SAVE-IT

SAfety VEhicles using adaptive Interface Technology (Task 3A)

Typical Values for Driving Performance with Emphasis on the Standard Deviation of Lane Position: A Summary of the Literature

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December 2004

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3.0 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.

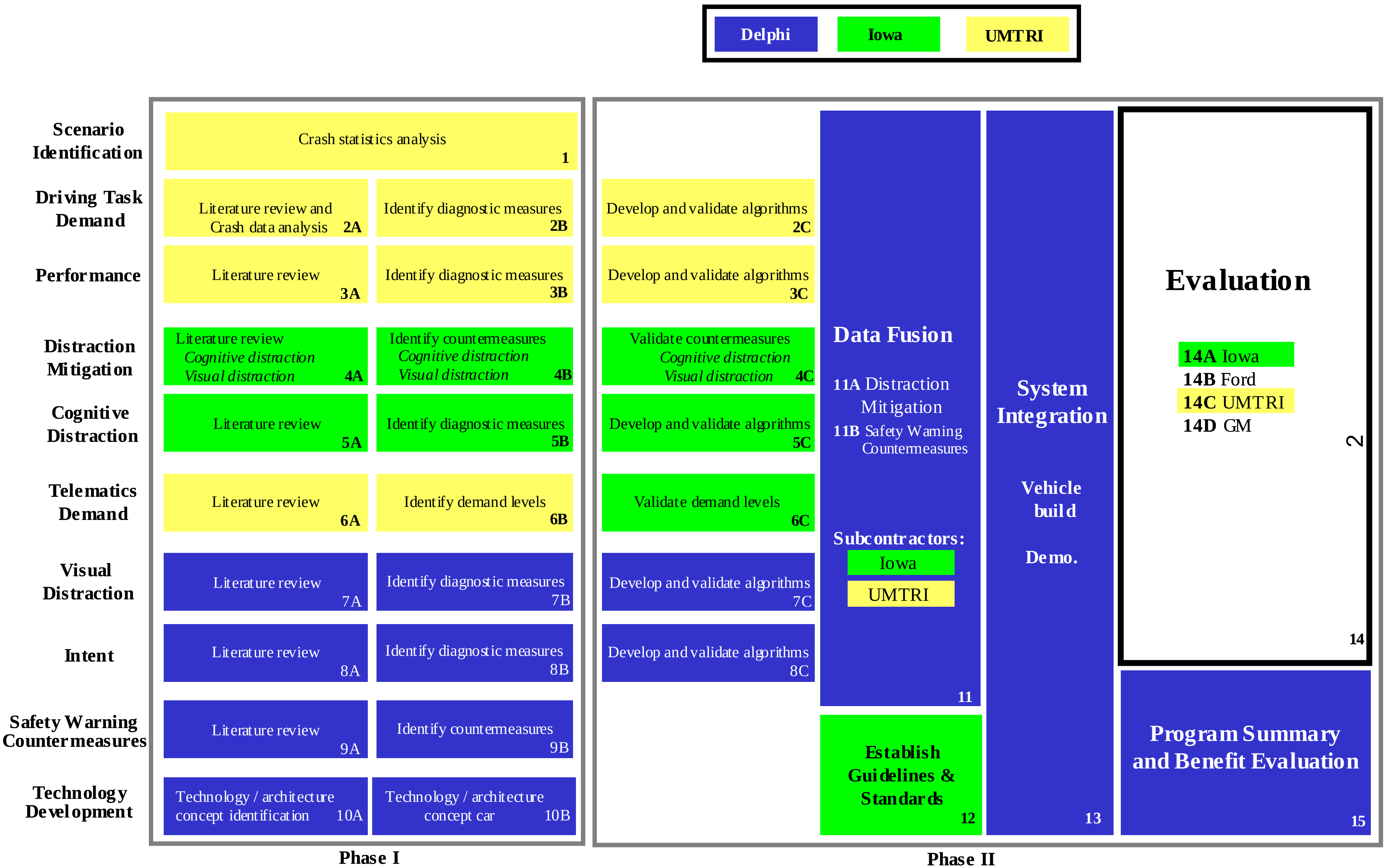


Figure i: SAVE-IT tasks

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.

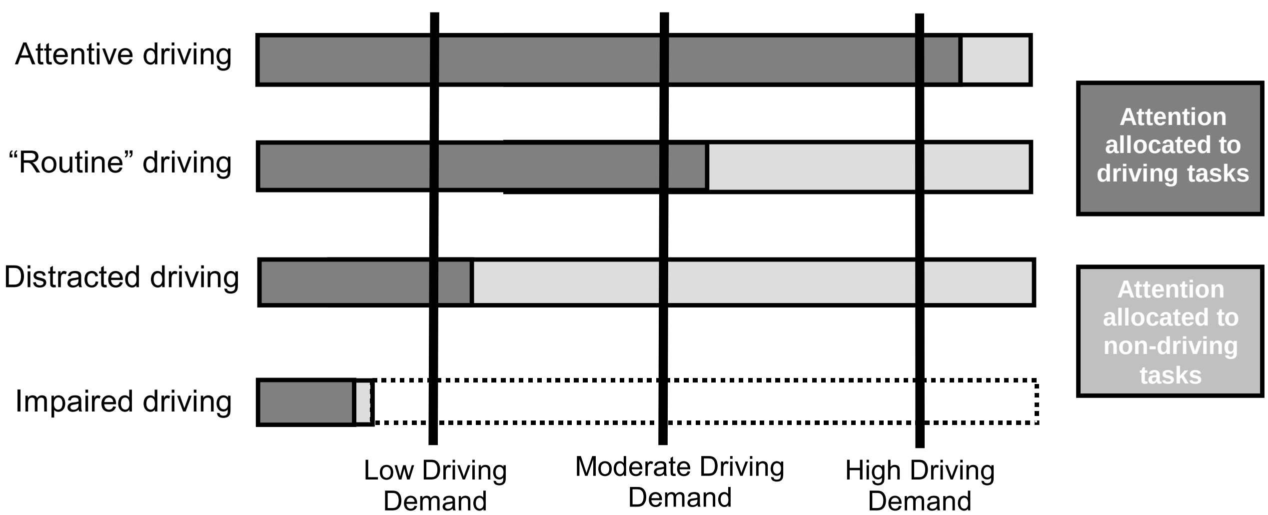


Figure ii. Attention allocation to driving and non-driving tasks

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™ (formerly called GlobalSim™) from Drive Safety Inc., and the same eye tracking system, FaceLab™ from Seeing Machines, Inc. are used in Phase I tasks at all sites. The performance variables (e.g., steering angle, lane position, headway) and eye gaze measures (e.g., gaze coordinate) are defined in the same manner across tasks.

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

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

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

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

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

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

The Content and Structure of the Report

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

3.1 INTRODUCTION

3.1.1 Background

Motor vehicle crashes are a major cause of death, especially among young individuals. In 2003, approximately 43,945 people died in crashes in the U.S. (http://www.madd.org/stats/0,1056,1298,00.html). In 1998 worldwide, an estimated 1.17 million people died as a direct result of injuries from a motor vehicle crash and 38.85 million were injured (World Health Organization, 1999). Reducing the number of driving-related fatalities and injuries is a major public health and safety issue.

Recently, there has been a great deal of interest in crashes related to distraction, especially where a telematics device such as a cell phone or navigation system is involved (e.g., Goodman, Bents, Tijerina, Wierwille, Lerner, and Benel, 1997; Stutts, Reinfurt, Staplin, and Rodgman, 2001).

One proposal to minimize distraction-related crashes is to equip vehicles with a workload manager. That system will determine the demand of driving at any given moment and, based on that information, determine if the driver can concurrently perform the in-vehicle task without overload. In a practical sense, this might take the form of automatically routing incoming cell phone calls to an answering machine when the driver is performing a high demand maneuver (e.g., turning or exiting an expressway). Workload managers are not a new idea (e.g., Verwey, 1990; Michon, 1993; Green, 2000; Remboski et al, 2000; Hoedemaeker, de Ridder, and Janssen, 2002).

This report is part of a large project (SAVE-IT, SAfety VEhicles using adaptive Interface Technology) funded by the U.S. Department of Transportation. The intent of this project is to conduct research and develop new technology that will reduce driver distraction (and resulting crashes) induced by telematics devices. Delphi is the prime contractor and the University of Michigan, the University of Iowa, Ford, GM, and Seeing Machines are subcontractors. A unique aspect of this project is the linkage of the workload manager with safety countermeasure and warning systems.

To develop an effective workload manager, researchers need to understand the complex and highly practiced task of driving. There are a large number of ways to measure distraction (e.g., Green, 1995; Tijerina, Angell, Austria, Tan, and Kochhar, 2003). One can assess driving performance, task performance, spare capacity, ratings of difficulty, and so forth. Measures of several aspects of driving, such as task performance (Green and Shah, 2004), are discussed in other reports that are part of this project.

This particular report examines primary task demand. Measures of primary task demand include the number of lane departures, mean speed and speed variance, mean headway and headway variance, eyes off-the-road time, mean throttle angle and throttle angle variance, mean steering wheel angle and angle variance, numerous spectral analysis measures of steering wheel angle, and so forth (Godthelp, 1984; Green, 1995; Gawron, 2000).

