.85***	0.893***	0.71***	0.86***	0.856***
SDLP				0.874***	0.81***	-0.229	0.639**	0.814***	0.885***	0.893***	0.87***
# of Lane Departures					0.935***	-0.388	0.344	0.559**	0.734***	0.678***	0.67***
Lane Departure Duration						-0.269	0.276	0.471*	0.677***	0.611**	0.567**
Mean Glance Duration							-0.037	-0.084	-0.36	-0.129	-0.246
Glance Frequency								0.94***	0.68***	0.845***	0.88***
Total Glance Duration									0.852***	0.972***	0.974***
Attention Variability										0.933***	0.917***
Attention Vector											0.976***

Note. *: p<0.10; **: p<0.05; ***: p<0.01.

Table 7.12. Pearson correlation coefficients between eye glance and performance variables with a 60-s time window (N=14).

	$(\text{Mean Glance Duration})^{0.5}$ * (Glance Frequency)	(Mean Glance Duration) * (Glance Frequency)	$(\text{Mean Glance Duration})^{1.5}$ * (Glance Frequency)	$(\text{Mean Glance Duration})^{2}$ * (Glance Frequency)
ART	0.50*	0.495*	0.336	-0.054
BRT	0.373	0.361	0.256	-0.019
Steering Entropy	0.883***	0.897***	0.656**	-0.032
SDLP	0.76***	0.825***	0.512*	-0.225
# of Lane Departures	0.492*	0.565**	0.236	-0.376
Lane Departure Duration	0.41	0.488*	0.251	-0.258
TLX	0.956***	0.97***	0.558**	-0.249

Note. *: p<0.10; **: p<0.05; ***: p<0.01.

Table 7.12 presents the correlation coefficients for Type I and Type II eyes-off-road exposures. Type I exposure was correlated with ART and performance variables, and

Type II exposure was correlated with SDLP and steering entropy but not ART. Using other exponents for the mean glance duration did not improve the correlation. Table 7.12 clearly demonstrates that a simple linear function of mean glance duration and glance frequency, Type I exposure, was more consistently and reliably correlated with performance and reaction time variables than other functions.

7.3.3.3. Regression Results

Because eye glance variables such as total glance duration, attention variability, attention vector, and Type I eyes-off-road exposure were correlated with steering entropy, performance and reaction time variables (e.g., ART, SDLP), linear regression equations were computed between them. The regression equations shown below used a 60-s time window.

With ART (in s) as the dependent variable, the regression equations were as follow.

ART = 1.446 + 0.024 X (Total Glance Duration)
ART = 1.328 + 0.049 X (Attention Vector)
ART = 1.699 + 0.00167 X (Attention Variability)
ART = 1.414 + 0.025 X (Type I Exposure)

With SDLP as the dependent variable, the regression equations were as follow.

SDLP = 0.1962 + 0.0037 X (Total Glance Duration)
SDLP = 0.1545 + 0.00915 X (Attention Vector)
SDLP = 0.2011 + 0.00044 X (Attention Variability)
SDLP = 0.188 + 0.0040 X (Type I Exposure)

With steering entropy (Nakayama, et al., 1999; Boer, 2001) as the dependent variable, the regression equations were as follow.

Entropy = 0.4738 + 0.0019 X (Total Glance Duration)
Entropy = 0.4606 + 0.0041 X (Attention Vector)
Entropy = 0.4876 + 0.000162 X (Attention Variability)
Entropy = 0.47 + 0.002 X (Type I Exposure)

Using the total glance duration as the independent variable, for every 25%-50% increase in total glance duration (15-30 s over a 60-s window), ART, SDLP, and steering entropy would increase significantly. Table 7.13 presents the increases based on the preceding regression equations.

Table 7.13. Increase of ART, SDLP, and steering entropy as a function of total off-road glance duration.

If "total glance duration" is increased by	Corresponding Increase in		
	ART (s)	SDLP (m)	Steering Entropy
25% (15 s over a 60-s window)	0.36	0.056	0.029
50% (30 s over a 60-s window)	0.72	0.111	0.057

7.3.3.4. Analyses of Events Surrounding Lead Vehicle Braking

Because the braking event was tied with the off-road glances, the eye glance data between the moment that the lead vehicle braked and the moment that the subject depressed the brake pedal were examined in more detail and additional variables were defined. One variable was whether the driver's eye glance was on the forward road when the lead vehicle braked. A second variable was whether the driver's eye glance was on the forward road when the subject released the accelerator pedal to avoid a crash with a decelerating lead vehicle. Another variable was whether the eye glance was on the forward road when the subject depressed the brake pedal to avoid a crash with a decelerating lead vehicle. As shown in Figure 7.20, subjects may look away from the forward road a few times between the moment that the lead vehicle braked and the moment that the subject depressed the brake pedal. The duration of the final off-road glance (FORG) prior to a braking event (either accelerator pedal release or brake pedal depression) was analyzed ($FORG_A$ for accelerator release reaction time, and $FORG_B$ for brake reaction time). Shortly before subjects released the accelerator pedal or depressed the brake pedal, they usually returned their eye glance to the forward road. The time interval between the moment that the lead vehicle braked and the moment that the subject made a final return of eye glance back to the forward road prior to a braking event (either accelerator pedal release or brake pedal depression) was called glance reaction time (GRT) (GRT_A for accelerator release reaction time and GRT_B for brake pedal reaction time, respectively). The time difference between GRT and ART was called T_A and the time difference between GRT and BRT was called T_B.