Of these measures, lane departures, also known as lane busts and lane exceedances, are directly linked to safety. If a driver unintentionally departs from the lane, the opportunities for run-off-road, side-swipe, or collision-with-fixed-object (telephone pole, parked car, etc.) crashes are much greater. Unfortunately, there is no agreed-upon definition for this measure. Is it when a tire touches part of the lane line edge, when any part of the vehicle (including a wing mirror) is over any part of the lane, when any part of the vehicle has crossed to the far edge of the lane marker, or something else? Table 3.1 below lists possible boundaries for lane departures in terms of the two boundary elements: the subject vehicle and external object. The boundary element "external object" refers to static objects independent of the actual vehicle that could serve as the delineation for a lane departure. In spite of the disagreement concerning how to measure lane departure, there is no doubt that when it occurs, however defined, crash risk increases.

Table 3.1. Possible Boundaries for Lane Departure Calculations

Boundary Element	Boundary	Comment
Subject Vehicle	Outside edge of wing mirror	This is the widest part of the vehicle and could contact another vehicle or fixed object. Mirrors can break off with minimal damage.
	Edge of the body (often widest near the door handle height)	The collision is serious when the body is struck.
	Outside edge of outmost tire	If the boundary is a curb, contact is with the outside edge of the curve.
	Centerline of tire	This could make sense in simulators since the center point of the tire contact patch is used in calculations and is often readily determined.
External Object	Edge of lane marking closest to the object	If both drivers use this as the boundary, there is no contact assuming maximum width. However, it may be the "psychological edge."
	Centerline of the lane marking	At this point, vehicles at the outer edge of their lanes would just touch.
	Far edge of lane marking	This makes sense if the edge marking is considered a neutral zone.
	Actual edge of the pavement or lane	It is often the case that the paint is imperfectly applied to the road surface, so the lane marking is not painted on the edge of the pavement.
	A likely position of a vehicle or object in another lane	For fixed objects, this could be as much as a few feet from the lane edge. This is really the no-contact zone width.

To provide some perspective, for passenger cars, a tire is about 6-1/2 to 9 inches wide, the contact patch is a bit less, the outer tire edge to outer body edge is another 2-3 inches, and the wing mirror extends another 2-3 inches. Further, a typical expressway lane might be 12-feet wide, and occupied by a 6-foot wide car, nominally has 3 feet on each side.

Lane departures can occur because of a mechanical failure (tire blowing out), the driver being forced out of the lane (by another vehicle), and for other reasons. In ordinary driving, lane departures often may be the result of a lack of attention to maintaining lateral position. Because lane departures do not occur very often, alternative measures are often sought so that statistically significant differences can be readily identified.

The most commonly used measure of lateral control in human factors studies is the standard deviation of lane position. All of the factors that lead to lane departures influence the standard deviation of lane position in a similar manner. Furthermore, several simulator experiments and an on-the-road experiment in this project measured the standard deviation of lane position, so some sense of typical values and likely variation would provide a useful perspective for the data to be collected.

When this report was being planned, consideration was given to looking at other measures of vehicle control, in particular the standard deviation of speed. However, the review of the human factors literature showed that even though other measures had been reported for both baseline and other conditions, there were insufficient data to support a thorough statistical analysis, especially if driver age and road characteristics were to be considered. In the absence of statistical analysis, collected values were averaged and presented.

3.1.2 Research Issues

The following issues were examined:

1. What are the most commonly used measures of driving performance and what are their typical values?

2. For the most commonly cited measure, what are typical values for baseline (normal) driving?

3. For the most commonly cited measure, what are typical values when drivers are performing tasks that can distract them?

4. For the most commonly cited measure, what are typical values when drivers are debilitated in other ways, such as by drugs or alcohol?

5. How is the most commonly cited measure affected by traffic, speed, driving context (simulator vs. on-the-road tests), and other factors that should be considered in assessing the data and implementing a workload manager?

3.2 METHODS

The goal of this report was to determine typical values for common measures of driving performance criteria as presented in the human factors literature, and then perform an in-depth analysis of the most common measure. After reviewing said literature, standard deviation of lane position stood out as the primary measure to examine further. Therefore, a sub-goal of determining values for the standard deviation of lane position and how they varied as a function of common test conditions became apparent. Following an 8-step process, tables summarizing the literature were created and analyzed.

Step 1. Develop list of relevant documents. Searching the first author's personal collection and the UMTRI Library database identified relevant studies. Initially, the search of the library database was confined to documents coded as "distraction" and "driver information systems," and articles with "telematics" in their titles, but that led to very few items. Many of the documents coded with those terms were also coded as "multiple task performance," "driver performance testing," "driver behavior," and "adaptive cruise control," so the search was expanded to include them. This expanded search identified several relevant documents concerning drugs and driving. Because those documents included data both on normal driving (the control condition) and on abnormal conditions (drugged states), they were included in the data set.

Furthermore, it was apparent that several individuals were making repeated and significant contributions to this literature (e.g., Wierwille, Brookhuis, Nilsson, and O'Hanlon). To ensure that none of their research was omitted because of erroneous or incomplete keyword coding in the library database, their names were used as search terms.

In addition to this formal search, care was taken to include relevant UMTRI driver interface studies that may not have been keyword-coded properly by the Library.

Finally, the reference lists of the articles found in these initial steps were examined for additional leads.

The combined lists contained close to 1,000 documents with only a few items repeated across lists.

Step 2. Retrieve the most relevant articles from the list. Paul Green reviewed these lists and identified those articles that were most likely to have relevant information based on the title, authors, date, keywords, and other criteria listed below. Depending on the list, anywhere from a majority of all the articles to as few as 1 out of 8 were identified as candidates for review.

Articles were considered relevant when the following criteria were all met:

a. The topic seemed relevant. This decision was usually based on the title.

b. The context was appropriate – on the road, on a test track, or in a driving simulator of reasonable fidelity (not an abstract tracking task).
c. There was some confidence in the quality of the research because of where it was reported (in a proceedings paper, journal article, or technical report of a known organization (student reports for courses were excluded, for example)) or due to the reputation of the authors.
d. The publication was in English, the language of the authors. (Several studies in Japanese were not reviewed for this reason.)
e. The study examined real tasks.
f. The article could be readily obtained. This confined the list to articles in the UMTRI Library, online, or otherwise available to University of Michigan Transportation Research Institute staff. A few articles were requested, but the project timeframe limited the number of requests.
g. The article concerned passenger cars.

The search was reasonably comprehensive, but not exhaustive. One consequence of the availability criteria and the limited resources is that research from Europe and Japan is not covered as extensively as research done in the U.S. The authors apologize for this situation.

Step 3. Delegate and review the articles. Each of the coauthors selected a particular list or subset of a list to review. Each list was cohesive (grouped by author or by keyword and publication date).

Step 4. Construct a study synopsis table. If the article was relevant, summary information was added to a study synopsis table. Information recorded included the authors, publication date, title, context (simulator, test track, or road), road type (for example, curving expressway), speed driven, weather, traffic (ADT if provided), vehicle driven, number of subjects with their ages, gender, and relevant medical information (such as a drug dose examined), and the research issue at hand. Values were obtained from body text, tables, and figures. Appendix A contains the main synopsis table.

Step 5. Construct a driving performance summary table. This table (actually, an Excel file) listed the authors, publication date, condition (road or simulator, a drug examined, or other characterizing information), subjects' age and gender, standard deviation of lane position, standard deviation of speed, and other information (standard deviation of headway, lane departures, and so forth), depending on what was documented in each study. This file was used for data analysis.

In constructing the synopsis and driving performance tables, studies were partitioned to the degree afforded by the original documents. For example, if there were two test conditions, baseline and alcohol, the means for both conditions were included in the master table. If each of those two conditions examined two other conditions (say, both expressways and rural roads), all four data points were included (where available) in the table. If not, only the first two condition (in this case, baseline and alcohol driving) means were included.

Some of the analyses include subject age. If the mean subject age was given, that value was used in the calculations. However, if, as in many of the cases, the subject mean age was not given, nor was data provided to compute it, the mean age was estimated by summing the minimum and maximum values and dividing by 2. So if subjects ranged in age from 18-72, the mean used was 45 ((18+72)/2). The authors' experience suggests that subjects are more likely to be from the lower end of that range, so the estimate is a bit high. However, no data was available to suggest a correction.

In some cases, a maximum age value was not provided; for example, where subjects were reported to be ages 65 and above. In that case, experience suggests a range of 10 or so years, and accordingly a mean of 70 was used. Had these estimates for mean age not been used, there would not have been sufficient data to examine age in detail.

Step 6. Conduct the preliminary analysis. The preliminary analysis revealed some inconsistent coding in the performance summary table. To re-code the data, many of the original articles were re-examined. This was necessary because at the onset it was uncertain which details were contained in the yet-to-be-read articles.

Step 7. Summarize all non-standard deviation of lane departure criteria. After it was concluded that standard deviation of lane position was the primary measure to examine, 9 of the original 36 articles were selected and all other criteria were summarized. These 9 articles were selected by reviewing the previous driving performance summary table (Step 5) for measures other than the standard deviation of lane position. A table presenting all criteria and their averaged presented value was then created.

Step 8. Analyze standard deviation of lane position data to find trends. Of particular interest were the range of values reported, differences due to context (on the road vs. simulator vs. test track), and differences due to driver age. Special emphasis was given to the standard deviation of lane position because it was reported far more often than others and was amenable to in-depth analysis.