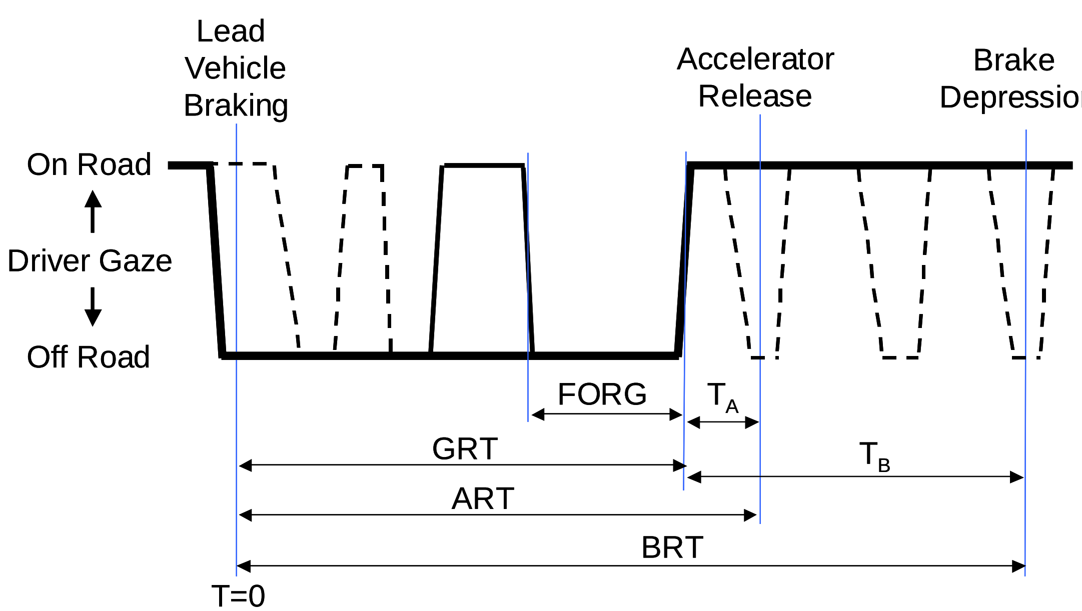

Figure 7.20. Sequence of events between lead vehicle braking and subject vehicle braking and definition of variables. The solid lines represent the eye glances that took place frequently, and the dashed lines represent the eye glances that took place less frequently.

It seemed reasonable to expect subjects to respond to the lead vehicle braking event more quickly if their eye glance was on the forward road when the lead vehicle braked than if their eye glance was away from the forward road. Figure 7.21 presents the means and standard deviations for ART and BRT as a function of whether a subject's eye glance was on the forward road or not at the moment that the lead vehicle braked. The expected results were not obtained. Whether or not a subject's eye glance was on the forward road when the lead vehicle braked did not affect ART or BRT. The lack of the effect could be due to the limitations in the experimental procedure and resultant data. In order to couple a lead vehicle braking event with an off-road eye glance perfectly, the lead vehicle braking event should be triggered by an off-road eye glance. This was not accomplished in Experiment 2. Instead, the coupling was accomplished by tying the lead vehicle braking event with the display of a new page of words. Because the braking event was often associated with the display of a new page, it was not truly random, which could have biased a subject's responses. It was also possible that the lead vehicle braking was not immediately noticeable because changes in the visual angle and expansion rate were not large initially. If the braking event was not noticeable, whether the subject's eye glance was on the forward road would not make any difference. In addition, the resultant data in this analysis were incomplete and noisy (only half of the data were included in the analysis and the other half was not usable). In order to perform this analysis, data from different conditions (e.g., with various levels of visual distraction and display eccentricity) were merged, and therefore the differences in visual distraction level and display eccentricity were not controlled in the analysis.

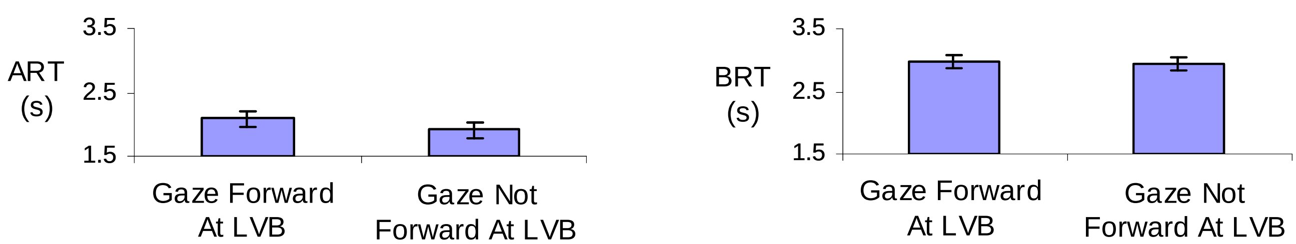

Figure 7.21. ART and BRT (in s) as a function of whether eye glances were on the forward road at the moment that the lead vehicle began to brake