3.3 RESULTS

3.3.1 Overview of Selected Articles for Initial Review

Nine key documents were initially examined. Table 3.2 lists the driving performance measures reported in each of those studies. The selection was admittedly biased towards prior UMTRI research because of the authors' knowledge of those studies and because they were known to report multiple measures of driving performance.

Table 3.2. Summary Table for Driving Performance Criteria

Author (Year)	Title	SD Lane Position	SD Steering Wheel Angle	SD Velocity	SD Throttle Position	SD Lateral Speed	TLC	SD Headway	Headway	Lane Exceedance	SD of Avg. Decel.
Baker & Boardman (2001)	Human Factors Studies…	X	X	X							
De Waard & Brookhuis (1991)	Assessing Driver Status…	X	X								
Fancher et al. (1998)	Intelligent Cruise Control Field…			X				X			X
Godthelp, Milgram, & Blaauw (1984)	Development of a Time-Related…	X	X			X					
Green, Williams, Hoekstra, George, & Wen (1993)	Initial On-the-Road…	X	X	X	X						
Green, Hoekstra, & Williams (1993)	Further On-the-Road…	X	X	X	X						

Author (Year)	Title	SD Lane Position	SD Steering Wheel Angle	SD Velocity	SD Throttle Position	SD Lateral Speed	TLC	SD Headway	Headway	Lane Exceedance	SD of Avg. Decel.
Noy (1990)	Attention and performance …	X		X			X		X	X	
Tsimhoni, Green, & Lai (2001)	Listen-ing to Natural…	X	X								
Tsimhoni, Watanabe, Green, & Friedman (2000)	Display of Short Text…	X	X								
TOTALS:		**8**	**7**	**5**	**2**	**1**	**1**	**1**	**1**	**1**	**1**

The most commonly reported measure was the standard deviation of lane position (8 of the 9 studies) followed by the standard deviation of steering wheel angle (7 studies) and the standard deviation of speed (5 studies). The authors suspect that if a more extensive review was conducted, the relative frequency ratio of the standard deviation of lane position to other measures would be even greater.

Table 3.3 provides some sense of typical values for each of these measures, except for the standard deviation of lane position, which is summarized later. The number for values for each measure in the table exceeds the number of studies because most studies reported more than one value for each measure (for example, a value for normal and distracted driving). The raw data on which this table is based is contained in Appendix B.

Table 3.3. Mean Values for Collected Driving Performance Criteria

	Driving Performance Criteria	#	Mean
Driver Inputs	SD steering wheel angle (deg)	45	1.59
	SD throttle position (%)	6	3.27
Vehicle Parameters	SD velocity (m/s)	12	1.09
	SD lateral speed (m/s)	12	0.07
	SD of avg. decel. (g)	2	0.05
	Headway (m)	2	55.1
	SD headway (s)	1	0.6
	Time-to-line crossing (s)	2	3.19
	Lane exceedance (%)	2	0.01

Table 3.4 provides mean values for several measures of driving performance for normal (baseline) driving and while performing an in-vehicle task (that is, while distracted). For many measures, the number of data points is limited and across studies, the test context (on-road versus simulator), subject ages, and other factors of importance vary, and may be confounded with the normal-distracted differences of interest. Because of this confounding, simple statistical tests of mean differences may be misleading. In terms of percentage, the largest change is the decrease in the SD of velocity with distraction (about 40 %). There is a reduction in headway and lane exceedances, but there are only two data points for each. The raw data from which this table was derived is in Appendix B.

Table 3.4. Mean Driving Performance Values for Normal vs. Distracted Driving

		Normal		Distracted	
	Driving Performance Criteria	**#**	**Mean**	**#**	**Mean**
Driver Inputs	SD steering wheel angle (deg)	5	1.44	10	1.51
	SD throttle position (%)	2	3.25	4	3.29
Vehicle Parameters	SD velocity (m/s)	5	1.18	6	0.75
	SD lateral speed (m/s)	NA	NA	NA	NA
	SD of mean decel (g)	1	0.05	NA	NA
	Headway (m)	1	53.5	1	56.7
	SD headway (s)	NA	NA	NA	NA
	Time-to-line crossing (s)	1	3.47	1	2.9
	Lane exceedance (%)	1	0.00	1	0.02

3.3.2 Standard Deviation of Lane Position Analysis

Given the resources available, it was only feasible to perform an in-depth analysis of one of these measures, so the most common measure, the standard deviation of lane position, was selected.

3.3.2.1 What Is the Standard Deviation of Lane Position?

Unfortunately, there is no official, standard, or even well accepted definition of the standard deviation of lane position, and, in fact, it is extremely rare for research reporting results to define it.

The standard deviation has been defined as:

SD = Sqrt [∑ (xi - μ) ^2 / (N-1)]   (raw score standard deviation)
Sigma = Sqrt [∑ (xi – μ) ^2 / N]   (population standard deviation)

> Where xi are the lateral displacement values of the vehicle from the mean lane position at each point in time.

The mean lane position is determined by computing the mean of the lane position values over a period of time, usually sampled at 5-60 Hz, and except for very short tasks, 1 Hz is probably sufficient. The sampling frequency is usually not specified.

The drawback of this approach is that it assumes that the intended path is down the center of the lane. In fact, drivers cut corners when driving curves, increasing the standard deviation for curves for both baseline and distracted situations. The only way to determine lateral path variance is to repeatedly drive the same road to determine the desired path (hopefully not affected by other vehicles) or in some other way to determine the intended path. The authors do not know of any literature that addresses path determination or sampling frequency effects.

3.3.2.2 Overview of the Data

Overall, 36 studies reporting the standard deviation of lane position were examined, from which 121 data points were identified, each representing the mean for a condition for which the standard deviation of lane position was reported. For each data point, information was obtained on the mean age of subjects, context, road, traffic, test condition, speed driven or posted, and, of course, standard deviation of lane position. The only missing data points included 7 for age, 26 for traffic, and 15 for speed.

Table 3.5 shows the number of instances of each code for each of the four categorical variables (context, road, traffic, and condition). Notice that there were few test track studies, measurements taken on freeways/expressways predominated, and few data points pertained to heavy traffic.

Table 3.5. Categorical Variables Examined for Standard Deviation of Lane Position

Context	Count	**Road**	Count	**Traffic**	Count	**Condition**	Count
Public road	64	Freeway	68	None	38	Baseline	41
Simulator	50	Rural	35	Light	7	Task	28
Test track	7	Mix	9	Light-moderate	3	Drug	22
		Test track	7	Moderate	27	Occlusion	7
		Urban	2	Heavy	8	Sight distance	6
				Mixed	12	Alcohol	6
				Unknown	26	Road width	5
						Tires	2
						Cruise	1

In terms of conditions, baseline refers to the control conditions where subjects just drove. Task refers to where subjects performed in-vehicle tasks such as dialing a phone or entering a destination. The other conditions should be self-evident.

The master table containing the data for all tasks appears in Appendix A. The data are grouped by study and listed alphabetically by first author. The standard deviations were those values reported either in the body of the documents cited or in tables. In contrast to Green and Shah (2004), there was no need to estimate points from figures.

Across all 121 data points, the mean standard deviation of lane position was .26 m with a standard deviation of .12 m. Values ranged from .13 to .85 m.

As an initial cut at the data, ANOVA was used to see if there was a relationship between the discrete variables (context (road/simulator/test track), road type, and traffic) and the standard deviation of lane position. There were too many empty cells for a factorial analysis, so each factor was examined in a 1-way ANOVA. The outcomes of those analyses are described in the subsequent section.

Similarly, for the continuous variables (speed, subject age), stepwise regression analysis was used to determine if they affected the standard deviation of lane position. Neither of these two factors entered the regression ($p<.05$).

3.3.2.3 Context

Figure 3.1 shows the effect of the driving context on reports of standard deviation of lane position for all of the data examined. The mean standard deviations were .24 m for the road, .30 m for simulators, and .22 m for test tracks with standard deviations of .10, .14, and .04 m respectively. The differences among context means were statistically significant when all data were considered ($F(2,118)=4.05$, $p<.05$). Keep in mind that these deviations represent data across all conditions and there were very few data points from test track studies.