It seemed reasonable to assume that subjects would look at the forward road when they began to brake in response to a lead vehicle braking event. However, that was not found in Experiment 2. Subjects frequently looked away from the forward road when they released the accelerator pedal or when they depressed the brake pedal. This was possible because in the simulator experiment the lead vehicle braking profile was fixed and subjects could have taken advantage of the fixed profile and anticipated what would happen in the next few moments. It remains to be seen if similar results can be replicated on real roads where the lead vehicle braking profile is rarely fixed.

If subjects indeed anticipated the simulator events, no reaction time differences would be expected between trials in which a subject's eye glance was on the forward when the subject released the accelerator pedal or depressed the brake pedal and trials in which a subject's eye glance was not on the forward road. This was exactly what was found in Experiment 2. The left panel of Figure 7.22 presents the ART results as a function of whether the eye glances were on the forward road at the moment that the subject released the accelerator pedal. No significant difference was found. The right panel of Figure 7.22 presents BRT results as a function of whether the eye glances were on the forward road at the moment that the subject depressed the brake pedal. No significant difference was found.

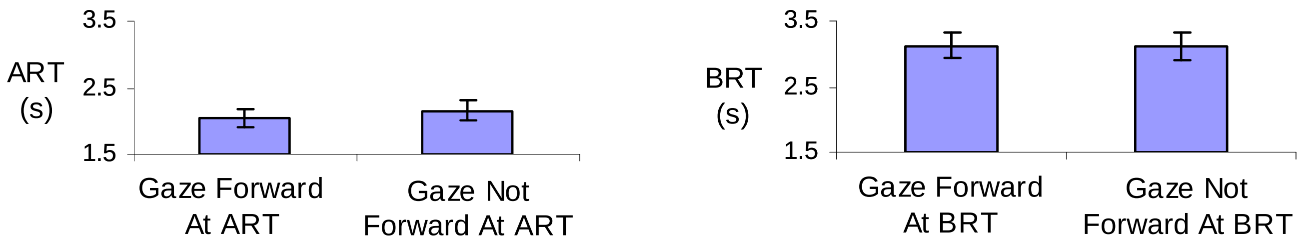

Figure 7.22. ART and BRT (in s) as a function of whether eye glances were on the forward road at the moment that the subject released the accelerator pedal (left panel) or depressed the brake pedal (right panel).

Table 7.14 presents the Pearson correlation coefficients among ART, glance RT, and FORG. The glance RT was positively correlated with ART and negatively correlated with T_A, the time difference between GRT and ART. In other words, if subjects looked away longer, their reaction times would be slower. Because with longer GRT the situation was usually more severe at the moment they returned their gaze to the forward road, the time lag between the moment they returned the gaze to the forward road and the moment they released the accelerator pedal was shorter.

Table 7.14. ART and eye glance measures

	T_A	$FORG_A$	GRT_A
ART	0.07	0.534	0.988***
T_A		-0.183	-0.77***
$FORG_A$			0.275

Table 7.15 presents the Pearson correlation coefficients among BRT, glance RT, and FORG. The glance RT was positively correlated with BRT and negatively correlated with T_B, the time interval between GRT and BRT. Again, if subjects looked away longer, the brake reaction time was slower and the time interval between the moment they returned the gaze to the forward road and the moment they depressed the brake pedal

was shorter. The FORG and BRT were positively correlated, indicating that the final off-road glance duration influenced the brake reaction time.

Table 7.15. BRT and eye glance measures

	T_B	$FORG_B$	GRT_B
BRT	-0.249	0.635**	0.973***
T_B		0.385	-0.937***
$FORG_B$			0.396

7.3.4. Discussion

Similar to Experiment 1, several eye glance measures including total glance duration, attention variability, attention vector, and Type I eyes-off-road exposure are found to be highly correlated with driving performance measures such as SDLP, number and duration of lane departures, and steering entropy. The link between eye glance variables and performance variables is also demonstrated by the high correlations between glance reaction time or final off-road glance duration and accelerator release reaction time (ART) or brake reaction time (BRT). The high correlations hold true for a wide range of time windows between 3-60 s.

The mean glance duration is again not sensitive to visual distraction variations. The glance frequency variable is sensitive to visual distraction variations in some cases but not in other cases. Overall, it is not as reliable and sensitive as other eye glance measures such as total glance duration and Type I eyes-off-road exposure.

Again, both accelerator release reaction time and brake reaction time are sensitive to visual distraction manipulation. Like Experiment 1 but unlike Lee et al. (2002), the accelerator-to-brake transition time is longer at the baseline condition than for visual distraction conditions. When subjects are attentive to the driving task, they frequently release the accelerator pedal faster, but take a longer time to decide when to apply the brake. The effect on the transition time could be due to the compensatory mechanism described previously. Because of this compensation, the brake reaction time effect is diluted. Thus, the accelerator release reaction time is demonstrated again to be a more sensitive measure of visual distraction. Similar to Experiment 1, several other performance measures, including SDLP, number and duration of lane departures, and steering entropy are also sensitive to visual distraction variations.

The correlation for reaction times, especially for BRT, is considerably weaker in Experiment 2 than in Experiment 1 (see Tables 7.3, 7.4, and 7.5 for Experiment 1 and Tables 7.11 and 7.12 for Experiment 2). This weaker correlation is largely due to one BRT value, the surprisingly short BRT for one of the rural road conditions (the side display condition) in Experiment 2. The short BRT value is likely caused by a high level of predictability of the braking events in Experiment 2 (because the braking event was tied with the display of a new page). Some subjects figured out the coupling between the display of a new page and the lead vehicle braking event and deployed a different strategy for the side display condition. They frequently waited a few seconds before looking at the side display when a page of words was presented and consequently their eye glance was frequently on the forward road when the lead vehicle braked. Because of that, subjects responded to the lead vehicle braking event quickly. This condition has the largest display eccentricity and large values for total glance duration, attention variability, attention vector, and Type I eyes-off-road exposure. If this condition is excluded, the correlations for ART and BRT would be considerably higher, as shown in Tables 7.16 and 7.17. As shown in these tables, the correlations between ART or BRT and eye glance variables such as glance frequency, total glance duration, attention vector, and Type I eyes-off-road exposure are statistically significant.

Table 7.16. Correlation coefficients with one of the rural road conditions (the side display condition) removed from analysis (N=13) and using a 60-s time window

	BRT	Steering Entropy	SDLP	# of Lane Departures	Lane Departure Duration	Mean Glance Duration	Glance Frequency	Total Glance Duration	Attention Variability	Attention Vector	TLX
ART	0.898***	0.723***	0.355	0.325	0.113	-0.092	0.524*	0.586**	0.462	0.582**	0.589**
BRT		0.722***	0.535*	0.60**	0.412	-0.147	0.491*	0.571**	0.461	0.583**	0.617**
Steering Entropy			0.694***	0.41	0.23	0.053	0.859***	0.878***	0.651**	0.836***	0.831***
SDLP				0.794***	0.741***	-0.094	0.684***	0.811***	0.833***	0.865***	0.86***
# of Lane Departures					0.87***	-0.309	0.332	0.483*	0.588**	0.552*	0.61**
Lane Departure Duration						-0.092	0.274	0.381	0.509*	0.469	0.499*
Mean Glance Duration							0.008	0.007	-0.273	-0.007	-0.161
Glance Frequency								0.953***	0.708***	0.88***	0.899***
Total Glance Duration									0.842***	0.978***	0.972***
Attention Variability										0.913***	0.907***
Attention Vector											0.974***

Table 7.17. Correlation coefficients between eye glance variables and performance variables with one of the rural road conditions (the side display condition) removed from analysis (N=13) and using a 60-s time window

	$(\text{Mean Glance Duration})^{0.5}$ * (Glance Frequency)	(Mean Glance Duration) * (Glance Frequency)	$(\text{Mean Glance Duration})^{1.5}$ * (Glance Frequency)	$(\text{Mean Glance Duration})^{2}$ * (Glance Frequency)
ART	0.561**	0.578**	0.359	-0.085
BRT	0.547*	0.578**	0.343	-0.126
Steering Entropy	0.872***	0.881***	0.654**	0.067
SDLP	0.769***	0.819***	0.538*	-0.095
# of Lane Departures	0.434	0.482	0.188	-0.3
Lane Departure Duration	0.347	0.396	0.263	-0.086
TLX	0.958***	0.967***	0.55*	-0.168

7.4. SUMMARY OF FINDINGS AND RECOMMENDATIONS

7.4.1. Summary of Findings

It has been estimated that driver distraction and inattention lead to approximately 20%-30% of crashes (Wang, Knipling, & Goodman, 1996). The driver distraction problem may become worse in the near future because an increasing number of vehicles are equipped with wireless entertainment, information, and telematics systems. To combat this problem, the SAVE-IT program has been launched to develop, demonstrate, and evaluate adaptive interface technologies in order to help reduce distraction-related crashes and enhance the effectiveness of collision avoidance systems.

The SAVE-IT program builds upon, but goes beyond, other driver distraction and workload programs such as the NHTSA-sponsored CAMP workload program (Deering, 2002; Tijerina, 2001). Although both the CAMP workload program and the SAVE-IT program investigate driver distraction issues and have a great deal of overlap (e.g., to develop metrics, methods, and protocol for distraction), they have different focuses. The CAMP workload program is focused on developing distraction metrics and methods that can be used by product designers to make more useful and less distracting devices. These metrics and methods may not be real-time measures (Tijerina, 2001). On the other hand, the SAVE-IT program is focused on developing real-time measures that can be used to mitigate driver distraction and adapt safety warning countermeasure systems based on distraction information. Because of this difference in program focus, the measures and methods may be different for the CAMP workload program and the SAVE-IT program. In addition to the requirement that the distraction measures must be reliable and diagnostic for both programs, the SAVE-IT program requires the measures to be non-intrusive (e.g., no electrodes attached to drivers), timely (e.g., in seconds rather than minutes or hours), and realistic (e.g., no expensive imaging and scanning machines).