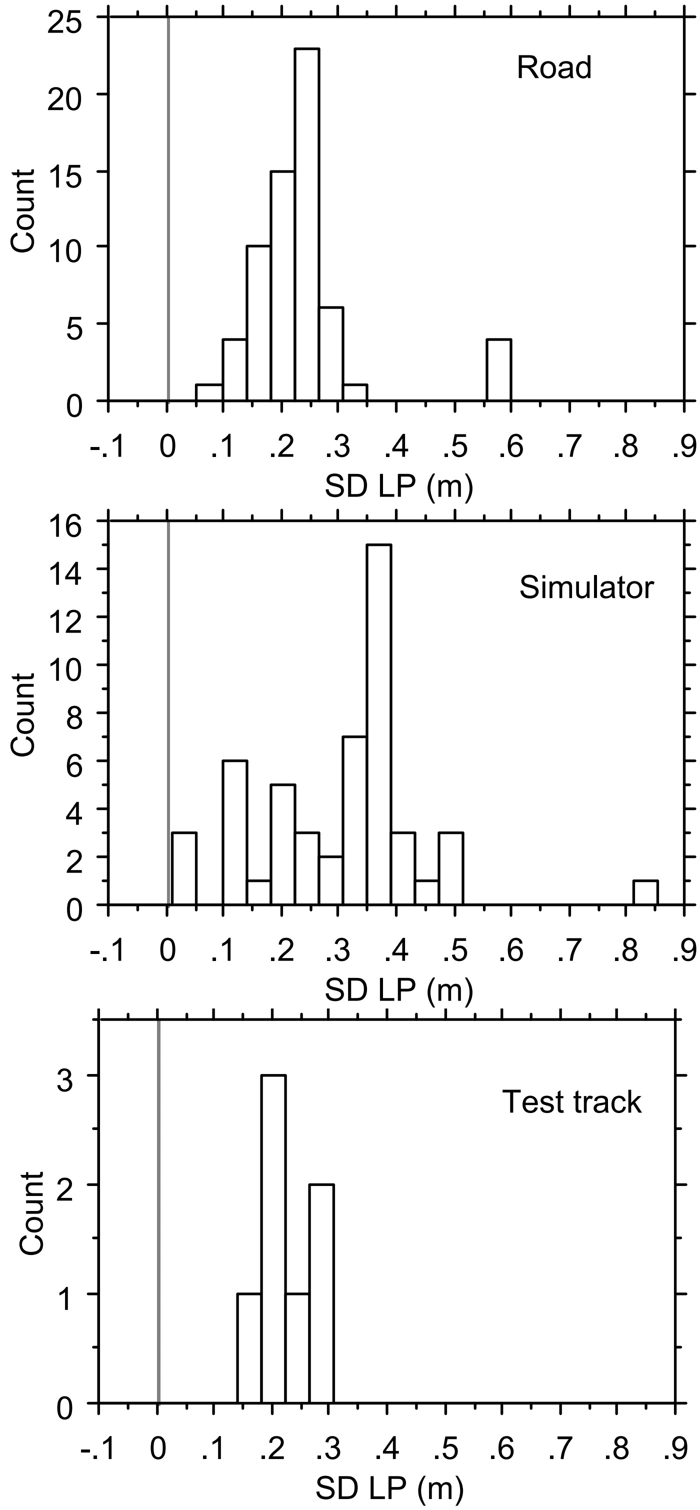


Figure 3.1. Standard Deviation of Lane Position for Various Contexts (All Data)

However, when only the baseline data was considered, the differences were not statistically significant ($F(2,36)=1.65$, $p=.21$), with means of .18, .23, and .21 m, respectively (and standard deviations of .04, .13, and .05 m). (See Figure 3.7 in Appendix C for the baseline distributions.)

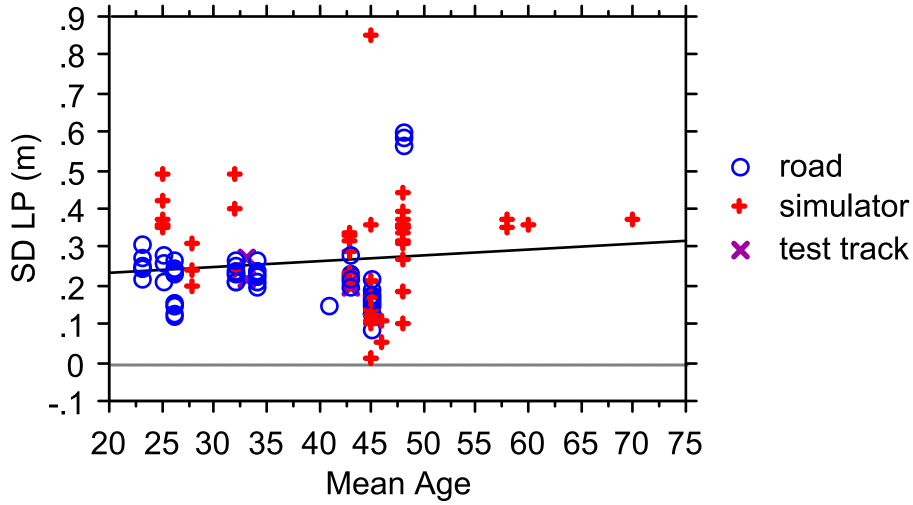
Why would the standard deviations be so much more variable in simulators, and why would they be slightly larger? The slightly elevated mean may be due to the lack of pressure to attend to the primary task of driving, mainly because the consequences of not attending to driving are less severe – there is no chance of dying in a simulator. The elevated mean may also reflect the lack of feedback. On a real road, departing from the lane can be scary: The vehicle jerks when the pavement drops off and shakes because of the uneven surface. Further, the sounds of driving on dirt or gravel are distinctive and the quality of this feedback varies considerably across simulators, but not as much across real vehicles, leading to larger differences among simulators.

Also, the first author has observed that in many simulators insufficient attention is paid to the disturbance function that leads to lateral drift. There are no unsteady crosswinds, the road surface is perfectly flat (not crowned), and the tire pressures are all exactly equal. In some cases, the disturbance function is the driver. For example, drivers may minimize the standard deviation of lane position by carefully aligning the vehicle with the road before deciding to take their hands off the wheel, maybe for as long as 10 s. This strategy may have few repercussions in a simulator, but it is not a good survival strategy for real-world driving.

The greater variability of lane deviation data gathered in simulator studies, versus that gleaned from real-world data, has not been a big issue for researchers. However, such differences could diminish the data's credibility with engineers making product decisions, especially if they have a vehicle dynamics background. Until now, researchers collecting simulator data stated that only *relative* differences – and the *order* of these differences – are of interest, and that these differences are preserved across simulator and real-world contexts. However, as simulator use increases and the scenes become more realistic, the demands for performance that mimics the real world will grow. In turn, this will decrease the significance of whether lane deviation data was gathered using a simulator or real-world driving.

3.3.2.4 Driver Age

Driver age has a consistent and large effect on driver performance (Green, 2001). As shown in Figure 3.2, standard deviation of lane position increases slightly (.002 m/yr) with driver age, but only age differences in excess of a decade are likely to be of even some importance (0.02 m/yr), which is 10% of the mean. The effect was not statistically significant. Recall that some of these data points represent estimated means for subject groups, in some cases over a wide range (e.g., 18-72). For that reason there are many data points clustered around age 45 and variability is large.

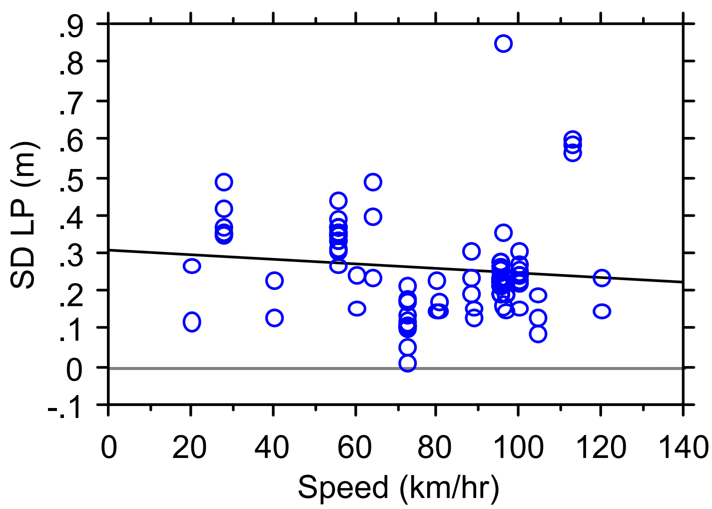


SD LP (m) = .198 + .002 * Mean Age; R^2 = .016

Figure 3.2. Standard Deviation of Lane Position vs. Age

3.3.2.5 Speed

As shown in Figure 3.3, the standard deviation of lane position decreased slightly with increasing speed, but the difference was not statistically significant. Higher speeds occur on roads with wider lanes, providing for more lateral maneuvering room and greater standard deviations. However, this is countered by the greater consequences of a lateral position error due to higher speeds, which require tighter control. Also, higher speed roads tend to be less demanding than slower speed (often urban) roads, allowing drivers to focus more on the driving task, hence lateral control.



SD LP (m) = .307 - .001 * Speed (km/hr); R^2 = .012

Figure 3.3. Effect of Speed on Standard Deviation of Lane Position

Figure 3.4 shows the relationship between driver age and the speed driven. Notice the very slight trend for drivers to decrease their speed as their age increases (collapsed across many factors), which makes sense. Older drivers tend to drive slower than younger drivers, all other things being equal.

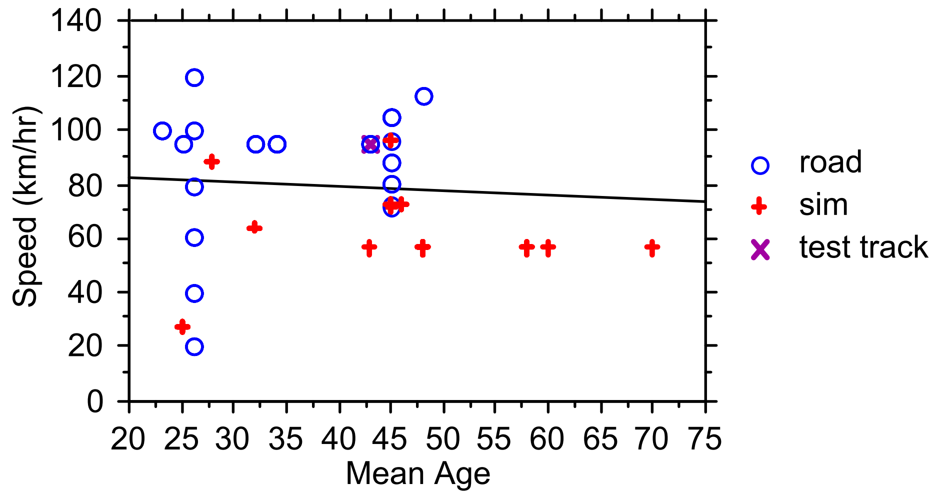


Figure 3.4. Speed vs. Mean Age

3.3.2.6 Road Type

Table 3.6 shows the standard deviation of lane position for various types of roads. The differences in the baselines were not statistically significant ($F(4,36)=0.56$, $p=0.69$) but the differences for all data were significant (F4,116)=2.58, $p<.05$). The "all data" case may reflect the use of more difficult test conditions on freeways and rural roads where it is safer to do so. Without a theory of how people drive, it is difficult to predict how the standard deviation of lane position should vary as a function of road type (or in fact, as any of the other factors examined).

Table 3.6. Standard Deviation of Lane Position for Various Road Types

Road Type	Baseline			All Data		
	Mean	SD	N	Mean	SD	N
Mixture of roads	.15	.02	3	.15	.03	9
Expressway	.20	.05	20	.27	.13	68
Test track	.22	.05	5	.22	.04	7
Rural	.23	.15	12	.29	.15	12
Urban	.23		1	.23	.00	2

(Mixture of roads refers to experiments where the results from several types of roads (urban, expressway, etc.) were pooled.)

3.3.2.7 Traffic

Table 3.7 shows the relationship between road types and traffic levels. There are too few data points to establish a connection, even when all of the data is used. (For baseline data only, see Appendix C.) Note: For the mixed road types (not shown), the traffic level was mixed.

Table 3.7. Standard Deviation of Lane Position as a Function of Traffic Levels and Road Type (All Data)

Traffic Level	Rural	City	Freeway	Test Track
None	26		12	
Light			5	2
Light-moderate				3
Moderate	2		25	
Heavy		2	6	

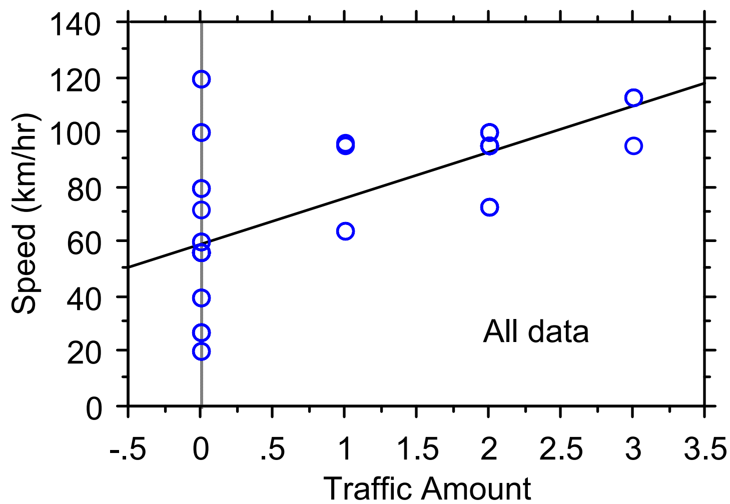
For reference purposes, Table 3.8 shows summary statistics for the standard deviation of lane position as a function of the traffic level for both the baseline and all data. When all of the data was included (including the conditions for which traffic level information was not available), there was a statistically significant difference between traffic levels ($F(6,114)=4.35$, $p<.001$). When only baseline data was considered, the difference was not statistically significant ($F(6,34)=0.84$, $p=.55$). With no traffic, there are fewer constraints on the driver, so the standard deviation of lane position should be moderately high. As the number of local vehicles increases, the maneuvering envelope around the driver decreases, which also decreases the standard deviation of lane position. On the other hand, drivers might be tempted to change lanes more frequently due to traffic, but lane changes become dangerous at high levels of traffic. Unfortunately, no studies in the literature have examined this relationship.

Table 3.8. Standard Deviation of Lane Position for Various Traffic Levels

Traffic Level	Baseline			All Data		
	Mean	SD	N	Mean	SD	N
None	.24	.13	13	.30	.12	38
Light	.21	.04	3	.28	.12	7
Light-moderate	.25	.04	2	.26	.03	3
Moderate	.15	.07	6	.22	.05	27
Heavy	.23	.00	2	.19	.08	8

Furthermore, as task loading increases (such as for the task conditions) or driver capabilities decrease (for example due to drugs or alcohol), as in the all data case, the mean standard deviation should increase. However, because of traffic constraints, the mean standard deviation was relatively lower as traffic levels increased. There are some indications (in Table 3.4) that these changes occur.

The various factors examined tended to be independent in terms of their influence on the standard deviation of speed, though there was a relationship between traffic and mean speed. Figure 3.5 shows the relationship for all data. A similar, but less striking, relationship for the baseline data is shown in Appendix C. In brief, speed increases with traffic; that is, higher speed roads were more congested.

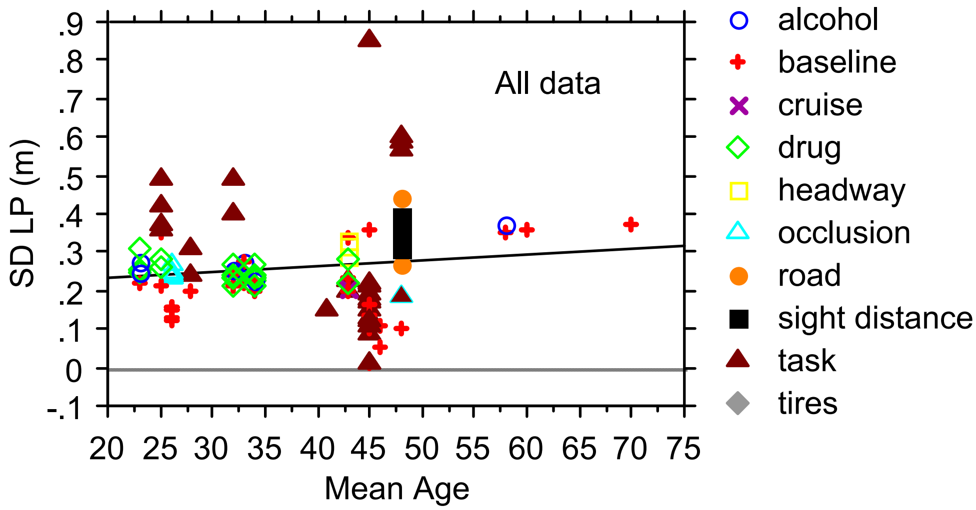


Speed (km/hr) = 58.515 + 16.818 * Traffic Amount; R^2 = .485

Figure 3.5. Speed as a Function of Traffic (All Data)

3.3.2.8 Experimental Condition Differences

Figure 3.6 shows the scatter of the data and the relationship between the various conditions explored and mean age. Note the considerable amount of overlap, at least across studies, between the baseline measurements and the experimental variables explored. This is not intended to say that these factors do not matter, only that within-study comparisons will be required to determine the statistical significance.



SD LP (m) = .198 + .002 * Mean Age; R^2 = .016

Figure 3.6. Experimental Differences Examined in the Literature
(Tires refer to varying the type of tires on the driven vehicle.)

Another perspective of these differences appears in Table 3.9, where the mean standard deviations by condition are sorted in increasing order. These differences were statistically significant ($F(9,111)=3.00$, $p<.01$). Across studies, the standard deviation due to task effects (talking on phones, entering destinations, etc.) increased the standard deviation of lane position by just under 50%. The size of this effect is larger than that reported for drugs and alcohol.

Table 3.9. Rank Order of Mean Standard Deviation by Condition

Condition	Mean	SD	N	Minimum	Maximum
Baseline	.21	.09	41	.01	.37
Cruise	.21	-	1	.21	.21
Occlusion	.23	.03	7	.18	.27
Drug	.24	.03	22	.21	.31
Alcohol	.27	.05	6	.22	.37
Headway	.31	.02	3	.29	.33
Task	.31	.20	28	.01	.85
Lane Width	.35	.06	5	.27	.44
Sight distance	.35	.03	6	.31	.39
Tires	.44	.09	2	.38	.50

3.3.2.9 Limitations of the Data

The data presented here are not without limitations. The authors relied on summary documents for means of the conditions. In some cases, the mean age was not provided, but instead estimated. In many of the studies, the appropriate category for a road was not specified. For example, was it appropriate to categorize a Dutch motorway as a divided highway (similar to that of a U.S. interstate highway)? There were no resources or time for follow-up to obtain this information.

Traffic was coded based on the terms used by authors of the original documents (e.g., light, moderate). In almost no cases was the traffic quantified (e.g., in terms of vehicles/lane/hr). Further, there are pronounced differences in congestion, the consequence of traffic, with greater congestion in Europe and Japan than in the U.S., and greater congestion in urban areas than rural areas.