For Task 7 (Visual Distraction), the ultimate objective is to identify reliable, non-intrusive, and timely measures that are diagnostic of visual distraction. Visual distraction is ubiquitous in the driving environment and is involved in reading a message or a label on an in-vehicle device, reading a map on a navigation system, searching for a street to turn into, dialing a phone number, answering a phone call, and picking up objects. Auditory tasks with high levels of cognitive load are not studied in Task 7, but they will be the focus in another SAVE-IT task, Task 5 (Cognitive Distraction). Because of the recent development of non-intrusive eye tracking systems, the present task focuses on eye glance measures. In the literature, eye glance measures have been shown to be critical to driving performance and traffic safety and they have been frequently regarded as good safety measures. These measures have not been used widely, however, because the determination of eye glance has been difficult until recently. The current focus on eye glance measures is also motivated by the need to identify visual distraction measures that are diagnostic and directly reflective of visual distraction. In this regard, performance measures are indirect and less diagnostic because poor performance could be a result of cognitive distraction (Lee et al., 2001; Recarte & Nunus, 2000), driver fatigue, drowsiness (Dinges, Mallis, Maislin, & Powell, 1998), and alcohol-induced driver impairments.

The literature on visual distraction research suggests several eye glance measures that influence driving performance and traffic safety (see Zhang & Smith, 2004, for a review). They include mean eyes-off-road glance duration, glance frequency, total eyes-off-road glance duration, and combinations of these measures (e.g., Type I or Type II eyes-off-road exposure). Tasks with greater off-road glance duration and frequency are more difficult and take a longer time to perform. They also lead to poorer performance and an elevated level of risk. The previous studies, however, assess these measures on a task-by-task basis. The task-based measures are suitable for product designers in determining whether or not a particular task is overly demanding. They may not be adequate for a real-time system (e.g., the SAVE-IT system) for several reasons. One reason is that the manner in which drivers group and chunk tasks cannot be determined in advance. A particular in-vehicle task may manifest different patterns of eye glance behaviors for different drivers at different circumstances and times. Another reason is that some tasks, when considered in isolation, may be low in visual demand, but when performed together within a small time window, they could manifest a high level of off-road glances. In other words, a more meaningful and useful measure for the SAVE-IT system appears to be time-based.

To fill the research gap, two related driving simulator experiments were conducted. In the experiments, subjects completed several drives on rural roads or highways while following a lead vehicle that could brake gradually (non-imminently) and erratically. They were visually distracted by being asked to read aloud a varied number of unrelated words on a display that is located at different eccentricities. This manipulation of conditions successfully produced a wide range of task difficulty and workload as measured in NASA-TLX. They also resulted in statistically significant differences for driving performance variables. As the number of words (or the visual distraction level) increased, the standard deviation of lane position (SDLP), the number and duration of lane departures, and steering entropy also increased. Driving performance was also degraded with an increasing level of display eccentricity. Because these performance variables have direct relevance to traffic safety under all driving situations (e.g., including single-vehicle run-off-the-roads crashes), it seems reasonable to expect that reducing visual distraction will enhance safety.

Importantly, a subject's reaction times to the lead vehicle braking events (in terms of both accelerator release reaction time and brake reaction time) lengthened with an increasing level of visual distraction or display eccentricity. This finding has practical implications. Because responding to roadway events in a timely fashion is critical to traffic safety, the present finding suggests that more time should be allowed for distracted drivers. This finding has direct relevance to driving scenarios such as rear-end collisions and intersection crashes. The present experiments demonstrated that the accelerator-to-brake transition time is shorter for the distraction conditions than for the baseline conditions. This effect is likely due to a compensatory mechanism. Distracted drivers decide to apply the brake immediately after they notice the evolving threat (release of the accelerator pedal) because they have to under more severe circumstance. Because of the compensatory mechanism, the accelerator release reaction time is more sensitive to visual distraction variations than is the brake reaction time.

Similarly, as the number of words on a display increased, many time-based eye glance measures that were calculated within a 60-s time window increased accordingly. These measures included the glance frequency, total glance duration, Type I eyes-off-road exposure, attention variability, and attention vector. This result demonstrated that subjects were more visually distracted with an increasing number of words to be read. Consistent with the literature, mean glance duration did not seem to vary as the number of words increased. As Wierwille (1993) put it, subjects tend to look away from the road for 1-2 s (the so-called 2-s rule), and if information is not completely gathered in one glance, they typically make multiple glances. As the display eccentricity increased, time-based measures such as total glance duration, attention variability, and attention vector increased accordingly. The mean glance duration and glance frequency did not increase. This result indicated that subjects did not tend to make more frequent glances or longer glances to locations of larger eccentricity if the number of words on a display was equal.