The value used for speed was the driven speed when reported, or the posted speed limit if driven speed was not available.

Finally, the standard deviation of lane position values was used as presented in tables in the original authors' reports. About half of the 25 articles reported some or all of their data to three significant figures, in this case the nearest mm. The authors' experience suggests such accuracy is doubtful, with centimeter accuracy representing a more reasonable best case. None of the studies reported any data on the reliability of the lane position measurements and, for that matter, there is very little data in the literature on the accuracy of lane position sensors in general.

The authors hope that pointing out these shortcomings encourages researchers to report more engineering information concerning the driving situation to help make future research more amenable to analysis and application.

3.4 CONCLUSIONS AND COMMENTS

3.4.1 Questions That Were Addressed

1. What are the most commonly used measures of driving performance and what are their typical values?

In a sample of nine studies used to focus this analysis, the most commonly cited measures of driving performance were two driving input measures (standard deviation of steering wheel angle and standard deviation of throttle position) and seven vehicle performance measures (standard deviation of lane position, standard deviation of velocity, standard deviation of lateral speed, standard deviation of average deceleration, mean headway, standard deviation of headway, time-to-line crossing, and lane exceedances). Table 3.10, a repetition of Table 3.3, shows those values, except for the standard deviation of lane position, which is summarized later.

Table 3.10. Mean Values for Collected Driving Performance Criteria

	Driving Performance Criteria	#	Mean Value
Driver Inputs	SD steering wheel angle (deg)	45	1.59
	SD throttle position (%)	6	3.27
Vehicle Parameters	SD velocity (m/s)	12	1.09
	SD lateral speed (m/s)	12	0.07
	SD of avg. deceleration. (g)	2	0.05
	Headway (m)	2	55.1
	SD headway (s)	1	0.6
	Time-to-line crossing (s)	2	3.19
	Lane exceedance (%)	2	0.01

2. For baseline (normal) driving, what are typical values for the standard deviation of lane position?

A typical standard deviation of lane position for baseline driving is just under .2 m, approximately .18 m for driving on the road and approximately .23 m for simulators. The standard deviations of those values were approximately .10 and .14 m respectively, about half of the mean.

3. What are typical values for lane variance when drivers are performing tasks that can distract them?

When performing in-vehicle tasks, the mean increases to approximately .31 m and its standard deviation is about .20 m, most likely reflecting the wide range of task effects on driving. These values are from both on-the-road and simulator studies.

4. What are typical values for lane variance when drivers are debilitated in other ways, such as by drugs or alcohol?

The mean standard deviation of lane position is .27 m for studies involving alcohol and 0.24 m for studies involving drugs, averaged across simulator and on-the-road experiments.

5. How is lane variance affected by factors such as lane width and others that should be considered in assessing the data and implementing a workload manager?

The standard deviation increases with lane width, with speed, and with driver age, though none of these effects were statistically significant. The effects of traffic are unclear. Hugging the left or right side of the lane does affect mean lateral position, but not the change in SDLP between the baseline and distracted driving conditions.

3.4.2 Closing Thoughts

Although the search of the literature was fairly extensive, there are likely to be many studies that were not examined in this review. However, it is likely that even after a much more extensive review, there will still be significant gaps in the literature, in part because of inadequate reporting. Authors are not stating the mean age of subjects, providing details on the roads driven (e.g., lane width, the number of lanes, and sometimes even the speeds driven), and other information needed for the analysis completed here.

Most troublesome is the lack of predictive information in the literature that identifies how these and other factors are likely to influence the quality of driver control of a vehicle, in this case as measured by the standard deviation of lane position. Without such information, it is very difficult to assess if driving performance from baseline conditions is representative of the driving population at large (beyond the values presented here). More importantly, it is not possible to predict the degree to which a task or task combination is likely to disrupt driving. This makes interface engineering and workload manager design extremely difficult. Hopefully, future research will report more detailed condition information so results can be more easily analyzed and applied.

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3.6 APPENDIX A – MASTER TABLE

Table 3.11. Summary of Studies Examined

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Authors, year		(Sim, Rd., Track) / (None, Light, Mod, Heavy, NA)	Type (example, x-way), road width, surface type, edge markings, route #, etc.	(Km/hr) / (vehicle)	X men, y women; A ages b-c, etc.	Effect of ___ on driving
Baker & Boardman (2001)	HF Studies of Vehicle Int. Prod. - Interactive Driving Sim. Applied Res.	Sim / NA	X-way	88 / NA	31 total,17 male, 14 female; Overall average age of 28	in-vehicle display
Brookhuis, De Vries, & De Waard (1991)	The Effects of Mobile Telephoning on Driving Perf.	Road / Heavy & Light	Quiet motorway track, heavy traffic 4 lane ring road	95 / Volvo 245 GLD	12 total: 4 (23-35 yrs), 4 (35-50 yrs), 4 (50-65 yrs)	cell phone use on driver performance. Subjects drove for 1 hr/day for 3 wks, w/& w/o traffic
Davis & Green (1995)	Benefits of Sound for Driving Simulation: An Experimental Evaluation	Sim / None	Mixed left & right curves of equal radii, 2 lane road, each was 12ft wide	72.4 / Plymouth Laser	16 total: 4 male/4 female < 30 yrs, 4 male/4 female > 60 yrs	sound in a simulator & driver performance.
De Waard & Brookhuis (1991)	Assessing Driver Status: A Demonstration Experiment on the Road	Road / Light-Mod	Quiet motorway track - 75km, or low level traffic motorway track of 150km	100 / Volvo 245 GLD	20 males - 25-40 yrs old	alcohol (BAC<.05%) & vigilance (driving >150 min) on driver performance

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Fancher et al. (1998)	Intelligent Cruise Control Field Operational Test	Road / NA	All types (cars were driven in 2-5 week basis on all types of road)	NA / NA	108 total; 18 subjects in each group: males/female: (20-30 yrs, 40-50 yrs, 60-70 yrs)	operational test of ACC system
Feyen et al. (2000)	Effects of Shared Secondary Controls and Operational Modes on Performance and Perceived Workload During a Simulated Driving Task	Sim / None	27 road scenarios with identical lane configurations, speed requirements, and four curves of equal radii	NA / NA	16 total; 2 male and 2 female in each age group 17-30 yrs, 31-45 yrs, 46-60 yrs, 61-75 yrs	# of secondary controls (2,4,6), system modes (1,2,3), & number of functions per control (1,2,3) on driving performance
Fleming, Green, & Katz (1998)	Driving Performance and Memory for Traffic Messages: Effects of the # of Messages, Audio Quality, & Relevance	Road / Heavy	Fairly straight, flat highway; 2 and 3-lane road	113 / 1991 Honda Accord Wagon	32 total; 8 male/8 female 18-29 yrs; 8 male/8 female 65-81 yrs	# of traffic messages, audio quality & relevance on driver performance
Godthelp, Milgram, & Blaauw (1984)	The Development of a Time Related Measure to Describe Driving Strategy	Road / None	2 km stretch of a straight section of 4-lane unused highway	20-120 / Icarus	6 males (24-29 yrs)	occlusion & driving & determining a method for Time to Lane Crossing

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Green et al. (1993)	Initial On-the-Road Tests of Driver Information System Interfaces: Route Guidance, Traffic Information, IVSAWS, and Vehicle Monitoring	Road / Light-Heavy	Mixture of expressways, residential, suburban, & city roads - 19 turns required (35 min total)	40-105 / 1991 Honda Accord Wagon	43 total; 24 aged 18-30 yrs; 19 aged 60-74 yrs	route guidance system use & driver performance - only looked at the straight sections of road
Green et al. (1997)	Effects of Alcohol, Age, and Gender on Measures of Driving Performance in a Simulator	Sim / None	Curving 2 lane road, 12 ft (3.66m lanes), dashed centerline with single solid edge line	56 / Plymouth Laser	108 total: 18 male/18 female 31-54 yrs; 18 male/18 female 55-64 yrs; 18 male/18 female > 65 yrs	administering alcohol under the legal limit, a placebo, and a secondary task
Green, Hoekstra, & Williams (1993)	Further On-the-Road Tests of Driver Interfaces: Examination of a Route Guidance System and a Car Phone	Road / Light-Heavy	Mixture of expressways, residential, suburban, & city roads - 19 turns required (35 min total)	80-105 / 1991 Honda Accord Wagon	8 total; 4 20-23 yrs, 4 62-75 yrs	route guidance system and a car phone use on driver performance - only looked at the straight sections of road
Green, Lin, & Bagian (1994)	Driver Workload as a Function of Road Geometry: A Pilot Experiment	Sim / None	6 road sets (varying sight distance from 150 to 1140 ft, each having varying width from 7.5 -12 ft)	89 / Plymouth Laser	8 total; 2 male/2 female <35 yrs, 2 male/2 female > 65 yrs	road geometry & sight distance on driver performance