The two simulator experiments provided the converging evidence that an increased level of visual distraction contributed to poor driving performance and slower reaction times. The Pearson correlation coefficients between several time-based glance measures (including total glance duration, Type I eyes-off-road exposure, attention variability, and attention vector) and driving performance variables (including SDLP, number and duration of lane departures), steering entropy, or reaction time variables (accelerator release reaction time, and brake reaction time) were reliably high. The high correlations were obtained from both experiments and with a wide range of time windows (ranging between 3-60 s). These results provided the strong evidence for the claim of using time-based glance measures identified in this report as diagnostic measures of visual distraction to be used in the SAVE-IT system. Because several glance measures were identified, we have the luxury to choose one measure or a combination of measures to be implemented in the SAVE-IT system. Because statistically reliable correlations were obtained with different time windows, we also have the luxury to pick a relatively short time window (e.g., 3-5 s), or a relatively long time window (e.g., 15-60 s).

In two experiments, the relationship between the visual glance measures and driving performance measures was determined with regression equations. The regression equations, especially the scaling factors in the regression equations, were remarkably similar for the two experiments. Because of the similarity, the data from the two experiments are combined to generate regression equations that are based on both experiments. If the same condition (e.g., with same roads, same number of words on a display, and same display eccentricity) is used in both experiments, the data from the two experiments are merged to generate the mean values. There were ten conditions that were common between the experiments and four unique conditions in each experiment. Thus, the combined data set has a total of eighteen conditions. The regression equations for the combined data set are as follow.

ART = 1.502 + 0.027 X (Total Glance Duration)
ART = 1.39 + 0.0532 X (Attention Vector)
ART = 1.619 + 0.0023 X (Attention Variability)
ART = 1.476 + 0.028 X (Type I Exposure)

BRT = 2.6497 + 0.0149 X (Total Glance Duration)
BRT = 2.5829 + 0.0296 X (Attention Vector)
BRT = 2.7126 + 0.0013 X (Attention Variability)
BRT = 2.6361 + 0.0153 X (Type I Exposure)

SDLP = 0.1804 + 0.004 X (Total Glance Duration)
SDLP = 0.1349 + 0.0097 X (Attention Vector)
SDLP = 0.1898 + 0.00037 X (Attention Variability)
SDLP = 0.1752 + 0.0042 X (Type I Exposure)

Entropy = 0.4685 + 0.0018 X (Total Glance Duration)
Entropy = 0.4583 + 0.00378 X (Attention Vector)
Entropy = 0.4837 + 0.00013 X (Attention Variability)
Entropy = 0.4666 + 0.0019 X (Type I Exposure)

These regression equations express the relationships between one reaction time or performance variable and one eye glance variable. They can be used to convert eye glance variables to performance variables. Because of the outlier BRT value described previously, the slopes of the regression lines were shallower for BRT than for ART. The actual slopes could be steeper than the regression lines represent.

7.4.2. Recommendations For Preliminary Human Factors Guidelines

Based on the research presented in this report and the findings from the two simulator experiments, the following preliminary human factors guidelines are recommended. Because the research focus in Task 7 is visual distraction, the recommendations are restricted to methods and measures pertaining to the assessment of visual distraction in a real-time system using adaptive interface technologies. No recommendation regarding cognitive distraction (e.g., cell phone conversations) will be made in this report. These preliminary recommendations should be considered in the future in order to establish formal human factors guidelines and standards that may be applied to a wider group of audiences.

Recommendation 1: Non-intrusive, automatic, and reliable eye tracking systems should be used to examine a driver's visual behavior and assess the level of visual distraction. These systems can provide a large amount of eye glance data efficiently to facilitate the research and development process in the area of visual distraction, an extremely important type of driver distraction that has significant implications for traffic safety.

Recommendation 2: For a real-time system that is designed to mitigate driver distraction and adapt safety warning systems, time-based eye glance measures (e.g., glance duration and frequency over a 5-s time window) are more appropriate than task-based eye glance measures (e.g., glance duration and frequency for a radio-tuning task).

Recommendation 3: Several visual glance measures are reliable and diagnostic measures of visual distraction that can be used in a real-time system using adaptive interface technologies. The recommended measures include time-based total eyes-off-road glance duration, Type I eyes-off-road exposure, attention variability, and attention vector. The total glance duration and Type I eyes-off-road exposure appear to have one technical advantage over attention variability and attention vector because they do not require highly accurate eye tracking systems. The only requirement for them is the determination of whether the driver gaze or head orientation (attention) is on the forward road or away from the forward road. The precise determination of a driver's gaze and attention in terms of XY coordinates is more difficult than the determination of whether the driver gaze or head orientation (attention) is in a forward area and typically requires a more costly system.

If a precise gaze determination cannot be achieved but the driver's gaze or head orientation can be categorized into forward or not forward, it is recommended to use time-based total eyes-off-road glance duration and Type I eyes-off-road exposure for detection of visual distraction. If precise gaze coordinates can be obtained, two other measures, attention variability, and attention vector, are recommended. Because of performance, practicality, and cost considerations, time-based total glance duration and Type I eyes-off-road exposure are recommended as first choices, and attention variability and attention vector are recommended as second choices.

Recommendation 4: The above-mentioned eye glance measures are reliable measures of visual distraction over relatively short time window (3-5 s) and relatively long time window (15-60 s). Because of this finding, systems engineers and product designers may use different time windows to optimize different system components and subsystems. In some situations (e.g., when an environmental threat is present), short time windows may be used so that the driver's awareness of the environmental threat can be determined. In other situations (e.g., when an environmental threat is not present), longer time windows may be more appropriate. The relatively short time windows may be preferred sometimes because fewer samples need to be stored in the memory and processed in the computer chip.

Recommendation 5: Traditional eye glance measures such as mean glance duration and glance frequency do not seem to be best suited for applications in real-time systems. The mean glance duration is typically between 1-2 s and does not appear to vary with the amount of visual distraction. The glance frequency varies with the amount of visual distraction, but its correlations with performance and reaction time variables are not as reliable and strong as other eye glance measures such as time-based total glance duration. Thus, when the first and the second choices described above are not available or applicable, glance frequency may be used as an alternative measure of visual distraction.

Recommendation 6: The forward road area should be defined as a rectangular area around the focus of expansion. The exact size for that area may be best determined with a simulator or on-road study. The present experiments suggest an area that spans approximately +/-12° both vertically and horizontally (a 24° by 24° rectangular area) as the forward road area.

Recommendation 7: The above-mentioned eye glance measures can be converted to reaction times using linear regression equations. The reaction times can be fed into safety warning countermeasure systems to adapt the systems based on visual distraction information.

Recommendation 8: The above-mentioned eye glance measures are related to performance variables such as lane keeping performance. When lane keeping performance variables (e.g., SDLP and lane departures) cannot be obtained in real driving, these eye glance measures, along with the regression equations obtained in the present experiments, may be used to predict the lane keeping performance. When lane keeping variables can be obtained in real driving, they can be used in addition to the eye glance measures to provide the converging evidence for the distraction state and augment the confidence level of the system. The use of multiple sensors and measures will reduce the probability of false detections.

7.4.3. Recommendations For Future Research (Phase II)

Further studies should be conducted to generalize the present findings to broader and more realistic circumstances. Each of the two present experiments employed fourteen subjects and the Pearson correlation coefficients and regression equations were averaged across the subjects. The averaging across subjects is typically adopted in the literature. Averaging is often required in research to filter out noise and obtain reliable data. This is especially acute for reaction time research because reaction times are highly variable and single reaction time data points are often too noisy. In the present study, the statistically significant correlations between eye glance variables and performance variables provided strong evidence for using the eye glance variables as the diagnostic measures of visual distraction. However, what is missing from the averaged data is the inter-subject variability. It is well known that there are individual differences with respect to driving behaviors and eye scanning patterns. To address this issue, correlation analyses and ANOVAs may be performed on the individual basis. The research findings from the present study could be strengthened by similar positive correlations within single individual driver. Ultimately, the SAVE-IT system will be used by individual drivers. It is important to demonstrate that the eye glance measures identified in the present experiments can still be diagnostic of visual distraction within individual drivers.

A follow-up simulator experiment could be performed in which a small number of subjects (e.g., two or three subjects) are studied in multiple sessions. The type of roads (rural roads vs. highways), the visual distraction conditions (reading aloud varied number of words on a display), and the display eccentricity could be similar to the present experiments. Instead of using a large number of subjects and one session per subject, the future experiment could use a small number of subjects and multiple sessions per subject. The averaging method will still be needed to filter out noise in the data. Instead of averaging across subjects to reduce noise associated with the raw data, however, the future experiment could average across multiple sessions to reduce noise in the data. Multiple exposures may also allow the analysis of momentary eye glances to further assess the effect of momentary eye glances on reaction times. If the future experiment can demonstrate similar patterns of correlation coefficients with individual subjects, the claim of using eye glance measures such as time-based total glance duration, Type I eyes-off-road exposure, attention variability, and attention vector will be substantiated.

The present experiments were performed in a fixed-based driving simulator with one forward visual channel. The field of view was approximately 50° X 40° and did not represent the 360° field of view that is present in the real driving. It would be helpful to perform a similar experiment on a more advanced simulator (e.g., the NADS at the University of Iowa) to determine if similar results can be obtained.

The driving simulator was used in the present experiments because the high levels of visual distraction that were essential to produce a wide range of visual distraction levels could jeopardize safety if the experiments were carried out on real roads. It was also deployed to maximize the level of control. The visual environment in the simulator, however, is not the same as the real driving environment that drivers experience on a daily basis. For example, the traffic lights, buildings, billboards, real traffic patterns, trees and vegetations are not fully represented in the simulator. The distance cues and the vividness associated with a 3-D environment are difficult to be replicated in a driving simulator. It is conceivable that drivers exhibit different eye glance behaviors in the real driving than in a driving simulator.