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Hoede-maeker et al. (1998)	Effects of driving style on headway preference and acceptance of an Adaptive Cruise Control (ACC)	Sim / Light-Heavy	2-lane highway with lane widths of 3.5 m & a third emergency lane	NA / BMW 518	38 total: (25 male/13 female, 25-60 yrs)	driving on headway preference and acceptance of an ACC
Hoede-maeker & Brookhuis (1998)	Behavioral adaptation to driving with an adaptive cruise control (ACC)	Sim / Heavy	2 lane highway with lane widths of 3.5 m & a third emergency lane	NA / BMW 518	38 total: (25 male/13 female, 25-60 yrs)	driving with adaptive cruise control
Katz et al. (1997)	On-the-Road Human Factors Evaluation of the Ali-Scout Navigation System	Road / Mod-Heavy	X-ways, arterial roads, & residential	45-105 / 1991 Honda Accord Wagon	9 male/9 female 19-30 yrs (mean 21) 9 male/9 female 40-55 yrs (mean 48) 9 male/9 female 65-79 yrs (mean 72)	navigation entry & driving performance
Liu, Schreiner, & Dingus (2000)	The effect of advanced traveler information display modality on driver performance	Sim / NA	No data	NA / Saturn	32 total younger (18-25 yrs), 0lder (> 60)	information modality
Manser & Even (2002)	Effects of in-vehicle distracter complexity on driving and emergency response performance	Sim / Light	Rural	64 / 1992 Saturn SC2	30 total, 15 male/15 female Overall mean 33 (18-71 yrs)	distraction complexity & driving performance

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Nowa-kowski, Freedman, & Green (2001)	Cell phone ring suppression and HUD caller ID: effectiveness in reducing momentary driver distraction under varying workload levels	Sim / Moderate	12-foot continuous roads, 1 straight section, & 2 curves	72.5 / NA	6 male/6 female 20-30 yrs, 6 male/6 female 60-75 yrs	cell phone ring suppression and use of HUD
Noy (1990)	Attention and performance while driving with auxiliary in-vehicle displays	Sim / Light	16 3-m, 2-lane roads; each with random seq. of straight and circular arc road segments with spiral transitions	60 / NA	30 total male and female subjects; 19-37 yrs	Basic human factors issues relating to the design and use of auxiliary in-vehicle displays
O'Hanlon et al. (1995)	Anxiolytic's Effects on the Actual Driving Performance of Patients and Healthy Volunteers in a Standardized Test	Road / NA	4-lane, divided highway	95 / NA	Experiment 1: 8 male/8 female 25-43 yrs (mean 34) Experiment 2: 9 male/9 female 22-34 yrs (mean 25) Experiment 3: 20 male/36 female 24-64 yrs (mean 43)	anxiolytics' effects & actual driving performance
Pape et al. (1999)	Performance Considerations for Run-off-road Countermeasure Systems for Cars and Trucks	Road / NA	Test track and X-way	96.5 / car, minivan, heavy truck	Not stated (summary of other articles)	performance considerations for a run-off-road countermeasure system

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Ramaekers & O'Hanlon (1994)	Acrivastine, terfenadine and diphenhydramine effects on driving performance as a function of dose and time after dosing	Road / NA	4-lane, divided highway	95 / NA	18 women, age 21-45 yrs	various antihistamines & driving performance
Ramaekers, Muntjewerff, & O'Hanlon (1995)	A comparative study of acute and subchronic effects of dothiepin, fluoxetine and placebo on psychomotor and actual driving performance	Road / NA	Highway	95 / NA	18 total, 10 men, 8 women 21-45 yrs	antidepressant medications & driving performance
Reed & Green (1999)	Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialing task	Road & Sim / Light	On-road: Two-lane surface streets & highway; Simulator: matched the geometry of the highway route	96.5 / Plymouth Laser & 1991 Honda Accord Wagon	Same subjects for both sections: 3 males/3 female 20-30 yrs, 3 male/3 female >60 yrs	driving performance on-road and in a low-cost simulator
Repa, Leucht, & Wierwille (1982)	The Effect of Simulator motion on Driver Performance	Sim / None	Not stated	NA / NA	3 research engineers	motion cues on driver performance in a simulator

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Robbe & O'Hanlon (1999)	Marijuana, Alcohol and Actual Driving Performance	Road / Moderate	4-lane, divided highway	100 / Volvo 240 GL	18 total, 9 male/9 female 20-28 yrs (mean of 22.7)	Determine the separate and combined effects of marijuana and alcohol on driving performance
Rudin-Brown & Noy (2002)	An Investigation of Behavioral Adaptation to Lane Departure Warnings	Road & Sim / NA	Simulator: rural, 2-lane highway; on-road: 6.9 km low-speed test track	Sim:60 & road:70 / 1999 Toyota Camry	Simulator: 60 students between 21-34 yrs; On-road: 26 participants 21-44 yrs;	Ability of lane departure warnings to induce behavioral adaptation in drivers performing a secondary number-entry task
Salvucci (2001)	Predicting the Effects of In-car Interface use on Driver Performance: an Integrated Model Approach	Sim / None	1-lane roadway - 3.66m wide	99.3 / Nissan 240SX	11 total - 5 female/6 male (mean age of 25)	drivers dialing cell phones using 4 interfaces vs. no dialing on lateral deviation
Sato et al. (1998)	A Study on Lane Departure Warning System Using Steering Torque as a Warning Signal	Sim / NA	Simulated road (1.6 m wide, 3.5 km long) with one lane	100 / NA	9 total	Normal driving (baseline SDLP) was necessary to determine the requirement for the torque warning

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Soma, Suzuki, Hiramatsu, & Ito (1999)	Experimental Investigations of Dynamical Lateral Vehicle Position on Japanese Expressways for Design and Standardization of Lane Departure Warning System	Road / NA	Japanese expressways	NA / passenger car	10 total; all males between 20-50 yrs	dynamic lateral vehicle position on Japanese expressways for a lane departure warning system
Stein, Parseghian, & Allen (1987)	A simulator study of the safety implications of cellular mobile phone use	Sim / NA	15-mile rural highway with obstacles (box appearing in road)	NA / 1981 Honda Accord	72 total; 12 male/12 female subjects in each grouping: <25 yrs, 25-55 yrs, & >55 yrs	safety implications of cellular mobile phone use
Tsimhoni & Green (2001)	Visual Demand of Driving and the Execution of Display-Intensive in-Vehicle Tasks	Sim / NA	3 different curve radii (582 m, 291 m, 194 m), 2 lane (3.66 m wide lanes), left & right curves alternating	NA / Plymouth Laser	16 total; 4 male/4 female 21-28 yrs; 4 male/4 female 66-73 yrs	telematics on driver performance - when telematics can be distracting using occlusion method
Tsimhoni, Green, & Lai (2001)	Listening to natural and synthesized speed while driving: effects on user performance	Sim / Moderate	Curving 2-lane road, 12 ft (3.66 m lanes)	72.5 / Plymouth Laser	24 total, 6 male/6 female 21-28 yrs, 6 male/6 female 65-71 yrs	listening to messages on driving performance

Study	Title	Context/ Traffic	Road	Speed/ Vehicle	# Subjects, Genders, Ages	Research issue
Tsimhoni et al. (2000)	Display of Short Text Messages on Automotive HUDs: Effects of driving workload and message location;	Sim / NA	3.66 m wide road with varying curvature levels: straight, moderate (582 m rad) & sharp (194 m rad)	72.5 / Plymouth Laser	16 total, 4 male/4 female 22-27 yrs, 4 male/4 female 65-71 yrs	driving workload and message location when short text messages were displayed on an automotive HUD
Vermeeren & O'Hanlon (1998)	Fexofenadine's effects, along and with alcohol, on actual driving and psychomotor performance	Road / Moderate	X-way	95 / NA	24 total, 12 male/12 female 22-44 yrs (mean 31.5)	fexofenadine with and without alcohol on driving performance
Vermeeren, Ramaekers, & O'Hanlon (2002)	Fexofenadine's effects, along and with alcohol, on actual driving and psychomotor performance	Road / Moderate	X-way	95 / NA	24 total, 12 male/12 female 22-44 yrs (mean 31.5)	fexofenadine with and without alcohol on driving performance

3.7 APPENDIX B – SUPPLEMENTAL FIGURES AND TABLES

Index:

Driver Inputs:	SD Steering Wheel Angle
	SD Throttle Position
Vehicle Parameters:	SD Velocity
	SD Lateral Speed
	SD Avg. Decel.
	Headway
	SD Headway
	Time-to-Line Crossing
	Lane Exceedance

Table 3.12. Driving Performance Values

SD Steering Wheel Angle (degrees)		
Study	**Value**	**Notes:**
Green, Williams, Hoekstra, George, & Wen (1993)	1.13	an IP interface
	1.01	a HUD interface
	0.89	an auditory interface
	1.63	mean male subject value
	0.96	mean female subject value
Tsimhoni, Green, & Lai (2001)	2.86	curves
	0.92	straights
Tsimhoni, Watanabe, Green, & Friedman (2000)	1.72	no task (young subjects)
	1.60	detection task (young subjects)
	1.78	reading task (young subjects)
	2.00	no task (old subjects)
	2.29	detection task (old subjects)
	2.46	reading task (old subjects)
	1.35	straight section (young subjects)
	1.66	moderate curves (young subjects)
	4.01	sharp curves (young subjects)
	1.03	straight section (old subjects)
	1.32	moderate curves (old subjects)
	2.86	sharp curves (old subjects)
	2.58	young male subjects
	1.43	old male subjects
	2.29	young female subjects
	2.23	old female subjects