It would be of value to validate the eye glance measures that are identified in the present experiments with additional data that are collected from naturalistic on-road driving. Because it is unreasonable in realistic driving for the experimenter to expose subjects to high levels of visual distraction that could compromise driver safety, the engagement of visually distracting tasks will be at the driver's discretion (naturalistic) and therefore opportunistic. A naturalistic on-road driving experiment will be conducted in other SAVE-IT tasks during Phase II. The naturalistic driving data from that experiment will be used to test the robustness of the eye tracking system and validate the reliability of eye glance measures in realistic driving conditions. The correlation coefficients between the eye glance measures such as time-based total glance duration, Type I eyes-off-road exposure, attention variability, and attention vector and the performance and safety measures such as SDLP and lane departures can be determined from the on-road data. The on-road data may also be analyzed to optimize the range and threshold values for these eye glance variables. If the findings from the present simulator experiments are validated with naturalistic on-road data, the confidence level for using the eye glance measures identified in the present experiments as diagnostic measures of visual distraction will be considerably augmented.

The faceLab system used to measure eye glance variables are non-intrusive and when calibrated, can operate automatically without a driver's interventions. It works under a wide range of lighting conditions. It can generate driver gaze coordinates and attention pitch and yaw angles reliably and accurately most of the time. However, the system can sometimes lose tracking or track the wrong features. The system may sometimes generate noisy data. It may not work with some eyeglasses or sunglasses. The size of the system (e.g., two cameras and a Pentium PC) may be too big for automotive applications and the associated cost may be prohibitive. These represent significant challenges in the effort to bring the SAVE-IT system to the mass market. The development of eye tracking systems is beyond the scope of the SAVE-IT program. We hope, however, that the human factors research presented in the present report and other SAVE-IT reports will accelerate the pace of development in eye tracking systems.

A related technology challenge is in the area of lane position determination. Consistent with the previous findings, the present study demonstrates the importance of SDLP, number and duration of lane departures. These performance measures are not readily available in today's vehicles. These measures, however, could provide the converging evidence for diagnosing visual distraction. Again, the development of such technologies is beyond the scope of the SAVE-IT program. We hope the SAVE-IT research will accelerate the development for reliable lane tracking systems.

In Phase I, we have adopted a "divide-and-conquer" approach and partitioned driver distraction research into two tasks: Task 5 (Cognitive Distraction) and Task 7 (Visual Distraction). As a result, auditory tasks are employed in Task 5 and visual tasks are employed in Task 7. The partitioning is a crucial step in identifying reliable measures that are diagnostic of one type of distraction but not the other. It is reasonable to expect different behavioral manifestations for these two types of distraction. Each task has a high level of complexity that requires a concentrated effort. After the diagnostic measures are identified for visual and cognitive distraction respectively, the next step is to investigate them in a single experiment in order to examine their relative impacts and their interactions. It is conceivable that their effects are interactive rather than additive.

In Phase II (Task 11: Data Fusion), a simulator experiment may be carried out that includes experimental conditions with varied levels of visual and cognitive distraction. For the cognitive distraction tasks, auditory as well as visual information may be presented (Lee et al., 2001; Recarte & Nunus, 2000). The diagnostic measures and regression equations developed in Task 5 (Cognitive Distraction) will be employed to gauge the level of cognitive distraction. By the same token, the diagnostic measures and regression equations developed in Task 7 (Visual Distraction) will be employed to gauge the level of visual distraction. In this manner, the levels of visual and cognitive distraction will be determined for various experimental conditions. Driving performance and reaction times will be measured for the same experimental conditions. Correlation analyses and regression analyses will be performed with three types of variables: performance or reaction time variables (e.g., ART, BRT, SDLP, lane departures), level of visual distraction (e.g., with time-based total glance duration, Type I eyes-off-road exposure, attention variability, attention vector), and level of cognitive distraction (e.g., with eye scanning patterns, interactions with in-vehicle devices). For example, if visual distraction is diagnosed with total glance duration, cognitive distraction is diagnosed with a driver's interactions with in-vehicle devices, and effects of visual and cognitive distraction are additive, the following linear regression equation may be generated to represent the reaction time impact of composite distraction.

$$ART = a + b \times f(\text{total glance duration}) + c \times f(\text{a driver's interactions})$$

If effects of visual and cognitive distraction are interactive rather than additive, the regression equations will be more complex. Graphic depiction of the data and advanced statistical methods may be employed to determine the relationships among these variables.

The ultimate goal of the SAVE-IT program is to demonstrate the feasibility and a proof of concept to use distraction information and adaptive interface technologies to reduce distraction-related crashes and enhance safety warning countermeasure systems. The research on the measurement of visual distraction with time-based eye glance measures is the first step toward this goal. In Phase II, the diagnostic measures of visual distraction will be implemented in terms of algorithmic logics. These findings will be considered together with findings from the cognitive distraction task. Methods of using distraction information to mitigate driver distraction and adapt safety warning countermeasure systems will be investigated. The algorithms will be optimized through iterative testing. The system effectiveness and user acceptance for these systems will be evaluated in Phase II.

7.5. REFERENCES

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