De Waard & Brookhuis (1991)	1.20	baseline driving
	1.75	vigilance driving condition
	1.30	alcohol driving condition
Godthelp, Milgram, & Blaauw (1984)	3.00	20 km/h with occlusion
	2.10	40 km/h with occlusion
	1.80	60 km/h with occlusion
	1.60	80 km/h with occlusion
	1.50	100 km/h with occlusion
	1.60	120 km/h with occlusion
	1.20	20 km/h without occlusion
	0.90	40 km/h without occlusion
	0.85	60 km/h without occlusion
	0.90	80 km/h without occlusion
	1.10	100 km/h without occlusion
	1.20	120 km/h without occlusion
Baker & Boardman (2001)	1.47	control condition
	1.69	task condition
Green, Hoekstra, & Williams (1993)	0.8	baseline driving
	0.86	younger drivers under navigation condition
	0.99	older drivers under navigation condition
	0.7475	younger drivers while using phone
	0.935	older drivers while using phone

SD Throttle Position (%)

Study	Value	Notes:
Green, Williams, Hoekstra, George, & Wen (1993)	3.50	baseline driving
Green, Hoekstra, & Williams (1993)	3.00	baseline driving
	3.63	younger drivers under navigation condition
	3.83	older drivers under navigation condition
	3.11	younger drivers while using phone
	2.58	older drivers while using phone

SD Velocity (m/s)		
Study	***Value***	**Notes:**
Green, Williams, Hoekstra, George, & Wen (1993)	0.72	baseline driving
Noy (1990)	0.79	controlled driving
	0.94	driving with dual task
Fancher et al. (1998)	2.86	all drivers with manual control
	2.65	all drivers ACC control
Baker & Boardman (2001)	1.03	control condition
	0.99	task condition
Green, Hoekstra, & Williams (1993)	0.50	baseline driving
	0.64	younger drivers under navigation condition
	0.65	older drivers under navigation condition
	0.67	younger drivers while using phone
	0.62	older drivers while using phone

SD Lateral Speed (m/s)		
Study	**Value**	**Notes:**
Godthelp, Milgram, & Blaauw (1984)	0.02	20 km/h with occlusion
	0.04	40 km/h with occlusion
	0.05	60 km/h with occlusion
	0.06	80 km/h with occlusion
	0.07	100 km/h with occlusion
	0.08	120 km/h with occlusion
	0.07	20 km/h without occlusion
	0.08	40 km/h without occlusion
	0.10	60 km/h without occlusion
	0.10	80 km/h without occlusion
	0.12	100 km/h without occlusion
	0.13	120 km/h without occlusion

SD Mean Deceleration (g)		
Study	**Value**	**Notes:**
Fancher et al. (1998)	0.05	manual control for all drivers (55-85 mph)
	0.05	ACC control for all drivers (55-85 mph)

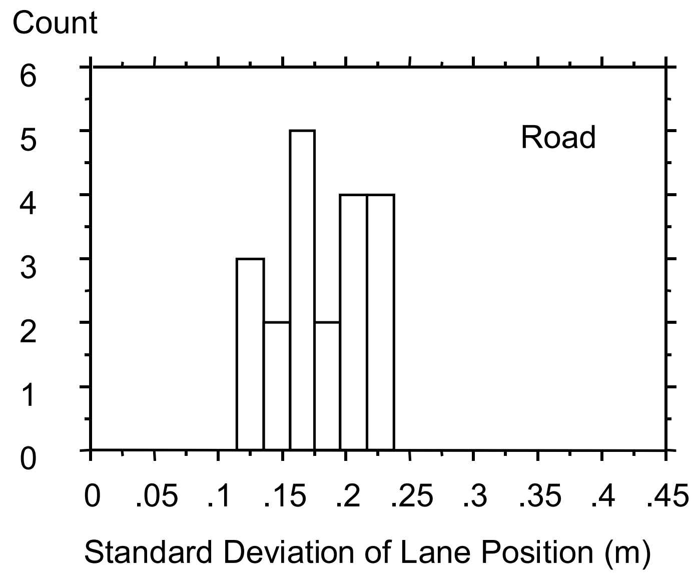
Headway (m)		
Study	**Value**	**Notes:**
Noy (1990)	53.50	controlled driving
	56.70	driving with dual task

SD Headway (s)		
Study	**Value**	**Notes:**
Fancher et al. (1998)	0.60	all drivers for ACC control

Time-to-Line Crossing (s)		
Study	**Value**	**Notes:**
Noy (1990)	3.47	controlled driving
	2.90	driving with dual task

Lane Exceedance (%)		
Study	**Value**	**Notes:**
Noy (1990)	0.00	controlled driving
	0.02	driving with dual task

3.8 APPENDIX C – SUPPLEMENTAL FIGURES AND TABLES



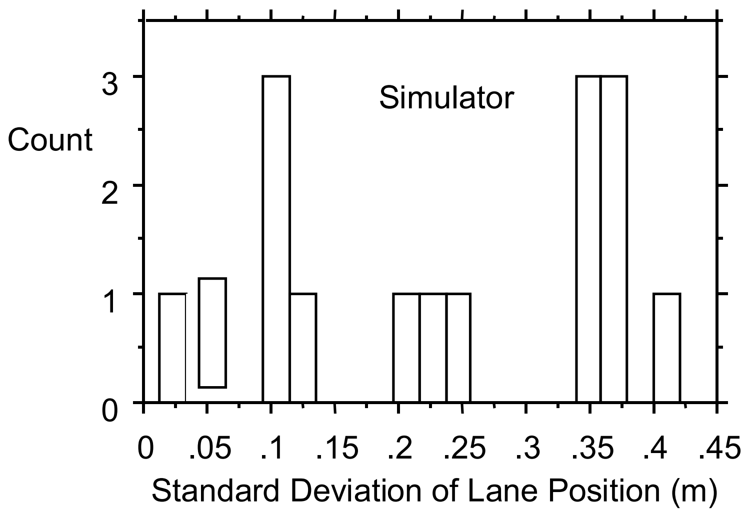


Figure 3.7. Baseline Standard Deviation of Lane Position
(Figure continued on next page)

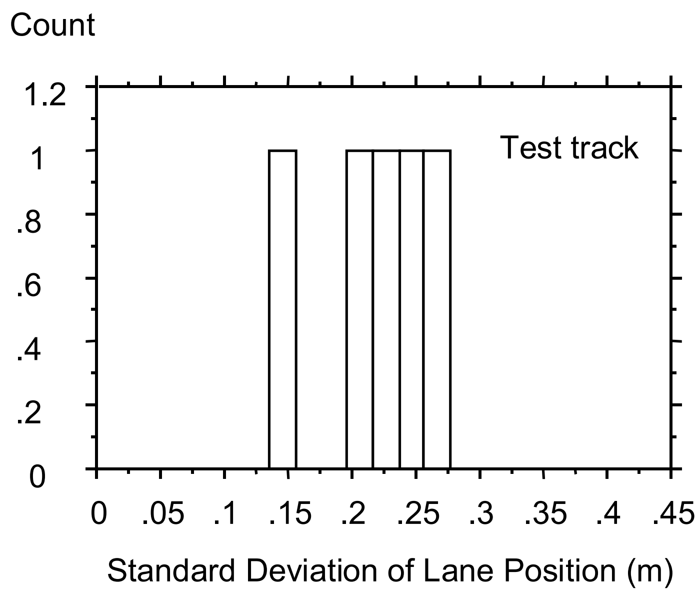
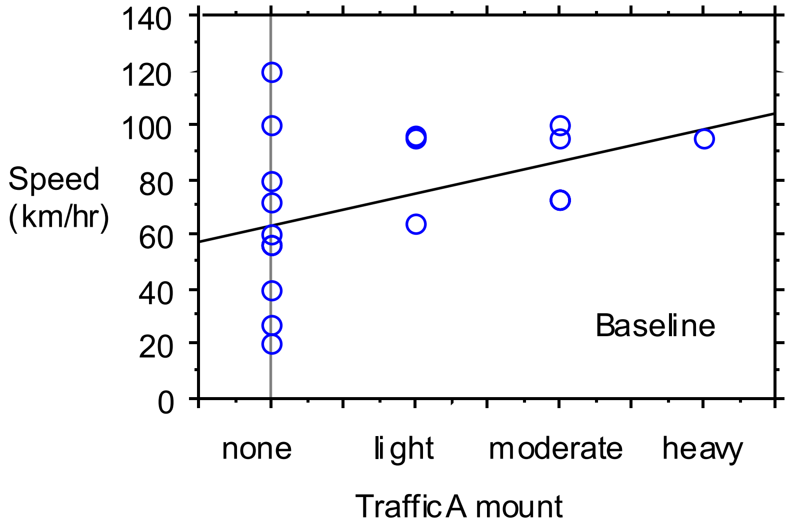


Figure 3.8. Baseline Standard Deviation of Lane Position

Table 3.13. Traffic Levels for Various Types of Roads (Baseline)

	Rural	City	Freeway	Test Track
None	7	-	6	-
Light	-	-	2	1
Light-moderate	-	-	-	2
Moderate	2	-	4	-
Moderate	-	-	-	-
Heavy	-	1	1	-



Speed (km/hr) = 63.385 + 11.502 * Traffic Amount; R^2 = .208

Figure 3.9. Relationship between Traffic and Speed for Baseline Conditions